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Delft University of Technology
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FEASIBLITY OF OFFSHORE WIND SUBSTRUCTURES IN ARCTIC ENVIRONMENTS

ADDENDUM – LITERATURE STUDY

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ADDENDUM

LITERATURE STUDY

PREFACE

As part of the thesis work an extensive literature study was performed regarding all facets related to offshore wind and arctic engineering. The results of the literature study are used to form a foundation for the performed case study. This addendum provides an overview of all literature that was examined as part of the scope of work for the thesis report.

This addendum contains all references regarding the relevant scientific articles, research papers, thesis reports, design standards, books and the curriculum of the TU Delft. The addendum is intended to provide a full background overview regarding related subject to the thesis report. In addition, the references contained within the thesis report relate to the overviews presented in this addendum. Not all literature examined during the literature study has been used or referenced to in writing of the thesis report. However, since the data had already been generated during the literature study, these unused references are still contained within this addendum for further reference.

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CHAPTER 1 – ARTICLES ON THE ARCTIC ENVIRONMENT

This chapter contains the overview of the scientific articles or research papers with relevant information about the Arctic Environment. The articles are focused on the environmental aspects of mainly the Barents and Baltic Seas. The Barents Sea was chosen as a reference area during the literature study, and the Baltic Sea was determined to be more suitable for the scope of the thesis.

Some parts of the large collection of articles are summarized, and other parts are included without performing an in-depth summary. An overview is presented of both the summarized and the not-summarized articles and papers in the following paragraphs. Summaries of the articles are included under Appendix A. Each article or paper is referenced and catalogued to correspond with the list of references contained in the thesis report.

1.1 OVERVIEW OF SUMMARISED ARTICLES

1.01	*Title:*	A study of the climatic system in the Barents Sea		
	Published by:	B. Adlaridsuik & H. Loeng	Bergen, NOR	1991
1.02	*Title:*	Anisotropy of Moderate and Strong Wind in Baltic		
	Published by:	T. Soomere & S. Keevallik	Tallinn, EST	2001
1.03	*Title:*	Atmospheric Forcing on the Barents Sea Winter Ice Extent		
	Published by:	A. Sorteberg & B. Kvingedal	Bergen, NOR	2006
1.04	*Title:*	Barents Sea drift ice characteristics		
	Published by:	T.Vinje & A.S. Kvambekk	Oslo, NOR	1990
1.05	*Title:*	Regional Reference: Barents Sea		
	Published by:	Fugro	Trondheim, NOR	2005
1.06	*Title:*	Features of the physical oceanographic conditions of the Barents Sea		
	Published by:	H. Loeng	Bergen, NOR	1991
1.07	*Title:*	Identifying Critical Sources of Bridge Deterioration in Cold Regions		
	Published by:	Yail J. Kim & D. K. Yoon	North Dakota, USA	2009
1.08	*Title:*	Sea ice in the Baltic Sea		
	Published by:	M. Granskog, H. Kaartokallio & H. Kuosa	Rovaniemi, FIN	2006
1.09	*Title:*	Simulation of currents, ice melting, and vertical mixing in the Barents Sea using a 3-D baroclinic mode		
	Published by:	K. Stble-Hansen & D. Slagstad	Trondheim, NOR	1991
1.10	*Title:*	The Baltic Sea – Environment and Ecology		
	Published by:	E. Furman & H. Salemaa	Helsinki, FIN	2004

1.11	*Title:*	Meteoric Ice contribution and influence of weather on landfast ice growth in the Gulf of Finland		
	Published by:	J.Uusikivi, M.A. Granskog & E.Sonninen	Helsinki, FIN	2011
1.12	*Title:*	Geophysics of sea ice in the Baltic Sea		
	Published by:	T. Vihma & J. Haapala	Helsinki, FIN	2009
1.13	*Title:*	Statisctical properties of sea ice surface topology in the Baltic Sea		
	Published by:	J. E. Lewis & M. Leppäranta	Quebec, CAN	1992
1.14	*Title:*	Baltic Sea Ice Season in the 20th Century		
	Published by:	S. Jevrejeva & V. V. Drabkin	Birkenhead, UK	2004
1.15	*Title:*	Baltic Sea Ice Breaking Reports 2007-2010		
	Published by:	Baltic Icebreaking Managment	Helsinki, FIN	2010
1.16	*Title:*	Simulating the Baltic Sea ice season with a coupled ice-ocean model		
	Published by:	J. Haapala & M. Leppäranta	Helsinki, FIN	1996
1.17	*Title:*	Ice Dynamics in the Bothnian Bay inferred from ADCP measurements		
	Published by:	G. Björk & C. Nohr	Göteborg, SWE	2007
1.18	*Title:*	Ice Ridges in the Coastal Area of Finland		
	Published by:	E. Palosuo	Helsinki, FIN	1971
1.19	*Title:*	Physical Oceanography of Baltic Sea – Synthesis		
	Published by:	K. Myrberg	Klaipeda, LIT	2008
1.20	*Title:*	Numerical modelling of thermodynamics and dynamics of sea ice in the Baltic Sea		
	Published by:	A.Herman & J. Jedrasik	Gdynia, PL	2011
1.21	*Title:*	Design Ice Load Level in the Baltic Sea		
	Published by:	S. Hänninen	Espoo, FIN	2003

1.2 OVERVIEW OF NON-SUMMARISED ARTICLES

1.22	*Title:*	A case study of a polar low development over the Barents Sea		
	Published by:	E. Rasmussen	Copenhagen, DK	1985
1.23	*Title:*	An enhanced sea-ice thermodynamic model applied to the Baltic sea		
	Published by:	L. Tedesco & M. Vichi	Helsinki, FIN	2009
1.24	*Title:*	Assessment of Future Wave Climate on basis of Wind-Wave-Correlations and Climate Change Scenarios		
	Published by:	N. Dreler & C. Schlamkow	Rostock, PL	2011
1.25	*Title:*	Baltic Sea Climate - 200 Years of data on air temperature, sea level variation, ice cover, and atmospheric oscillation		
	Published by:	A. Omstedt & C. Pettersen	Göteborg, SWE	2004

1.26	*Title:*	SMHI – The Baltic Sea		
	Published by:	M. Meier	Norrköping, SWE	2012
1.27	*Title:*	Hydrographic processes and changes in the Baltic Sea		
	Published by:	J.S. Møler & I.S. Hansen	Hørsholm, DK	1994
1.28	*Title:*	Ice thickness, growth and salinity in Van Mijenfjorden, Svalbard, Norway		
	Published by:	K.V. Høyland	Svalbard, NOR	2009
1.29	*Title:*	An ice drift model for the Baltic Sea		
	Published by:	M. Leppäranta	Helsinki, FIN	1981
1.30	*Title:*	Ice-Force measurements at the Gulf of Bothnia by the instrumented Kemi-1 lighthouse		
	Published by:	M. Määttänen	Oulu, FIN	1977
1.31	*Title:*	Ice Management Requirement in the Baltic Sea		
	Published by:	M. Juva & K. Riska	Sjöfartsverket, SWE	2002
1.32	*Title:*	Influence of the Arctic Oscillation and El Nino-Southern Oscillation on ice conditions in the Baltic Sea		
	Published by:	S. Jevrejeva & J.C. Moore	Birkenhead, UK	2003
1.33	*Title:*	Investigation on the Impact of Seasonally Frozen Soil on Seismic Response of Bridge Piers		
	Published by:	L.M. Wotherspoon & S. Sritharan	Auckland, NZ	2010
1.34	*Title:*	Investigations into the Physical and Chemical properties of Baltic Sea Ice		
	Published by:	M. Granskog	Helsinki, FIN	2004
1.35	*Title:*	Long-term changes in the Baltic Sea Ice Regime in the Baltic Sea near the Estonian Coast		
	Published by:	J. Sooäär & J. Jaagus	Tartu, EST	2007
1.36	*Title:*	Modeling the evolution of snow, snow ice and ice in the Baltic Sea		
	Published by:	T.M. Saloranta	Helsinki, FIN	1999
1.37	*Title:*	Numerical Modeling of the Wave Climate in the Southern Baltic Sea		
	Published by:	S. Blomgren & M. Larson	Lund, SWE	2001
1.38	*Title:*	Nummerical Simulation of Sea Ice Drift in the Gulf of Bothnia		
	Published by:	Z.H. Zhang & M. Leppäranta	Helsinki, FIN	2009
1.39	*Title:*	Oceanographic studies of the Baltic Sea with emphasis on sea ice and mixing processes		
	Published by:	C. Nohr	Göteborg, SWE	2009
1.40	*Title:*	Evidence about climate changes and shifts in the Baltic Sea		
	Published by:	Tarmo Soomere	Tallinn, EST	2007

1.41	*Title:*	One hundred years of hydrographic measurements		
	Published by:	S. Fonselius & J. Valerrama	Västra Frölunda, SWE	2003
1.42	*Title:*	Simulations and Measurements of Mesoscale Flow Modifications in the Baltic Sea Area		
	Published by:	K. Törnblom & C. Johansson	Uppsala, SWE	2002
1.43	*Title:*	Singular Spectrum Analysis of Baltic Sea Ice		
	Published by:	S. Jevrejeva & J.C. Moore	Tallinn, EST	2001
1.44	*Title:*	Statistics on Ice Loads measured in the Baltic		
	Published by:	K.P. Suominen & M. Riska	Helsinki, FIN	2009
1.45	*Title:*	Study on the Transition Zone between Fast Ice and Drifting Ice in the Bothnian Bay		
	Published by:	S. Sandven & M. Lundhaug	Bergen, NOR	1999
1.46	*Title:*	Trends in Sea Ice conditions in the Baltic Sea and the Relationship to large scale atmospheric circulation		
	Published by:	J. Jaagus	Tartu, EST	1983
1.47	*Title:*	Simulated sea level in past and future climates of the Baltic Sea		
	Published by:	M. Meier & B. Broman	Norrköping, SWE	2006
1.48	*Title:*	Validation and correction of regionalized ERA-40 wind fields over the Baltic Sea using the Rossby Centre Atmosphere model		
	Published by:	A. Höglund, M. Meier, B. Broman & E. Kriezi	Norrköping, SWE	2009
1.49	*Title:*	Long-term characteristics of simulated ice deformation in the Baltic Sea (1962–2007)		
	Published by:	U. Löptien & S. Mårtensson	Norrköping, SWE	2013
1.50	*Title:*	Estimation of Local Ice Conditions in the Baltic Sea for Offshore Wind Turbine Design		
	Published by:	M. Tikanmäki & J.Heinonen	Espoo, FIN	2012
1.51	*Title:*	OWEC Ice Loads in Landfast Ice Zone		
	Published by:	M.Määttänen & K. Vähätaini	Espoo, FIN	2013
1.52	*Title:*	Baltic Sea Ice Breaking Report 2010-2011		
	Published by:	Baltic Icebreaking Managment	Helsinki, FIN	2011
1.53	*Title:*	Baltic Sea Ice Breaking Report 2011-2012		
	Published by:	Baltic Icebreaking	Helsinki, FIN	2012
1.54	*Title:*	Baltic Sea Ice Breaking Report 2012-2013		
	Published by:	Baltic Icebreaking	Helsinki, FIN	2013
1.55	*Title:*	Baltic Sea Ice Breaking Report 2013-2014		
	Published by:	Baltic Icebreaking	Helsinki, FIN	2014
1.56	*Title:*	Submarine Holocene sedimentary disturbances in the Gulf of Bothnia		
	Published by:	A. Kotilainena & K.L. Hutri	Espoo, FIN	2003

1.57	*Title:*	An acoustic view into Holocene palaeoseismicity offshore southwestern Finland, Baltic Sea		
	Published by:	K.L. Hutri & A. Kotilainena	Helsinki, FIN	2006
1.58	*Title:*	Introduction to the Physical Oceanography of the Baltic Sea Environment		
	Published by:	K. Myberg	Klaipeda, LIT	2011
1.59	*Title:*	Iron and manganese layering in recent sediments in the Gulf of Bothnia		
	Published by:	J. Ingri & C. Pontér	Luleå, SWE	1986
1.60	*Title:*	Land-ice interaction in the Baltic Sea		
	Published by:	M.Määttänen	Helsinki, FIN	2012
1.61	*Title:*	Measured and numerically-simulated autumn cooling in the Bay of Bothnia		
	Published by:	A. Omstedt & J. Sahlberg	Luleå, SWE	1982
1.62	*Title:*	Modelling of Ice influence on sea level variations in the Baltic Sea		
	Published by:	Zhan-Hai Zang & M.Määttänen	Beijing, CHN	1995
1.63	*Title:*	Proceedings of 3rd Annual Swedish-Finnish Seminar on the Gulf of Bothnia		
	Published by:	P. Kengas & M. Forsskähl	Pori, FIN	1984
1.64	*Title:*	Seabed geomorphic features in a glaciated shelf of the Baltic Sea		
	Published by:	A.M. Kaskela & A.T. Kotilainen	Copenhagen, DK	2012

CHAPTER 2 – ARTICLES ON ICE MECHANICS

This chapter contains the overview of the scientific articles or research papers with relevant information about Ice Mechanics. The articles focus on the internal mechanics of ice floes and ridges. Also the determination of various forces acting on structures, conical and vertical surfaces and piles are discussed. Various dynamic effects of ice loading on structures are reviewed.

Some parts of the large collection of articles are summarized, and other parts are included without performing an in-depth summary. An overview is presented of both the summarized and the not-summarized articles and papers in the following paragraphs. Summaries of the articles are included under Appendix B. Each article or paper is referenced and catalogued to correspond with the list of references contained in the thesis report.

2.1 OVERVIEW OF SUMMARISED ARTICLES

2.01	*Title:*	A Spectral Model for Forces Due to Ice Crushing		
	Published by:	Tuomo Kärnä	Helsinki, FIN	2007
2.02	*Title:*	Estimation of Local Ice Pressure Using Up-Crossing Rate		
	Published by:	Chuanke Li & Ian J. Jordaan	St. John's, CAN	2010
2.03	*Title:*	Wind Induced Static Ice Forces on Offshore Structures		
	Published by:	J.V. Danys	Ottawa, CAN	1977
2.04	*Title:*	Local Design Pressures for Structures in Ice		
	Published by:	R.S. Taylor & I.J. Jordaan	St. John's, CAN	2010
2.05	*Title:*	Ice Sheet Failure against Inclined and Conical Surfaces		
	Published by:	M. Kaldjian	Michigan, USA	1987
2.06	*Title:*	Ice Forces affected by Temperature and Thickness of the Ice		
	Published by:	J. Schwarz & P. Jochmann	Luleå, SWE	2009
2.07	*Title:*	Refined Ice-Structure Interaction Model based on Observations in Gulf of Bothnia		
	Published by:	A. Engelbrektson	Stockholm, SWE	1997
2.08	*Title:*	Dynamics of the Ice Sheet interaction with a sloping structure		
	Published by:	K. Shkhinek & E. Uvarova	St. Petersburg, RUS	2000
2.09	*Title:*	Simulation of Ice Pile-Up process in FEM		
	Published by:	J. Paavilainen & J. Tuhkuri	Espoo, FIN	2009
2.10	*Title:*	Effect of cone shaped structures of impact forces of ice floes		
	Published by:	J. V. Danys	Ottawa, CAN	1971
2.11	*Title:*	Failure mode effect on conical structure in dynamic ice forces		
	Published by:	Feng Li & Qianjin Yue	Dalian, CHN	2007
2.12	*Title:*	Ice Ridge to Structure interaction – Geometry and failure modes of First Year ice ridges		
	Published by:	B. Bonnemaire & M. Bjerkas	Trondheim, NOR	2004

2.13	*Title:*	Global Ice load dependency on structure width and ice thickness		
	Published by:	K. Shkhinek & S. Løset	Trondheim, NOR	2003
2.14	*Title:*	Global Loads due to Ice Ridges		
	Published by:	T. Karna & C. W. Rim	Espoo, FIN	2001
2.15	*Title:*	Ice Forces on an Isolated Circular Pile		
	Published by:	R. Frederking & L.W. Gold	Ottawa, CAN	1971
2.16	*Title:*	Ice Load Spectrum on Narrow Conical Structures		
	Published by:	Y. Qianjin & Q. Yan	Dalian, CHN	2006
2.17	*Title:*	Stability of Self-Exicted Ice Induced structural vibrations		
	Published by:	M. Maattanen	Oulu, FIN	1977
2.18	*Title:*	Ice Load and Structure Vibration when Ice acts Up-Down Cone		
	Published by:	N. Xu & Q. Yu	Dalian, CHN	2007
2.19	*Title:*	Ice Rubble Build-Up on Conical Structures during Ridge Interactions		
	Published by:	R.F. McKenna & S.E. Bruneau	St. John's, CAN	1997
2.20	*Title:*	Ice ridges interaction with Confederation Bridge piers		
	Published by:	M.O. El Seify & T.G. Brown	Calgary, CAN	2006
2.21	*Title:*	Global Ice Loads on Lighthouse in Gulf of Bothnia		
	Published by:	M. Bjerkas & S. Løset	Trondheim, NOR	2003

2.2 OVERVIEW OF NON-SUMMARISED ARTICLES

2.22	*Title:*	A Dynamic Model for Ice-Induced Vibration of Structures		
	Published by:	G. Luang & P. Liu	Beijing, CHN	2009
2.23	*Title:*	A numerical model of ice crushing using a foam analogue		
	Published by:	R.E. Gagnon	St. John’s, CAN	2006
2.24	*Title:*	An Elastic–Viscous–Plastic Model for Sea Ice Dynamics		
	Published by:	E.C. Hunke & J.K. Dukowicz	New Mexico, USA	1997
2.25	*Title:*	Determination of Ice Forces on a Conical Offshore Structure		
	Published by:	J.V. Danys & F.G. Bercha	Ottawa, CAN	1975
2.26	*Title:*	Dynamic Bending Failure of Ice Floe on a Sloping Plane		
	Published by:	C. Sørensen	Lyngby, DK	1976
2.27	*Title:*	Dynamic Ice Loads on a Lighthouse Structure		
	Published by:	A. Engelbrekston	Stockholm, SWE	1977
2.28	*Title:*	Energy Based Ice Collision Forces		
	Published by:	C. Daley	St. John’s, CAN	1999
2.29	*Title:*	Experiences of Offshore Lighthouses in Sweden		

	Published by:	E. Reinius & S. Haggärd	Stockholm, SWE	1971
2.30	*Title:*	Experimental Study on Ice Force on a Pile		
	Published by:	H. Saeki & K.I. Hamanaka	Sapporo, JAP	1977
2.31	*Title:*	First Year Ice Ridges acting on Conical Structures		
	Published by:	D. Nevel	Houston, USA	2001
2.32	*Title:*	First-year Ridge Loads on Moored Offshore Structures		
	Published by:	D. Molyneux & J.M. Cholley	Houston, USA	2011
2.33	*Title:*	Flexural Strength of Brackish Water Ice		
	Published by:	M. Määtänen	Oulu, FIN	1975
2.34	*Title:*	Forces in Moving Ice Fields		
	Published by:	A. Assur	Hanover, USA	1971
2.35	*Title:*	Ice Floe against Offshore Structure Interaction		
	Published by:	B. Roes & S. Hanagud	Palo Alto, USA	1971
2.36	*Title:*	Ice Forces acting on Inclined Wedges		
	Published by:	P. Tryde	Lyngby, DK	1975
2.37	*Title:*	Ice Forces acting on Slender Structures		
	Published by:	P. Tryde	Lyngby, DK	1975
2.38	*Title:*	Ice Forces on Old and New Offshore Lighthouses		
	Published by:	J.V. Danys	Ottawa, CAN	1977
2.39	*Title:*	Ice Loads Acting on a Model Podded Propeller Blade		
	Published by:	J. Wang & A. Akinturk	St. John's, CAN	2005
2.40	*Title:*	Ice Resistance Measurements in Ridges in the Baltic Sea		
	Published by:	E. Mäkinen & A. Keinonen	Helsinki, FIN	1975
2.41	*Title:*	Influence of Ice Speed and Thickness on Ice Pressure and Load		
	Published by:	K. Shkhinek & T. Kärnä	St. Petersburg, RUS	2001
2.42	*Title:*	Influence of Individual Parameters on the Effective Pressure of Level Ice on a Lighthouse		
	Published by:	P. Jochmann & J. Schwarz	Hamburg, DE	2005
2.43	*Title:*	Interaction of Ice and Compliant Vertical Structure		
	Published by:	Y. Huang & Q. Shi	Tianjin, CHN	2005
2.44	*Title:*	Model Test of Ice Forces on Conical Structures		
	Published by:	L. Zhang & Z. Li	Dalian, CHN	2005
2.45	*Title:*	Model Test of Non-Uniform Ice on Upward Breaking Slope		
	Published by:	G.W. Timco & A. H. Cornett	Ottawa, CAN	1997
2.46	*Title:*	Modelling Unconsolidated Rubble Forces on a Cylyndrical Structure		
	Published by:	R.F. McKenna & S.E. Bruneau	St. John's, CAN	1997

2.47	*Title:*	Numerical Simulation of the Ice-Structure Interaction in LS-DYNA		
	Published by:	H. Daiyan & B. Sand	Narvik, NOR	2011
2.48	*Title:*	Numerical Simulation of Ridge and Sheet Ice Loads on Faceted Conical Structure		
	Published by:	Z. Wang D.B. Muggeridge	St. John's, CAN	1997
2.49	*Title:*	Shear Cap Analysis		
	Published by:	M.O. Elseify & T.G. Brown	Calgary, CAN	2007
2.50	*Title:*	Simulation of Sea Ice Pile up on Semicircle Structure		
	Published by:	C. Li & Y. Wang	Dalian, CHN	2007
2.51	*Title:*	Static and Dynamic Interaction of Floating Wedge-Shaped Ice Beams and Sloping Structures		
	Published by:	R. Lubbad & S. Løset	Trondheim, NOR	2008
2.52	*Title:*	Comparison of Kemi-I and Confederation Bridge cone ice load measurements results		
	Published by:	T.G. Brown & M. Määttänen	Calgary, CAN	2008
2.53	*Title:*	An analysis of the shapes of sea ice ridges		
	Published by:	G.W. Timco & R.P. Burden	St. John's, CAN	1996
2.54	*Title:*	Interfacing of Ice Load Simulation Tools for Cylindrical and Conical Structures with OneWind simulation tool for offshore wind turbines		
	Published by:	V. Jussila & W. Popko	Espoo, FIN	2013

CHAPTER 3 – ARTICLES ON OFFSHORE ARCTIC ENGINEERING

This chapter contains the overview of the scientific articles or research papers with relevant information about Offshore Arctic Engineering. These articles focus on offshore arctic engineering issues in general. Arctic structures, global ice loads on structures and cold climate engineering is reviewed. Also new arctic concepts are discussed and examined.

Some parts of the large collection of articles are summarized, and other parts are included without performing an in-depth summary. An overview is presented of both the summarized and the not-summarized articles and papers in the following paragraphs. Summaries of the articles are included under Appendix C. Each article or paper is referenced and catalogued to correspond with the list of references contained in the thesis report.

3.1 OVERVIEW OF SUMMARISED ARTICLES

3.01	*Title:*	Cost Effect of Ice Loads on Offshore Wind Generator Foundation		
	Published by:	M. Määttänen	Helsinki, FIN	2001
3.02	*Title:*	When Will Ice Ride-Up or Pile-Up Occur		
	Published by:	G. Li & K.W. Brown	Anchorage, USA	2009
3.03	*Title:*	The effect of Structure Shape on the Broken Ice Zone Surrounding Offshore Structures		
	Published by:	A. Barker & G. Timco	Ottawa, CAN	2003
3.04	*Title:*	Ice Force Design Considerations for Conical Offshore Structures		
	Published by:	T.D. Ralston	Houston, USA	1977
3.05	*Title:*	Ice Loads for Offshore Wind Turbines in the Southern Baltic Sea		
	Published by:	H. Gravesen & T. Kärnä	Trondheim, NOR	2009
3.06	*Title:*	Life-Cycle Cost-Effective Optimum Design of Ice-Resistant Offshore Platforms		
	Published by:	G. Li & D. Zhang	Dalian, CHN	2009
3.07	*Title:*	Meeting the Challenge of Founding Wind Turbines in the Baltic		
	Published by:	E. Eranti & E. Holttinen	Espoo, FIN	2003
3.08	*Title:*	A novel Offshore Windmill Foundation for Heavy Ice Conditions		
	Published by:	E. Eranti & H. Pukkila	Espoo, FIN	2011
3.09	*Title:*	Sea ice and icing risk for offshore wind turbines		
	Published by:	L. Battisti & A. Brighenti	Trento, ITA	2006
3.10	*Title:*	Extreme Ice and Wind Loads to Foundations		
	Published by:	H. Gravesen & C. Brojas	Glostrup, DK	2002

3.11	*Title:*	Monocone - Mobile Gravity Platform for Arctic Offshore		
	Published by:	W. Jazrawi & J. Khanna	Calgary, CAN	1977
3.12	*Title:*	Corrosion Protection for Steel Surfaces against moving Sea Ice		
	Published by:	D.H. Teesen	Washington, USA	1975
3.13	*Title:*	Design considerations of ice-resistant structures for shallow water oil and gas areas		
	Published by:	Q. Yue & D. Zhang	Dalian, CHN	2009
3.14	*Title:*	DNV Recommended Practice for Ice Effects on Offshore Arctic Structures		
	Published by:	A.B. Cammaert & A.M. Horn	Høvik, NOR	2009
3.15	*Title:*	Fixed Offshore Platforms in the Arctic		
	Published by:	R.P. Stag	Austin, USA	1971
3.16	*Title:*	Ice and Offshore Wind Turbines in the Gulf of Bothnia		
	Published by:	M. Määtänen	Espoo, FIN	2009
3.17	*Title:*	Ice Forces against a Steel Lighthouse and Proposed Structural Refinements		
	Published by:	M. Määtänen	Oulu, FIN	1975
3.18	*Title:*	Ice Loads for Wind Power Foundations in the Gulf of Bothnia		
	Published by:	L. Fransson & L. Bergdahl	Luleå, SWE	2009

3.2 OVERVIEW OF NON-SUMMARISED ARTICLES

3.19	*Title:*	Aker Arctic Technology		
	Published by:	G. Wilkman	-	2008
3.20	*Title:*	Analysis and Design of Buried Pipelines for Ice Gauging Hazards - A Probabilistic Approach		
	Published by:	A. Nobahar & S. Kenny	St. John's, CAN	2007
3.21	*Title:*	Analysis of Limit Driving Force on the Confederation Bridge		
	Published by:	N. Shrestha & D. Tripathi	Calgary, CAN	2009
3.22	*Title:*	API and CSA Design Ice Forces		
	Published by:	D.E. Nevel	Houston, USA	1997
3.23	*Title:*	Conditions for using Concrete in Arctic Harbours		
	Published by:	G.M. Idorn	Karlslunde, DK	1975
3.24	*Title:*	Critical roles of constitutive laws and numerical models in the design and development of Arctic offshore installations		
	Published by:	A. D. Aouat	St. John's, CAN	2010

3.25	*Title:*	Development of New Baltic Machinery Ice Class Rules		
	Published by:	P. Koskinen & G. Edelmann	Helsinki, FIN	1999
3.26	*Title:*	Ice Forces to Offshore Wind Turbine foundations in Denmark		
	Published by:	H. Gravesen	Trondheim, NOR	2003
3.27	*Title:*	Ice Load Design Recommendation in Europe		
	Published by:	M. Määtänen	Helsinki, FIN	2001
3.28	*Title:*	Ice Load on Vessel Moored in Broken Ice		
	Published by:	E.H. Hansen & S. Løset	Trondheim, NOR	1999
3.29	*Title:*	Ice Scour and Arctic Marine Pipelines - Workshop		
	Published by:	R. Phillips	Hokkaido, JAP	1998
3.30	*Title:*	Interaction between Ice and Coastal Structures		
	Published by:	P.M. Bruun	Trondheim, NOR	1971
3.31	*Title:*	Measurement of Ice Forces acting on a Lighthouse		
	Published by:	C.H. Atkinson & D.L.R. Cronin	Niagara Falls, CAN	1971
3.32	*Title:*	NRC Centre for Ice Loads on Offshore Structures		
	Published by:	G. Timco	Ottawa, CAN	1998
3.33	*Title:*	Offshore Structures in Ice-infested Waters		
	Published by:	Q. Yue	Dalian, CHN	2007
3.34	*Title:*	Ship & Offshore - Arctic Issue		
	Published by:	-	-	2011
3.35	*Title:*	Techniques for study of Ice-Structure Interaction		
	Published by:	R.J. Robbins	Calgary, CAN	1975
3.36	*Title:*	Static and Dynamic Ice Actions New Design Codes		
	Published by:	M. Bjerkás	Trondheim, NOR	2010
3.37	*Title:*	Experimental Study of Ice Force on Combined Cone		
	Published by:	Yuexia Qu, & Yongxue Wang	Dalian, CHN	2001
3.38	*Title:*	Influence of velocity on ice-cone interaction		
	Published by:	M. Lau & S.J. Jones	St. John’s, CAN	2005

CHAPTER 4 – ARTICLES ON OFFSHORE WIND ENGINEERING

This chapter contains the overview of the scientific articles or research papers with relevant information about Offshore Wind Engineering. The articles focus on all relevant aspects of offshore wind farm design, economics, environmental impact, logistics and construction. Various dynamic effects of wind loads are reviewed, and different design concepts for offshore wind support foundations are examined and compared.

Some parts of the large collection of articles are summarized, and other parts are included without performing an in-depth summary. An overview is presented of both the summarized and the not-summarized articles and papers in the following paragraphs. Summaries of the articles are included under Appendix D. Each article or paper is referenced and catalogued to correspond with the list of references contained in the thesis report.

4.1 OVERVIEW OF SUMMARISED ARTICLES

4.01	*Title:*	Conceptual designs for large scale offshore wind farms – DOWEC Final Results		
	Published by:	M.B. Zaaijer & H.B. Hendriks	Delft, NL	2005
4.02	*Title:*	Monopile foundations for Offshore Wind Turbines		
	Published by:	V.J. Kurian & C. Ganapathy	Perak, MY	2010
4.03	*Title:*	Waves for design of wind-power plants in shallow seas		
	Published by:	L. Berghdal & L. Fransson	Luleå, SWE	2009
4.04	*Title:*	Modelling offshore wind resources - Comparison of a mesoscale model and measurements from FINO 1 and North Sea oil rigs		
	Published by:	E. Berge & ø. Byrkjedal	Trondheim, NOR	2008
4.05	*Title:*	Comparison of Design Guidelines for Offshore Wind Energy Systems		
	Published by:	R.K. Saigal & D. Dolan	Houston, USA	2007
4.06	*Title:*	Design and Construction Considerations Offshore Wind Foundation		
	Published by:	S. Malhotra	New York, USA	2008
4.07	*Title:*	Design Concepts, Methods and Considerations Offshore Wind		
	Published by:	T. Ashuri & M.B. Zaaijer	Delft, NL	2009
4.08	*Title:*	DNV Design Standard Offshore Wind Structures		
	Published by:	T. Feld	Roskilde, DK	2007
4.09	*Title:*	Bottom Founded Steel Support Structure for Offshore Wind Turbines in deep water North Sea		
	Published by:	H. Subroto & R. Narold	Delft, NL	2004

4.10	*Title:*	Foundations for offshore wind turbines		
	Published by:	B.W. Byrne & G.T. Houlsby	Oxford, UK	2003
4.11	*Title:*	Comparison of monopile, tripod, suction bucket and gravity base design for a 6 MW turbine		
	Published by:	M.B. Zaaijer	Delft, NL	2005
4.12	*Title:*	Integrated Support Structure Design Analysis		
	Published by:	T. Feld & J. Waegter	Virum, DK	2003
4.13	*Title:*	Offshore Foundations for Offshore Wind		
	Published by:	Ballast Nedam	Nieuwegein, NL	2004
4.14	*Title:*	Structural and Economic Optimization on Offshore Wind Support Structures		
	Published by:	T. Feld & J.L. Rasmussen	Virum, DK	2000

4.2 OVERVIEW OF NON-SUMMARISED ARTICLES

4.15	*Title:*	Engineering Challenges for Floating Offshore Wind Turbines		
	Published by:	S. Butterfield & W. Musial	Golden, USA	2005
4.16	*Title:*	Foundations for building the Offshore Wind Industry and its Supply Chain		
	Published by:	L. Lack	-	2002
4.17	*Title:*	Future for Offshore Wind Energy in the United States		
	Published by:	W. Musial & S. Butterfield	Golden, USA	2004
4.18	*Title:*	Innovation in Offshore Wind Support Structures		
	Published by:	Scottish Enterprise	Glasgow, UK	2010
4.19	*Title:*	Modelling of deep water support structures for offshore wind turbines		
	Published by:	T. Camp & G. Hassan	-	2006
4.20	*Title:*	Multi-MW Wind Turbines		
	Published by:	OPET	Helsinki, FIN	2004
4.21	*Title:*	Offshore Wind Farm Construction		
	Published by:	G. Hassan	-	2009
4.22	*Title:*	Offshore Wind Installation Vessels - Future Developments		
	Published by:	I. Østvik	Bergen, NOR	2011
4.23	*Title:*	Offshore Wind Support Structures - Design Standards and Design Optimisation by DNV		
	Published by:	J.B. Ipsø	-	2001
4.24	*Title:*	Offshore Wind Technology in Europe		
	Published by:	D. Quarton	-	2005

4.25	*Title:*	Optimization of Steel Monopod-Offshore-Towers Under Probabilistic Constraints		
	Published by:	H. Karade & T. Vrouwenvelder	Delft, NL	2010
4.26	*Title:*	Physical Modelling of Scour around Tripod Foundation Structures		
	Published by:	A. Stahlmann & T. Schlurmann	Hannover, DE	2010
4.27	*Title:*	Public Opinion about Large Offshore Wind Power - Underlying Factors		
	Published by:	J. Firestone & W. Kempton	Newark, USA	2005
4.28	*Title:*	Space Frame Wind Turbine Tower		
	Published by:	T. D. Anderson	Heber City, USA	2005
4.29	*Title:*	Suction Caissons for Offshore Wind Turbines		
	Published by:	G. T. Houlsby & B.W. Byrne	Oxford, UK	2000
4.30	*Title:*	Energy from Offshore Wind		
	Published by:	W. Musial & S. Butterfield	Golden, USA	2006
4.31	*Title:*	Offshore Wind Technology Final Report		
	Published by:	AWS Truewind	Albany, USA	2009
4.32	*Title:*	A review of offshore wind power grid connection options in the Bothnian Bay		
	Published by:	S. Niskanen	Tampere, FIN	2011
4.33	*Title:*	Evaluation of the Frequency Response of AC Transmission Based Offshore Wind Farms		
	Published by:	M. Zubiaga & G. Abad	Mondragon, SPA	2006
4.34	*Title:*	Drilled Concrete Monopile Foundations		
	Published by:	Ballast Nedam	Nieuwegein, NL	2007
4.35	*Title:*	The European offshore wind industry - key trends and statistics 1st half 2014		
	Published by:	G. Corbetta, EWEA	Brussels, BE	2014
4.36	*Title:*	Wind in power - 2013 European statistics		
	Published by:	EWEA	Brussels, BE	2014
4.37	*Title:*	Wind energy scenarios for 2020		
	Published by:	EWEA	Brussels, BE	2014
4.38	*Title:*	Foundations for larger & deeper offshore wind		
	Published by:	MEC+	Copenhagen, DK	2015
4.39	*Title:*	Offshore Wind Power China		
	Published by:	Quartz & Co	-	2013

CHAPTER 5 – RESEARCH REPORTS AND THESIS REPORTS

This chapter aims to provide an overview of the available research reports and thesis reports related to offshore wind foundations and the arctic environment. Although the researches can be performed by scholars, the driving forces behind these studies are companies developing offshore wind and arctic engineering.

Some parts of the large collection of articles are summarized, and other parts are included without performing an in-depth summary. An overview is presented of both the summarized and the not-summarized articles and papers in the following paragraphs. Summaries of the reports are included under Appendix E.

Each reportis referenced and catalogued to correspond with the list of references contained in the thesis report.

5.1 OVERVIEW RESEARCH REPORTS – ARCTIC ENVIRONMENT

This paragraph contains an overview of the research reports and thesis reports with relevant information about the arctic environment. The references and summaries contained in this paragraph are taken from the corresponding research reports.

5.01	*Title:*	Analysis of Lifetime of a Tubular Research Structure on Antarctica		
	Published by:	C. Saltner & W.D. Keij	Delft, NL	2002
5.02	*Title:*	Arctic Offshore Technology Assessment		
	Published by:	X. Shi & W. Rodriquez	Houston, USA	2011
5.03	*Title:*	Arctic Workability		
	Published by:	L. Burg	Delft, NL	2007
5.04	*Title:*	Characterizing and Reconstructing 500 years of Climate in the Baltic Sea Basin		
	Published by:	C. Eriksson	Göteburg, SWE	2009
5.05	*Title:*	Feasibility of New Terminal in Arctic Russia		
	Published by:	R.P. de Geus	Delft, NL	2002
5.06	*Title:*	Ice Management in Arctic Offshore Operations and Field Developments		
	Published by:	K.J. Eik	Trondheim, NOR	2010

5.2 OVERVIEW RESEARCH REPORTS – ICE MECHANICS

This paragraph contains an overview of the research reports and thesis reports with relevant information about ice mechanics. The references and summaries contained in this paragraph are taken from the corresponding research reports.

5.07	*Title:*	An Overview of First-Year Sea Ice Ridges		
	Published by:	G. Timco & K. Croasdale	Ottawa, CAN	2000
5.08	*Title:*	Dynamic Ice to Structure Interaction		
	Published by:	E. Eranti	Espoo, FIN	1982
5.09	*Title:*	First-Year ice ridge scour and some aspects of ice rubble behavior		
	Published by:	P. Liferov	Trondheim, NOR	2005
5.10	*Title:*	First-year sea ice features - Investigation of ice field strength heterogeneity and modelling of ice rubble behaviour		
	Published by:	S. Shafrova	Trondheim, NOR	2007
5.11	*Title:*	Chapter 6 - Ice forces on structures		
	Published by:	Unknown	-	2002
5.12	*Title:*	Nonlinear finite element simulations of ice forces on offshore structures		
	Published by:	B. Sand	Luleå, SWE	2008

5.3 OVERVIEW RESEARCH REPORTS – ARCTIC ENGINEERING

This paragraph contains an overview of the research reports and thesis reports with relevant information about arctic engineering. The references and summaries contained in this paragraph are taken from the corresponding research reports.

5.13	*Title:*	Evaluation of Canadian Artificial Islands		
	Published by:	M.J. Jansen	Delft, NL	1999
5.14	*Title:*	Friction of Sea Ice on Various Construction Materials		
	Published by:	R. Frederking & A. Barker	Ottawa, CAN	2001
5.15	*Title:*	Ice Actions on Offshore Structures		
	Published by:	M. Bjerkas	Trondheim, NOR	2006
5.16	*Title:*	Recommendations for design of offshore foundation exposed to ice loads		
	Published by:	L. Fransson & L. Bergdahl	Stockholm, SWE	2009
5.17	*Title:*	Static and dynamic response of structure subjected to ice forces: Evaluation of a lighthouse overloading event		
	Published by:	V. S. Bjoland	Trondheim, NOR	2010

5.4 OVERVIEW RESEARCH REPORTS – OFFSHORE WIND ENGINEERING

This paragraph contains an overview of the research reports and thesis reports with relevant information about offshore wind engineering. The references and summaries contained in this paragraph are taken from the corresponding research reports.

5.18	*Title:*	Adapting offshore wind power foundations to local environment		
	Published by:	L. Hammar & S. Andersson	Stockholm, SWE	2010
5.19	*Title:*	Alternatives and modifications of Monopile foundation or its installation technique for noise mitigation		
	Published by:	Z. Saleem	Delft, NL	2011
5.20	*Title:*	Design of Offshore Wind Turbine Support Structures		
	Published by:	C. LeBlanc	Aalborg, DK	2004
5.21	*Title:*	Dynamic Response Calculations of Offshore Wind Turbine Monopile Support Structures		
	Published by:	D. J. C. Salzmann	Delft, NL	2004
5.22	*Title:*	Gravity Base Foundations for Offshore Wind Turbines		
	Published by:	L. van Kessel	-	-
5.23	*Title:*	Lateral Behavior of Large Diameter Offshore Monopile Foundations for Wind Turbines		
	Published by:	L. Bekken	Delft, NL	2009
5.24	*Title:*	Load Reduction of Support Structures of Offshore Wind Turbines		
	Published by:	U. V. Anderson	Copenhagen, DK	2008
5.25	*Title:*	Chapter 10 – Selection, design and construction of offshore wind turbine foundations		
	Published by:	S. Malhotra	USA	-
5.26	*Title:*	Transport and Installation of Offshore Wind Farms		
	Published by:	S. A. Herman	-	2002
5.27	*Title:*	Design of Support Structures for Offshore Wind Turbines		
	Published by:	J. van der Tempel	Delft, NL	2006

5.5 OVERVIEW RESEARCH REPORTS – NON-SUMMARISED

This paragraph contains an overview of the research reports and thesis reports that are not summarized . The references and summaries contained in this paragraph are taken from the corresponding research reports.

5.28	*Title:*	Development of P-Y Curves for Monopiles in Clay using Finite Element Model Plaxis 3D Foundation		
	Published by:	D. L. Pradhan	Trondheim, NOR	2012
5.29	*Title:*	Definition of a 5-MW Reference Wind Turbine for Offshore System Development		
	Published by:	J. Jonkman & S. Butterfield	Golden, USA	2009
5.30	*Title:*	Reliability based design methodology of extreme response of offshore wind turbines		
	Published by:	P.W. Cheng	Delft, NL	2002
5.31	*Title:*	DOWEC Tripod Structure		
	Published by:	M.B. Zaaijer	Delft, NL	2002
5.32	*Title:*	Terminology, Reference Systems and Conventions		
	Published by:	R.van Rooij	Delft, NL	2001
5.33	*Title:*	The effects of wind power on marine life		
	Published by:	L. Bergström & L. Kautsky	Stockholm, SWE	2012
5.34	*Title:*	Holocene sedimentary environment and sediment geochemistry of the Eastern Gulf of Finland, Baltic Sea		
	Published by:	H. Vallius - GTK	Espoo, FIN	2007
5.35	*Title:*	Towards marine landscapes in the Baltic Sea		
	Published by:	Z. Al-Hamdani and J. Reker	Copenhagen, DK	2007
5.36	*Title:*	Fast- and drift-ice communities in the Bothnian Bay and the impact of UVA radiation on the Baltic Sea ice ecology		
	Published by:	J. Piiparinen	Helsinki, FIN	2011

CHAPTER 6 – OVERVIEW OF DESIGN STANDARDS

This chapter aims to provide an overview of the design standards used by the industry regarding offshore wind engineering and arctic engineering. For some design standards a summary was made, which are included under Appendix F.

Each design standard is referenced and catalogued to correspond with the reference list contained in the thesis.

6.01	*Title:*	Barents 2020: Phase 1 - Norwegian Baseline on HSE, Ice and Metocean		
	Published by:	Det Norske Veritas AS	Norway	2008
6.02	*Title:*	Design Standards for Offshore Wind Farms		
	Published by:	American Bureau of Shipping	U.S.A.	2011
6.03	*Title:*	Offshore Standard - DNV-OS-J101 Design of Offshore Wind Turbine Structures		
	Published by:	Det Norske Veritas AS	Norway	2011
6.04	*Title:*	Guide for Building and Classing Offshore Wind Turbine Installations		
	Published by:	American Bureau of Shipping	U.S.A.	2010
6.05	*Title:*	ISO/FDIS 19906: Petroleum and natural gas industries — Arctic offshore structures		
	Published by:	International Organization of Standardization	Switzerland	2010
6.06	*Title:*	IEC 61400-3: Wind turbines Part 3: Design requirements for offshore wind turbines		
	Published by:	International Electro Technical Commission	Netherlands	2009
6.07	*Title:*	Guideline for the Certification of Offshore Wind Turbines		
	Published by:	Germanischer Loyd	Germany	2005
6.08	*Title:*	Standard for Design of Offshore Wind Turbines		
	Published by:	BSH	Germany	2007
6.09	*Title:*	AISC 14th Edition		
	Published by:	American Institute of Steel Construction	U.S.A.	2010
6.10	*Title:*	API 21st Edition		
	Published by:	American Petroleum Institute	U.S.A.	2000
6.11	*Title:*	NEN-EN-10225:2001		
	Published by:	Stichting voor Nederlands Normalisatie Instituut	Netherlands	2001

CHAPTER 7 – OVERVIEW OF BOOKS

This chapter aims to provide an overview of relevant books regarding offshore wind engineering and arctic engineering. Certain books have been summarized, which are included under Appendix G.

Each book is referenced and catalogued to correspond with the reference list contained in the thesis.

7.01	*Title:*	Dynamics of Offshore Structures		
	Published by:	J. F. Wilson	ISBN: 0-471-26467-9	1993
7.02	*Title:*	Frontiers in Offshore Geotechnics II		
	Published by:	S. Gourvenec & D. White	ISBN: 978-0-203-83007-9	2011
7.03	*Title:*	Structural Integrity of Offshore Wind Turbines		
	Published by:	U.S. Transportation Research Board	ISBN: 978-0-309-16082-7	2011
7.04	*Title:*	Wind Energy: Fundamentals, Resource Analysis and Economics		
	Published by:	S. Mathew	ISBN: 978-3-540-30905-5	2006
7.05	*Title:*	Wind Energy Handbook		
	Published by:	T. Burton & D. Sharpe	ISBN: 0-471-48997-2	2001
7.06	*Title:*	Actions from Ice on Arctic Offshore and Coastal Structures		
	Published by:	S. Løset, K.N. Shkhinek & Knut V. Høyland	ISBN: S-8114-0703-3	2006
7.07	*Title:*	Engineering Aspects Related to Arctic Offshore Developments		
	Published by:	S. Løset, K.N. Shkhinek & Knut V. Høyland	ISBN: 978-5-8114-0723-1	2006
7.08	*Title:*	The Baltic Sea		
	Published by:	L. Håkanson	-	-
7.09	*Title:*	Planning the Bothnian Sea - Outcome of Plan Bothnia, a transboundary Maritime Spatial Planning pilot in the Bothnian Sea		
	Published by:	H. Backer & M. Frias	ISBN: 978-952-67205-5-5	2013
7.10	*Title:*	Physical Oceanography of the Baltic Sea		
	Published by:	M. Leppäranta & K. Myberg	ISBN: 978-3-540-79702-9	2009

CHAPTER 8 – OVERVIEW OF TUD CURRICULUM

This chapter aims to provide an overview of the TU Delft curriculum related to offshore engineering.

Each course is referenced and catalogued to correspond with the reference list contained in the thesis.

8.01	*Course:*	Offshore Hydromechanics - OE 4630
		Prof. Dr. Ir. R.H.M. Huijsmans
8.02	*Course:*	Probabilistic Design - CIE 4130
		Dr. Ir. P.H.A.J.M. van Gelder
8.03	*Course:*	Offshore Soil Mechanics - OE 4624
		Ir. J. Dijkstra
8.04	*Course:*	Bottom Founded Structures - OE 4651
		Ir. J.S. Hoving
8.05	*Course:*	Structural Dynamics - CIE 4140
		Prof. Dr. A. Metrikine
8.06	*Course:*	Introduction to Wind Energy - AE3W02TU
		Dr. Ir. W.A.A.M. Bierbooms
8.07	*Course:*	Arctic Engineering - OE 4680
		Ir. J.S. Hoving
8.08	*Course:*	Offshore Wind Farm Design - OE 5662
		Dr. Ir. D.J. Cerda-Salzmann
8.09	*Course:*	Offshore Wind Support Structures - OE 5665
		W.E. de Vries
8.10	*Course:*	Physical Oceanography - CIE 5317
		Prof. Dr. Ir. J.D. Pietrzak
8.11	*Course:*	Ocean Waves for Offshore - CIE 4325 OE
		Dr. Ir. J.H. Holthuijsen
8.12	*Course:*	Analysis of Slender Stuctures - CIE 4190
		Dr. Ir. A. Simone
8.13	*Course:*	Computational Modeling of Structures - CIE 5148
		Dr. Ir. M.A.N. Hendriks
8.14	*Course:*	Fatigue - CIE 5126
		M.H. Kolstein
8.15	*Course:*	Financial Engineering - CME 2300
		Prof. Dr. Ir. J.K. Vrijling

CHAPTER 9 – OVERVIEW OF WEB-BASED AND IMAGE REFERENCES

This chapter aims to provide an overview of the web-based references regarding subject related to offshore wind and arctic engineering. In addition, the following provides an overview of the references to images used in the thesis.

Each web-site is referenced and catalogued to correspond with the reference list contained in the thesis.

9.01	https://commons.wikimedia.org/wiki/File:Bathymetric_map_of_the_Baltic_Sea-fi.svg
9.02	https://de.wikipedia.org/wiki/Offshore-HG%C3%9C-Systeme
9.03	http://renews.biz/49212/ge-beefs-up-brazilian-hub/
9.04	http://www.wikiwand.com/en/Wind_turbine_aerodynamics
9.05	http://www.alstom.com/press-centre/2013/9/alstoms-6mw-haliade-offshore-wind-turbine-loaded-at-ostend/
9.06	http://tietkiemnangluong.com.vn/tin-tuc/pho-bien-kien-thuc/t12156/nguyen-ly-lam-viec-cua-tuabin-gio.html
9.07	http://gevwindpower.com/what-we-do.html/paint-damage
9.08	http://www.offshorewind.biz/2013/03/11/belgium-climate-chamber-tests-offshore-windturbine-service-hoist/
9.09	http://sustainnovate.ae/en/innovators-blog/detail/are-wind-turbines-improving
9.10	http://discuss.seasteading.org/t/breakwater-design/821/12
9.11	http://www.wind-energy-the-facts.org/offshore-support-structures.html
9.12	http://www.offshorewind.biz/2011/12/06/anholt-offshore-wind-farm-construction-to-begin-soon-denmark/
9.13	http://www.uni-kassel.de/fb14bau/fileadmin/datas/fb14/AMPA/Offshore/Offshore-AMPA-Uni-KS_TP-DanTysk.jpg
9.14	http://www.kinsajasa.com/exclusive-principles-malaysia-subsea-sscs.php
9.15	Seaway Heavy Lifting – Image repository
9.16	http://www.cranestodaymagazine.com/news/jumbo-completes-greater-gabbard-job/
9.17	http://www.erneuerbareenergien.de/drei-offshore-konzepte-fuer-die-zukunft/150/3882/78514/2
9.18	http://epicsoftware.com/index.php/tarpon_systems/
9.19	http://www.maritimejournal.com/news101/marine-renewable-energy/concrete-gravity-foundations,-the-future-for-windfarms2
9.20	http://tethys.pnnl.gov/technology-type/offshore-wind
9.21	http://www.rechargenews.com/wind/article1354974.ece
9.22	http://www.jandenul.com/nl/activiteiten/offshore-diensten

9.23	http://www.offshorewind.biz/2013/09/06/uk-gravity-base-foundations-to-reduce-environmental-impact/
9.24	http://www.redwave.nl/doelpagina/2743893/2743890/De-gravitaire-fundering.html
9.25	http://cleantechnica.com/2011/12/06/2-mw-windfloat-towed-to-atlantic-site-off-portuguese-coast/
9.26	http://subseaworldnews.com/2014/06/16/spt-offshore-sets-up-suction-piles-for-wintershall/
9.27	http://www.rechargenews.com/news/policy_market/article1295309.ece
9.28	http://flickrhivemind.net/Tags/tripile/Timeline
9.29	http://www.renewableenergyworld.com/articles/2008/11/5-mw-bard-near-shore-wind-turbine-erected-in-germany-54098.html
9.30	http://offshorewindpowersystemsoftexas.com/titan_200_deep_offshore_platform
9.31	http://eandt.theiet.org/magazine/2014/05/windfarm-foundations.cfm
9.32	http://www.foundocean.com/en/media-centre/news/foundocean-nordsee-ost-project-update/
9.33	http://www.portofoostende.be/news/detail2.asp?idnr=416
9.34	https://www.dredgepoint.org/dredging-database/equipment/rambiz-3000
9.35	http://www.offshorewind.biz/2014/03/27/bow-loads-out-jacket-piles-for-sylwin/
9.36	http://www.renewableenergyworld.com/content/dam/rew/migrated/assets/images/story/2009/5/27/1332-wind-in-deep-water-wind-foundations-and-special-structures.jpg
9.37	http://www.maritime-offshore-group.com/en/innovations
9.38	http://www.carbontrust.com/news/2011/11/offshore-wind-news-innovative-keystone-twisted-jacket-foundation
9.39	http://www.offshorewindindustry.com/sites/default/files/field/image/offshore_suction_bucket_1522.jpg
9.40	http://dopepicz.com/37832785-offshore-suction-caisson-foundation.html
9.41	http://www.theguardian.com/environment/2013/jan/22/suction-bucket-offshore-wind?intcmp=122
9.42	http://www.offshorewind.biz/2013/02/27/uk-dogger-bank-receives-first-bucket-foundation/
9.43	http://energy.gov/articles/top-10-things-you-didn-t-know-about-offshore-wind-energy
9.44	http://www.rechargenews.com/wind/offshore/article1353097.ece
9.45	http://electrical-engineering-portal.com/offshore-floating-wind-turbines-to-reap-green-electricity
9.46	http://www.technischweekblad.nl/nieuws/drijvende-windmolens-van-6-mw-voor-britse-kust/item1426
9.47	https://www.youtube.com/watch?v=p1mpDe7RSUQ
9.48	https://www.youtube.com/watch?v=OwSgbW4Xptk
9.49	http://www.havator.com/Reference%20Images/Offshore/Hywind-project.jpg

9.50	https://www.facebook.com/principlepower/photos/pb.195455976141.-2207520000.1438286352./10151268495486142/?type=3&theater
9.51	http://www.modec.com/fps/skwid/
9.52	http://www.maritimejournal.com/news101/marine-renewable-energy/a-flipping-good-idea-for-floating-turbines
9.53	http://sverigesradio.se/diverse/appdata/isidor/images/news_images/110/1550970_520_292.jpg
9.54	http://arctic271.rssing.com/chan-9339809/all_p2.html
9.55	http://www.smhi.se/en/theme/sea-ice-1.11198
9.56	https://www.card-arctic.ca/MIR
9.57	http://mikeusherphotography.com/photo_10009864.html
9.58	https://earthref.org/drupal/content/diving-cape-evans-and-turtle-rock
9.59	https://www.flickr.com/photos/eldt/4809661421/in/datetaken/
9.60	http://palotimo.blogspot.nl/2013_01_01_archive.html
9.61	http://www.offshore-mag.com/articles/print/volume-74/issue-4/engineering-construction-installation/ice-simulation-software-targets-protection-of-arctic-platforms-and-substructures.html
9.62	http://www.hydralab.eu/project_summary_report.asp?id=86
9.63	http://www.bmtargoss.com/metocean-web-portals/wwwwaveclimatecom/
9.64	http://helcom.fi/baltic-sea-trends/environment-fact-sheets/hydrography/wave-climate-in-the-baltic-sea
9.65	http://solarenergyengineering.asmedigitalcollection.asme.org/article.aspx?articleID=1770162

APPENDIX A – SUMMARY OF ARTICLES RELATED TO ARCTIC ENVIRONMENT

Ref:	Title:	Author:	Date:
1.01	A study of the climatic system in the Barents Sea	B. Adlaridsuik H. Loeng	1991

Summary:

Relevance to thesis
Wind conditions in the Barents Sea, influence of wind conditions on circulation and inflow of waters in the Barents Sea)

Summary
The paper concentrates on the influence of local wind conditions on variations in the Atlantic inflow to the Barents Sea. Based on model testing a general conclusion is that climatic variations in the Barents Sea depend mainly on the activity and properties of inflowing Atlantic Water.

The interrelationship between atmospheric and oceanic circulation complicates the task of identifying the most significant factors influencing the variations of sea ice.

The agreement of the fluctuations in all these climatic variables suggests that the climate of the Barents Sea oscillates between two states, a warm and a cold state.
The warm state is characterised by high temperatures. low air pressure, cyclonic circulation in the atmosphere, increased Atlantic inflow, and little ice coverage (Fig. 7). The cold state is characterised by low temperatures, high air pressure, anti-cyclonic air circulation, decreased Atlantic inflow and more severe ice conditions.

The transition from one climatic state to the other is likely to be enforced externally by variations in larger scale oceanic and atmospheric circulation. There is, however, one internal mechanism, the formation of bottom water, which can account for the transition from a cold to a warm state.

Ref:	Title:	Author:	Date:
1.02	Anisotropy of Moderate and Strong Wind in Baltic	T. Soomere S. Keevallik	01-2001
Summary:			

<u>*Relevance to thesis*</u>
Governing wind directions in Baltic Sea (with regard to direction of sea ice movements)
Wind speeds in Baltic Sea (with regard to wind energy)

<u>Introduction</u>
The governing wind direction in the Baltic Sea is south-west. The secondary wind direction is north. During summertime the directional distribution of geostrophic wind has a tertiary maximum at north-east and east winds. Dominance of south-west winds in the Baltic and Scandinavian countries results from a large low pressure area next to Iceland (North Atlantic Low), and a high air pressure area in the northern part of the Eurasian continent (Siberian High). The western peripheral area of the North Atlantic Low (in which south and southwest winds dominate) frequently covers the Baltic Sea and causes the domination of southwest winds during late autumn and winter. It is generally known that directional structure of moderate (6–10 m/s) and strong (over 10 m/s) winds differs from that of all the winds. Namely, in many measurement sites the wind roses of these winds are strongly anisotropic. However, traditional annual mean wind roses are more or less isotropic.

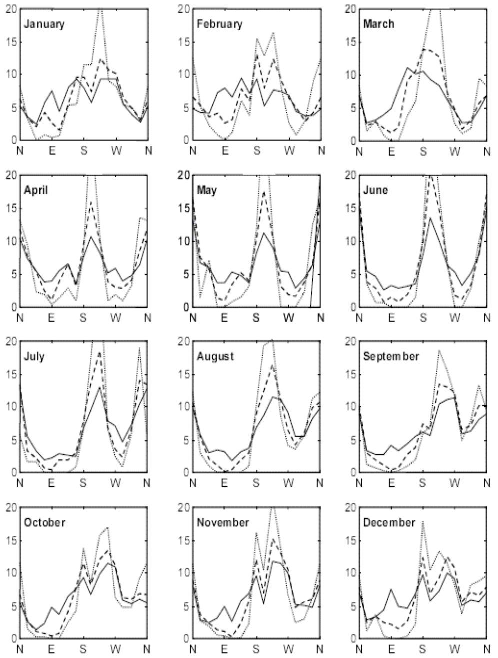
<u>Prevalence of anisotropic conditions</u>
Prevalence of certain wind directions in the coastal area of the Baltic Sea has been interpreted as evidence of the screening effect of the mainland. Perhaps the strongest evidence of the wind anisotropy is the historically well-known fact that the strongest storms in Estonia blow from south-west or west. A directionally homogeneous wind regime dominates in the Baltic Sea area. The area is void of global or large-scale effects causing strongly anisotropic wind fields such as monsoon, passat, sirocco, or mistral and it serves as a prolongation of the North Atlantic storm track. Frequent occurrence of high-latitude cyclones gives birth to high wind variability in the whole Baltic region and the concept of directionally more or less homogeneous wind is a good first assumption that can be made.

To obtain insight in dynamic wind properties one-year high-resolution wind measurements have been conducted over a 15 year period. Indeed, directional distribution of weak winds (50–70% from the total number of wind recordings) is perfectly isotropic. The situation changes drastically if one separates moderate and strong winds from the "background" of weak winds. For wind energy purposes, wind speeds under 5–6 m/s are unimportant [16]. Wind speeds under this value hardly may have any global importance and they are neglected also in wind wave studies [17]. The directional distribution of moderate and strong winds is surprisingly anisotropic.

On the figure below the seasonal variation of the angular distribution of all wind events (solid line), wind events with wind speed ε6 m/s (dashed line), and strong winds (dotted line) at one of the measuring points. Vertical axis represents relative frequency of occurrence of wind events, %.

<u>Directional distribution of extreme winds</u>
The above has shown an impressive anisotropy of frequency of strong wind events. However, in terms of plain counting, this feature does not cause significant divergence of the mean wind speed from different directions. The opposite figures show that angular distribution of annual mean wind speed is qualitatively similar with that of strong wind events. The quantitative deviations of the wind speed are about ±30% from the mean value. The fact that deviations of this distribution from isotropy are moderate is not surprising. The

number of strong wind events is about 1/6 from the total number of measurements but wind speed in the events is only 2–3 times higher than the mean wind speed. If focused on wind energy (proportional to wind speed squared) or capacity of a wind power generator (proportional to wind speed cubed within certain range of wind speeds), the result appears much less uniform. It shows that a great divergence can take place.



The most drastic anisotropy becomes evident in the distribution of maximum wind speed from different directions. The angular distribution of the maximum wind speed is similar to the distribution of the mean one. Both distributions have two-peaked structure whereas locations of the peaks practically coincide. Notice that this similarity is not necessarily natural since the strongest wind speeds in many other areas are caused by hurricanes and may correspond to any geographical direction.

Similarity of wind regimes at eastern and western sides of Baltic Sea

The anisotropy can be reformulated in terms of essentially reduced frequency of moderate and strong east winds, in particular, during summer months. The first argument is to refer to the screening effect of the mainland. This factor, in principle, may essentially damp east winds at the eastern coast of the Baltic Sea. As for the western coast, it is natural to expect that a mirrored feature should occur. Surprisingly enough, wind roses constructed on the western side are more anisotropic than those at the eastern sites. The directional distribution of moderate and strong winds is again strongly asymmetric. It has two peaks. The main peak corresponds to south-west winds and the minor peak – to north-west winds. The distribution of strong winds is totally asymmetric, with two maxima similar to the just described ones. Comparison of the directional distributions of wind parameters demonstrates amazing concordance between wind regimes at the opposite sides of the Baltic Proper.

A nontrivial feature of the presented data is that peaks of the directional distribution are located at the same direction at both sides of the Baltic Proper. If the directional anisotropy was caused by screening effect of the mainland, the minima of the distributions should correspond to different directions. Mainland-caused distortions should damp easterly winds in the eastern part of the Baltic Sea, but damp westerly winds at western parts. However, the mainland-caused effects on the directional distributions of wind parameters are inferior as compared to the dominating wind regime.

Comparison of wind regimes in Swedish and Estonian coastal areas indicates that a specific large-scale structure of dominating winds exists in the Baltic Proper. The structure consists of frequent and strong south-west and north winds and clearly weaker east winds, and reveals a well-defined secondary minimum corresponding to north-west winds. Data from the adjacent areas suggest that this structure does not penetrate into the mainland. The main difference between wind regimes of the Baltic Proper and the adjacent areas consists in a low frequency of strong north winds in mainland. Data from Moonsund area demonstrate domination of south winds among all wind events and a wide maximum covering all western directions in the angular distribution of wind power capacity.

Effects of wind anisotropy

The prevailing direction of moderate and strong winds in the Baltic Proper (as well as in any other region) has enormous consequences in areas where wind activity has to be taken into account.

A primary area of importance is constructing harbors, wave-protecting moles or possible wind turbines. Wind waves typically propagate in the direction of the wind. If dangerous waves are restricted to a single direction, it is relatively inexpensive to protect harbor areas or beaches against high waves.

The high anisotropy of directional wind distributions and their coinciding shapes over a large area suggests that relatively homogeneous storm events might be frequent in the Baltic Proper. The influence of events of spatially constant wind on the wind wave generation may be dramatic since fluctuations in the wind direction generally lead to fast decrease in the wave height. Parameters of wave generation are normally measured during typical wind regimes. Events of spatially constant wind may be one of the reasons why standard wave models underestimate wave heights during short storms.

Possible useful references:

Smedman, A.-S., Högström, U., and Bergström, H. Low level jets – a decisive factor for off-shore wind energy siting in the Baltic Sea. Wind Engng, 1996, 20, 137–147.

Ref:	Title:	Author:	Date:
1.03	Atmospheric Forcing on the Barents Sea Winter Ice Extent	A. Sorteberg B. Kvingedal	01-2006

Summary:

<u>*Relevance to thesis*</u>

Describes the mechanisms of the atmospheric effects on the sea ice extent and thickness in the Barents Sea, influence of weather patterns on sea ice extent.

<u>Introduction</u>

The amount and thickness of sea ice in the Arctic region are important factors in the global climate system. In the Barents Sea, the sea ice is relatively thin compared to the rest of the Arctic Ocean. The sea ice in this area has a large annual cycle with minimum ice in September and maximum ice in April. The thin layer of ice is very sensitive to changes in both the atmosphere and the ocean.

Many studies have focused on the connection between Arctic sea ice variability and the Arctic Oscillation or the North Atlantic Oscillation. Researchers strongly agree that at least part of the large-scale sea ice decrease in the Arctic is associated with the recent increase in the AO and NAO. The magnitude of the ice changes associated with the AO is much smaller than the regional ice trends. When discussing winter sea ice variability in the Arctic, the actual sites for variability are the Nordic, Labrador, Barents, and Bering Seas and the Sea of Okhotsk. Other areas in the Arctic Ocean are generally fully covered by sea ice during the winter.

The conceptual picture is that the strengthening of the NAO is associated with an intensification of the Icelandic low, which leads to the advection of anomalously warm air into the Nordic Seas and subsequent sea ice melting or reduced freezing. To the west of Greenland, the advection of colder air masses will lead to increased sea ice extent in the Labrador Sea. This Labrador–Nordic Sea dipole pattern in sea ice concentration anomalies exhibits large decadal variability.

Some of the winter sea ice extent in the Barents Sea can be explained by the large-scale NAO. However, more local and/or less-known large-scale processes should also be investigated. An alternate dynamic mode that was shown to be a more consistent indicator of Arctic sea ice export through the Fram Strait was the phase of the atmospheric SLP planetary. Also, the feedback mechanisms to the atmosphere due to the Barents Sea ice variability are of great interest. In wintertime, with large air–sea temperature differences, the (upward) turbulent heat flux from an open ocean may is almost two orders of magnitude larger than through the ice.

<u>Data and Methods</u>

Weekly sea ice concentration data for the Greenland and Barents Seas have been digitalized and gridded from sea ice charts. Up to 10 different ice types have been recorded each week, classified after their mean sea ice concentration. Monthly mean atmospheric fields, including near-surface air temperature (SAT) and mean sea level pressure (MSLP) are reanalyzed for the period 1967 to 2002.

Winter seasonal means were constructed from these monthly fields. An algorithm for feature tracking has been used to construct storm tracks from the reanalyzed data.

Wintertime Barents Sea ice extent

The time series of Barents Sea ice extent during winter shows that there are four distinct periods with above normal sea ice extent (Fig. 2) and a trend in ice extent of -3.5% per decade. Sharp decreases in the extent between successive winters, are followed by winters with less-than-normal sea ice extent. Sharp increases are followed by winters with greater-than-normal sea ice extent. Clearly, there are variations on both interannual and decadal time scales, and spectrum analysis indicates fairly strong variability around the 8- and 3–4-yr periods. Despite recent decreases in Barents Sea ice extent, examples of strong variability persist.

Relationship between Barents Sea winter ice extent and MSLP

Regression analysis indicates that during winters with extensive Barents Sea ice, the MSLP is generally higher than during winters with sparse sea ice extent both in the Nordic Seas and in the Barents Sea region. In addition to the MSLP being higher during extensive sea ice years, the east–west pressure gradient in the Nordic Seas is considerably weakened with the strongest increase in MSLP in the western part of the Nordic Sea. The MSLP anomalies during winters with extensive Barents Sea ice extent reveal higher-than-normal MSLP over Greenland. In the Barents region, this leads to southward anomalous geostrophic winds. This cold northerly wind favors freezing due to both thermodynamic freezing at the sea ice edge and the breakup and divergence of ice leading to open-water sea ice formation. These northerly winds may advect more and thicker sea ice into the Barents region from just north of Greenland. During sparse sea ice winters, the picture is reversed. Over the Barents Sea, advection of warm and humid air, which disfavors freezing, will contribute to a reduced sea ice extent by dynamically pushing the sea ice northward and keeping the thick ice (and therefore freshwater) confined to the area north of Greenland.

The MSLP anomaly pattern resembles some of the NAO pattern. The NAO accounts for more than one-third of the total variance in winter SLP in the North Atlantic. As the NAO/AO can be used as a measure of the strength of the North Atlantic westerlies, this indicates that the direct influence of the North Atlantic westerlies on the Barents Sea ice is fairly weak. An explanation of the relatively weak correlations may be that the NAO/AO index is less well suited for capturing important meridional wind anomalies that may be important for the wintertime Barents Sea ice extent.

The relationship between Barents Sea winter ice extent and temperature

The regression of DJF Barents Sea ice extent on DJF 2-m temperature (SAT) anomalies shows large positive (negative) values in the Barents and Nordic Seas during winters with sparse (extended) sea ice. In winters with relatively little Barents Sea ice, the SAT is constrained to the underlying ocean temperatures. During heavy ice winters, the SATs are effectively insulated from the effect of the warmer ocean and are more free to fluctuate in response to other influences. However, the MSLP and SAT anomalies related to the Barents Sea ice extent indicate a connection between the ice extent in the Barents Sea area and the Labrador and Bering Sea ice extent.

The relationship between Barents Sea winter ice extent and cyclone variability

To shed some light on the role of cyclone formation and cyclone track variability in the variability of the Barents Sea ice extent, a feature tracking method was used to calculate the wintertime (DJF) track genesis (where the cyclone forms) and track density (number of cyclones) and have correlated the gridded Northern Hemisphere track genesis and track density with the Barents Sea ice extent data. In addition, a lead–lag correlation analysis was performed.

In order for a cyclone generated or traveling through the region to have an effect on the Barents Sea ice extent, it should be moving into the Arctic region. Seemingly, the cyclones do not have any preferred pathways. Only a few of the cyclones actually reach the Barents Sea ice edge. However, the trajectories indicate the movement of the cyclone centers, thus, the atmospheric conditions over the Barents Sea may be influenced by the wind field surrounding the low pressure centers. In addition, the wind field induced by the cyclones affects the sea ice motion in the Arctic Ocean, and thereby the amount of ice moving into the Barents Sea region. The significantly stronger northerly winds over the Barents Sea are favorable for local freezing due to both thermodynamic freezing at the sea ice edge and the breakup and divergence of ice leading to open-water sea ice formation. In addition, the westerly wind anomalies north of the Barents Sea will increase the advection of thick ice into the region due to increased Ekman transport.

As an approach to quantify the sum of the total direct or indirect impact of the wintertime variability in northward-moving cyclones crossing East Siberia and the western Nordic Seas on the To gain some insight into the co-variability between the decadal fluctuations in the Barents Sea ice extent and the cyclone activity, the decadal component of the Barents Sea winter ice extent variability was constructed using a third-order Butterworth filter and compared to the decadal component of the cyclone activity.

<u>Discussion and conclusions</u>

This investigation of the wintertime atmospheric forcing on the Barents Sea winter ice extent aims to contribute to a better understanding of the actual processes acting on the ice on different time scales. The time series of Barents Sea winter ice extent reveals strong inter-annual variability and a slightly decreasing trend of -3.5% per decade, with the winter of 2005 marking a new record low in the wintertime Barents Sea ice extent.

The variability in the number of northward-moving cyclones in the East Siberian region results in the variability in the number of cyclones traveling into the (central) Arctic. This influences the winds over the central Arctic, and the Barents Sea region, which in turn influences both the sea ice export and local production of ice in the Barents Sea region. Years with a high production of cyclones over East Siberia favor northwesterly wind anomalies bringing cold air over the Laptev and Barents Sea area. These changes favor ice export into the Barents Sea area. The wind anomalies are also favorable for local freezing due to both thermodynamic freezing at the sea ice edge and the breakup and divergence of ice leading to open-water sea ice formation.

Reduced ice extent was suggested to favor local cyclone production, which might (if the locally produced cyclones stay in the Barents Sea) cause northwesterly wind anomalies in the area of Barents Sea inflow and therefore the increased inflow of Atlantic water.

The decadal variability in the Barents Sea ice extent is strongly governed by the decadal variability in the number of cyclones entering the Nordic Seas, with the ice extent lagging by 1–2 yr. The decadal variability of the Nordic Seas cyclone activity induces wind anomalies in the North Atlantic and the Nordic Seas. This mechanism is of great importance for the decadal ice extent variations.

The atmospheric effect on the ocean is not just the effect of increased southwesterly winds and the increased inflow of water, but also advection of warmer air into the region, which reduces the heat loss from the northward-traveling ocean heat anomalies. It is uncertain whether the Atlantic Ocean heat anomalies influence the decadal variability of the cyclonic activity or not.

Ref:	Title:	Author:	Date:
1.04	Barents Sea drift ice characteristics	T.Vinje A.S. Kvambekk	05-1990

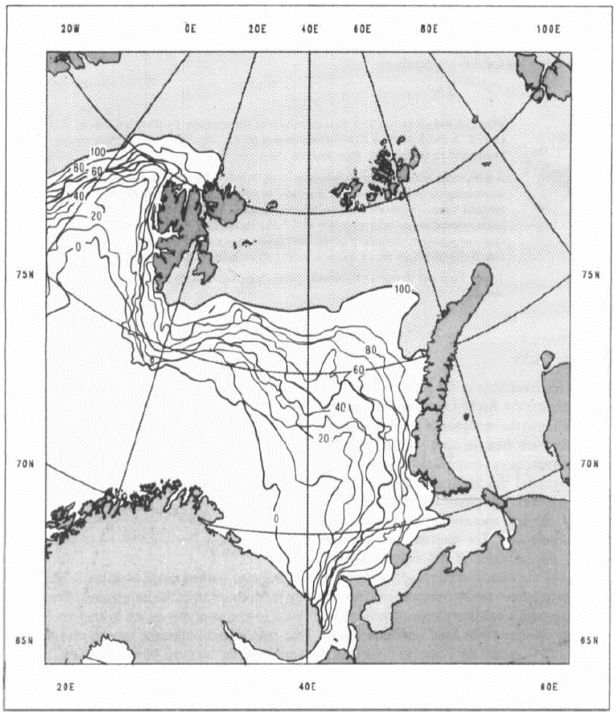
Summary:

<u>Relevance to thesis</u>
Ice field characteristics Barents Sea, probability of sea ice distribution, ice thickness, ice field spread and drift in Barents Sea.

<u>Introduction</u>
The sea ice conditions in the different marginal seas bordering the Arctic Ocean are determined by dynamic and thermodynamic processes characteristic for each area. In addition, the exchange with the Arctic Ocean may influence the age-composition of ice in the various seas. The physical boundaries of the different marginal seas are in this connection of major importance. The western and southern parts of the ice fields of the Barents Sea are bounded by the warmer currents spreading north and eastwards from the Norwegian Sea. The boundary towards the north is linked by a number of islands which to some extent govern the exchange of ice with the Arctic Ocean.

The ice drift in the Barents Sea is mainly wind driven. The exchange of ice with the Kara Sea and the Arctic Ocean may thus vary considerably from year to year in accordance with changes in the general atmospheric circulation. This exchange in turn determines to a large extent the amount of ice that remains in the Barents Sea through the subsequent summer. The composition of the ice fields may therefore at times be very complex, consisting of local and imported ice of various ages. The subsequent distribution of icebergs is determined by the prevailing wind field.

<u>Ice Distribution</u>
The denser, warmer modified Atlantic Water fills up the deeper part of the Barents Sea. The southward extension of the sea ice is therefore during the cold season indirectly, topographically controlled in the western part, where the bottom topography shows marked shelf breaks. The increasingly cooled water flowing eastward from the Norwegian Sea may here dive under the polar water at quite different latitudes. These features are reflected in the increasing variability of the ice edge position in the eastern part of the Barents Sea . The degree of cooling of the warmer water masses entering the southern area from the west as well as the ice formation during the cold season are determined by the atmospheric and oceanic circulation. The position and the intensity of the Barents Sea Low are in this regard of particular importance.



If the Barents Sea Low center is located in the central part of the Barents Sea, and if the Barents Sea drift ice characteristics circulation is more intense than normal, we will have an increased surface speed of warmer water as well as relatively high atmospheric temperatures and northward drift in the eastern part of the Barents Sea. If on the other hand the air pressure is high during the freezing season, there will be a retarding effect on the eastward flowing warmer water, and cold, continental winds may favour the cooling and freezing over of large areas. The seasonal variation of the ice-covered area of the Barents Sea and the adjacent part of the Arctic Ocean shows great inter-annual variations. The increasing difference between the annual minimum and maximum extension indicates that a reduction/ increment of the ice thickness/melting may havetaken place in the Barents Sea over the two last decades.

Ice Composition and Formation

When northerly winds prevail, newly formed ice is continuously transported southwards resulting in an opening outside of the rim of land-fast ice. Because of the considerable ice formation that takes place, there occurs a continuous brine production which results in vertical convection and the formation of cold, dense bottom water. The ice fields may contain ice of various age and origin. As the ice drift in the Barents Sea is mainly wind-driven, the ice exchange with the neighbouring seas is to a large extent determined by the atmospheric stress field. The Barents Sea may on an annual average be an ice source for the Arctic Ocean and an ice sink for the Kara Sea. On the average, there is a seasonal variation indicating a reversed ice exchange with the neighbouring seas during the warmer season

The dominant ice flow in the Arctic is the Transpolar Ice Drift Stream. The thickest ice encountered in the Barents Sea is generally imported from the Arctic Ocean. This influx of perennial or multi-year ice may be extra high during conditions with persistent northerly winds in the region. This will affect the heat budget of the area to a great extent, resulting in a larger extent of sea ice the following summer season. The multiyear ice drifting in from the Arctic Ocean is generally 2-4 m thick. In addition there is a considerable formation of ice in the lee polynyas to the south of the islands during conditions with northerly winds. If northerly winds prevail for some time. the result may be long lee-belts of thinner ice bordered by thicker winter ice or multi-year ice from the Arctic Ocean. During the freezing season off-ice winds will cause divergence and refreezing between the floes. thus producing larger floes consisting of smaller floes of different age.

Ridging events may take place with onshore winds. Rubble field are also frequently observed in this situation. Ice ridging occurs in convergences caused by wind, currents and land constraints. The accumulation of bottom material trapped in newlv formed ridges is a phenomenon that surely occurs during freezing in all shallow areas. When these ridges are consolidated during the following summer. storage of sediments as well as of nutrients, bacteria. or other biological material such as eggs and larvae will occur. Being transported over long distances. this storage may form a basis for new biological growth in new areas during the melting season. then mainly in the marginal ice zone.

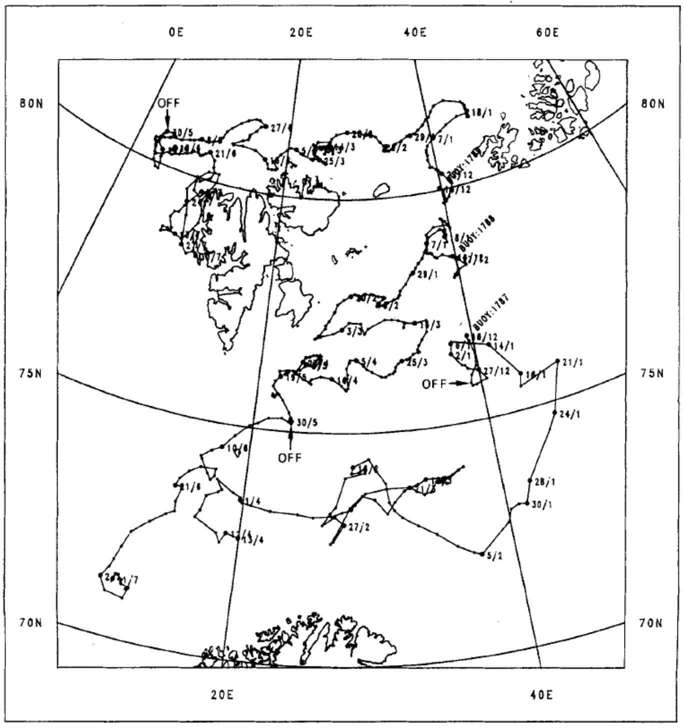
Another structure-forming agent is the melting and freezing that takes place in perennial ice. Freezing takes place at the bottom due to the conducted radiative heat loss during winter. Melting mainly takes place on the surface due to the positive radiation balance during the summer.

Ice Bottom Topography

The ice bottom topography has been studied using a scanning sonar. The measurements indicate that the multiyear ice has a relatively smoother bottom topography than the first-year ice in the marginal ice zone. This may reflect the effect of thermodynamic processes having acted over a longer time period for the former ice type.

Ice drift
Tidal or inertial effects play an important role for the daily movement of the ice, particularly over the shallow shelves, in passages, or along the coast. The movement of the ice fields due to tidal or inertial effects is clearly illustrated by the trails formed by grounded icebergs and depending on the corresponding water depth and wind stress. The twice-daily tidal wave causes a periodic divergence and convergence over shallow banks, near the coast or in narrow passages.

Information on the ice drift in the Barents Sea has been collected mainly from ice drift buoys since 1975. To illustrate the variance caused by the passage of lows, the drift of three buoys is shown in the figure below. According to these buoy drift observations, the ice velocity amounts to 1-2% of the geostrophic wind speed. This is in agreement with wind-induced ice edge displacements such as those observed on satellite images. The wind effect on the ice increases towards the margin, probably because of the increased form drag due to wave effects as well as to the scattering of ice floes.



Possible useful references:
*Vinje. T. **1988:**Dynamics and Morphology of the Barcnts Sea ice fields.*

*Lemkc. P 1980: Application of the inverse modelling technique to Arctic and Antarctic **sea** ice anomalics.*

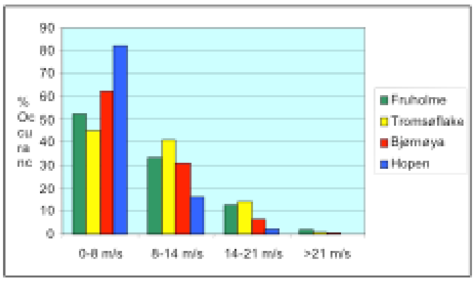
Ref:	Title:	Author:	Date:
1.05	Regional Reference: Barents Sea	Fugro	06-2005

Summary:

Relevance to thesis
Short summary of the geographical, oceanographic and meteorological properties of the Barents Sea area.

Geography
The total area of the Barents Sea is 1.4 million square kilometers with an average water depth of 230m. West of the continental slope the water depth is 2000m to 3000m. The depth on the Norwegian continental shelf varies between 200 and 500m, except for the area southeast of Svalbard, where the depth is less than 100m, and the banks in the Barents Sea and offshore the Norwegian coast where the depth ranges between 100m and 200m. On the Russian shelf the water depth is generally between 200m and 300m, decreasing to 100m north of Cape Kanin and west of Novaya Zemlya.

Winds
The meteorological conditions in the Barents Sea are dominated by cyclones that form in the North Atlantic and move into the Barents Sea. In general the winds in winter are from southwest except along the Norwegian coast where offshore winds (northeast) are more common due to land sea breezes. In summer the pressure gradients are weaker and the wind direction is more equally distributed between the main wind axes, along southwest-northeast, in the Barents Sea. Low pressure that occurs over northern Scandinavia during the summer leads to more frequent occurrence of northeasterly to easterly winds. The high storm frequency along the northern Norwegian coast is usually claimed to be a strengthening of the wind field due to the topography of the mainland.



% Occurrence of Wind Speeds

Polar lows

A polar low is a low pressure phenomenon which is normally generated during situations with outbreaks of cold arctic air over the sea. Energy to drive the system is provided by heat and moisture transferred from the sea, and by energy transformations within the atmosphere.

During the passage of a polar low the wind speed typically increases to storm force in a very short time with changing wind direction. Heavy snowfall takes place, and the visibility is poor. Sometimes high waves accompany the polar low, and they may occur simultaneously with the onset of the strong wind. All Norwegian coastal areas are affected by polar lows.

Waves

Most storms in the Barents sea are dominated by south-westerly weather, which is the sector with the longest wave generating fetches. Atlantic swell has also been tracked into the Barents Sea. The energy levels associated with this swell are generally significantly lower than further south. The wave height decreases eastward. The highest significant wave heights are between 10.5 and 13.6m. The ice edge also has an important influence on the wave climate in the northern and eastern areas. The resultant wave heights will be greater in summer than winter. In the marginal ice zone itself the presence of ice will tend to damp out and reflect some wave energy arriving from the off-ice sector.

Currents

The Norwegian Coastal Current follows the coastline of Norway into the Barents Sea. The highest velocities are found along the slope. At the banks, however, the velocities are reduced by bottom friction. The North Cape Current runs eastwards along the Norwegian Coast into the Barents Sea, and can be clearly identified to about 30°E. Further east, the current splits into several branches, but an essential part of the current follows the Russian Coast and turns north-west along the western coast of Novaya Zemlja. The other branch, called the West Spitsbergen Current, follows the slope northwards and runs along the western coast of West Spitsbergen, where it meets Polar Waters and turns southwards into the Greenland Sea. The Bear Island Current is a narrow cold current running in a west to south-west direction towards the Norwegian Sea. It comes from the northern parts of the Barents Sea and follows the southern slope of the Bear Island Bank. The current turns around Bj¯rn¯ya and then runs northwards parallel with the West Spitsbergen Current. The two currents are gradually mixed. The East Spitsbergen Current runs between Hopen and the Edge Island. It turns at the South Cape, and flows northwards along the West coast of Spitsbergen, inside the West Spitsbergen Current. This current carries polar or arctic water with temperatures below 0°C and low salinities.

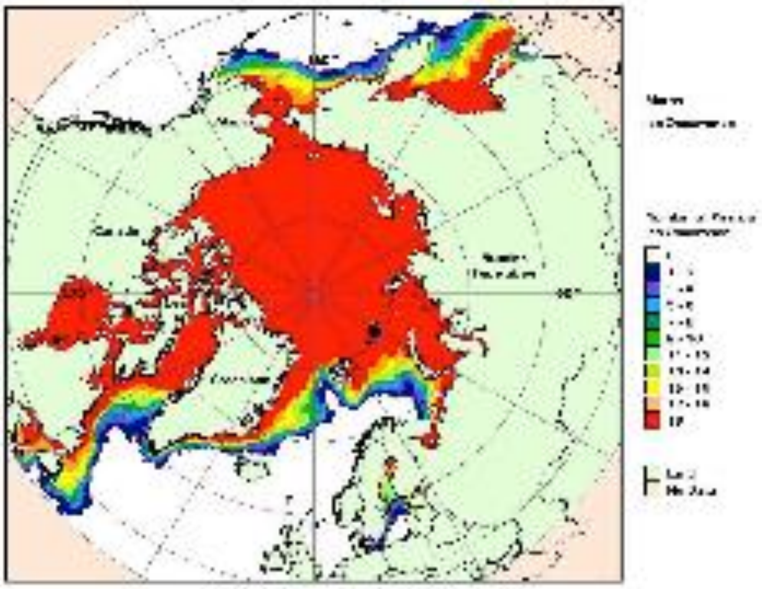
Sea level

The tidal wave moves eastward into the Barents Sea. The amplitude increases eastward along the Norwegian coast and the value of the major tidal component (M_2) in Vads¯ in the eastern part of Finnmark, is 1.09m. The amplitude increases further eastward along the Russian coast, and the M_2 constituent reaches a maximum north of the White Sea of 1.30m. The M_2 constituent then decreases eastward and in the Petchora Sea the amplitude is 20 cm.

An amphodromic point is situated southeast of Svalbard and one west of Novaja Zemlja. The amplitude in the northern part of the Barents Sea is therefore relatively small with an M_2 amplitude less than 50 cm.

Sea Ice

There is a large variation of the ice conditions in the Barents Sea. The Norwegian coast is ice free throughout the year, while the northernmost part of the Barents Sea is ice free only in July - September and some years there is ice all the year around. During the winter the ice grows from the coast of Svalbard and over the shallow part of the shelf. Heavy, warmer water, which flows northward and east- ward from the Norwegian Sea, fills the deeper part of the ocean, and hence the maximum distribution of the ice usually coincides with the limits between the shallower and deeper part of the ocean.



Icebergs

Icebergs drifting in the Barents Sea originate from the glaciers at Svalbard and Franz Josef Land. They are usually rather smooth, less than 100m thick and with a horizontal extension of maximum 300-400m. A number of giant icebergs have, however, been observed.

Sea Spray Icing

Wind speed and air temperature are the most important parameters affecting sea spray icing intensity. The wind speed has an obvious effect on the generation of sea spray. In addition it influences the cooling rate of the air- borne droplets. The intensity of icing will steadily increase with decreasing air temperature from about -2°C and down to the lowest temperature to be anticipated during offshore operations.

The influence of sea surface temperature on the icing intensity is less than for wind speed and air temperature. It is of importance in the initial stage of icing, but has a marginal influence at high icing intensities.

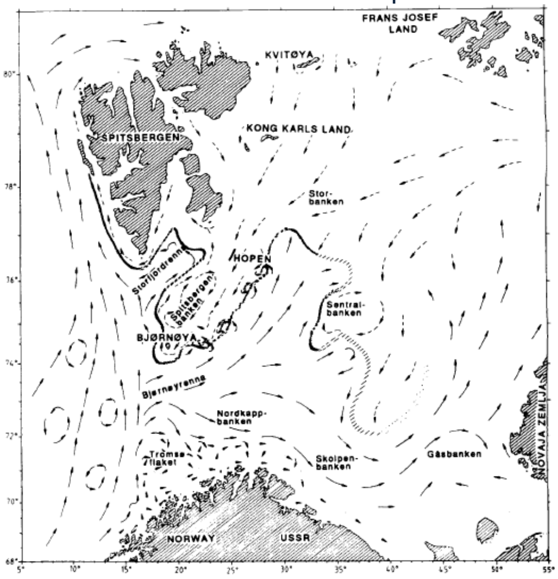
Ref:	Title:	Author:	Date:
1.06	Features of the physical oceanographic conditions of the Barents Sea	H. Loeng	1991

Summary:

<u>Relevance to Thesis</u>
Summary of the oceanographic properties of the Barents Sea area.

<u>Introduction</u>
In order to understand the biological production processes that take place in the ocean, it is important to have knowledge of the physical oceanographic conditions. Variations in temperature, ice, and current conditions are considered to be important. This article briefly describes the general physical conditions in the Barents Sea and emphasises features that are important for biological investigations

<u>Currents</u>
In the southern part of the Barents Sea, the currents are directed toward the east, while in the north the current direction is westward or southwestward. The Barents Sea is a relatively shallow continental shelf sea with an average depth of 230 m. The shallowest areas are found on Spitsbergenbanken and in the southeastern part, around Kolgujev, where the depths are less than 50 m. The bottom topography strongly influences the current conditions Along the coast of northern Norway the topography also strongly influences the currents, especially during winter when the stability is low. The Norwegian Coastal Current flows along the western and northern coast of Norway. During winter the current is deep and narrow, while during summer it is wide and shallow. The Norwegian Atlantic Current flows into the Barents Sea along Bjam0yrenna and is called the Nordkapp Current. It divides into two main branches. One branch continues eastwards parallel to the coastal current system and also changes names to the Murman. The other main branch of the Atlantic Current turns north along the Hopen Trench and divide into smaller branches. The influx of Arctic Water to the Barents Sea takes place along two main routes: firstly, between Spitsbergen and Frans Josef Land, and, more importantly, through the opening between Frans Josef Land and Novaja Zemlja. Little is known about the volume of water transported with the different currents.



<u>Water masses</u>
Each of the three main water masses, Coastal Water, Atlantic Water, and Arctic Water, is linked to one of the main current systems. The Atlantic Water is defined by high salinity. Both the temperature and salinity decrease northwards. Both the large variability in temperature

and salinity as well as the decrease in values from west to east are seen. The Coastal Water has almost the same temperature as the Atlantic Water, but the salinity is lower. The Coastal Water is, unlike the other main water masses in the Barents Sea, vertically stratified the entire year along the Norwegian coast. The Arctic Water also has low salinity, but it is most easily characterised by the temperature of below zero. During winter, the Arctic Water occupies the upper 150m of the water column, while during summer, it is covered by melt water with a thickness of 5-20m. The melt water has a low salinity, and it has a positive temperature due to heating from the atmosphere and it is separated from the Arctic Water by a sharp transition layer. In cold years, however, with very heavy ice formation, ice can drift south of the Polar Front. The ice starts to melt due to the heat from the Atlantic Water; it will then form a thin surface layer of melt water.

The formation of bottom water at the shallow shelf takes place in two steps. First the density is increased due to cooling of the water. This process becomes progressively slower as the temperature approaches freezing point. Secondly, beginning with the formation of ice, the density increases because of increased salinity resulting from brine rejection to the water. The amount of bottom water formed may vary from year to year.

The Atlantic Water in the eastern Barents Sea changes its characteristics due to the processes linked to ice formation and melting. The distribution may therefore vary with variations in the ice coverage. In the eastern basin, the Barents Sea water is found above the bottom water. The Polar Front Water, which is a mixture of Atlantic and Arctic waters, has almost the same characteristics as the Barents Sea Water.

Vertical stratification

The stratification of water masses in spring exerts a very strong influence on the development of spring blooms. Further on, the vertical mixing processes that take place during the winter are important in transporting nutrient rich water to the surface layer. Both the stratification and the mixing processes may develop differently in the various water masses. During the winter, vertical mixing due to cooling of the water masses takes place over the entire Barents Sea. In areas that have been covered by ice in the summer, the cooling process alone is not enough to create deep convection since the salinity gradient is too large.

The stability in the central and northern Barents Sea is caused by two mechanisms: ice melt and warming of the surface layer. Melting of ice can again be separated into two categories. In cold years with heavy ice formation, ice can drift south of the Polar Front and begin to melt due to the heat from the Atlantic Water. This melting, which initially is more or less independent of atmospheric conditions, produces an upper layer with reduced salinity. North of the Polar Front, the melting of ice begins when the air temperature rises above freezing. When the ice starts to melt a thin layer of melt water is progressively formed. The melt water layer is always well-mixed without any stratification. It is separated from the underlying Arctic Water by a sharp transition layer. In the Atlantic Water, which has not been covered by ice, the stratification starts to develop when the sun begins to warm the surface layer. The Coastal Water retains a weak vertical stability throughout the winter. In the spring and summer, the stratification increases because of the supply of fresh water and increased temperature.

Climatic variability

Climatic variations in the Barents Sea depend mainly on the activity and properties of the inflowing Atlantic Water. During the last 100 years the temperature in various regions of the Barents Sea swing back and forth. The variations of the related sea ice cover may be classified according to three different types:

1) short-term variations, which take place within periods from a few hours to one month
2) seasonal variability, which in its broad features is similar from year to year
3) large interannual variations.

Concerning the causes of the considerable interannual variations in the sea ice conditions, knowledge is still sparse. During the winter and early spring, the position of the ice edge follows the Polar Front in the Barents Sea. During rapid temperature increases, the decrease in ice coverage seems to be delayed. The melting of ice during summer is independent of the oceanic conditions, as it depends only on meteorological conditions.

The variability of the Barents Sea climate may be explained by similar fluctuations in the proper ties of the inflowing water. This means that an almost constant transport is bringing in Atlantic Water with changing temperature and salinity. A large volume flux corresponds to higher temperature than a small flux. The variability in the currents may be explained by external forcing, but may also be a result of processes taking place in the Barents Sea itself.

One process of importance in the Barents Sea is the formation and outflow of bottom water from the eastern basin. During the winter, water of high density is formed as a result of cooling and ice formation. The rate of production of dense bottom water may vary from year to year, and more than one year may be required before the eastern basin is filled after a massive purging. Most of this dense bottom water mass leaves the Barents Sea through the strait between Novaja Zemlja and Frans Josef Land. The outflowing volume may vary considerably from year to year, and so will the corresponding inflow. It has been shown that the variability in the Atlantic inflow is closely related to wind conditions. The warm periods in the Barents Sea are related to a stable low pressure situation in the area, while low temperature is linked to high pressure. It is then easy to believe that the pressure created by the wind-driven inflow will push the Bottom Water in the eastern basin out of the Barents Sea. The combination of an increased inflow caused by atmospheric circulation and the following outflow of bottom water allows large and rapid temperature increases.

Ref:	Title:	Author:	Date:
1.07	Identifying Critical Sources of Bridge Deterioration in Cold Regions	Yail J. Kim D. K. Yoon	01-2009

Summary:

Relevance to Thesis
Cold region engineering, material degradation due to cold climate, maintenance

Introduction
Constructed bridge structures experience a number of deterioration mechanisms, over time, induced by traffic volume and environmental conditions. An adequate evaluation of the present state of existing bridges is an important source to establish an effective bridge management program. The repair and strengthening of deteriorated members may be conducted after adequate evaluation of the structural systems. This article presents the performance of constructed bridges in cold regions through examining the bridges in the State of North Dakota that is one of the coldest regions in the United States.

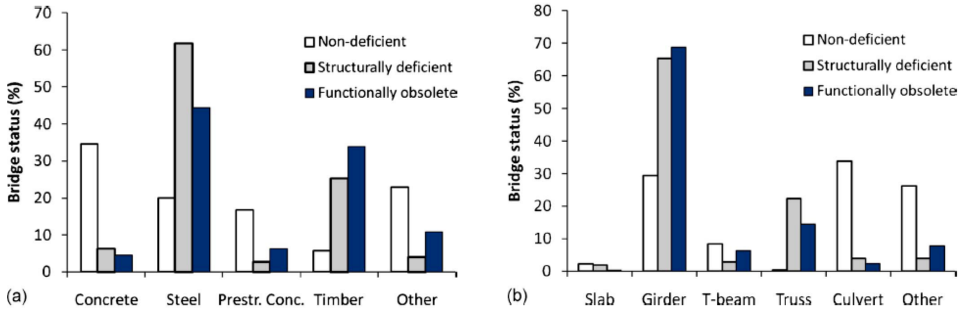
The focus of the study is on the superstructure of existing bridges (deck and supporting structural components). The bridges were typically categorized into three groups, namely, nondeficient, structurally deficient, and functionally obsolete bridges. To further examine the factors influencing the bridge deterioration, the data was additionally linked to the climate (precipitation and temperature, demographic, population and lane use, agriculture) information.

Bridge Evaluation
The bridges maintained by the county governments showed the highest structurally deficient and functionally obsolete levels. This observation may be attributed to the small number of bridge engineers and a relatively low maintenance budget of the county governments. The deck status of the major interstate highway bridges exhibited relatively poor conditions compared to that of other bridges. This is explained by the volume of heavy trucks running on the interstate highway.

Structural Features
The most critical bridges in North Dakota were found girder-type bridges with steel members. A third of the nondeficient bridges were concrete. The bridges consisted of prestressed concrete members and timbers included more functionally obsolete bridges than structurally deficient bridges. This implies that prestressed concrete bridges were durable. Timber bridges might not adequately accommodate the present traffic needs such as vehicle load and vertical clearance.
Corrosion was the primary source of deterioration for the steel bridges and the deck slabs. In particular, uniform corrosion was observed in a number of steel-plate girder bridges. Possible sources of the corrosion are the use of deicing salts and the contribution of rain and snowmelting, including the effect of chloride. The level of deterioration for the slab bridges and culverts was significantly lower than that of othertypes of structural systems. Most of the truss bridges reported here showed significant deterioration. This indicates that truss bridges may not be an adequate structural system in cold regions such as North Dakota and Minnesota.

Bridge Deck Deterioration
The present condition of the decks in North Dakota was structurally adequate. The number of failed bridge decks constructed during the 1970s was significant and the failure rate was reduced after 1990. The importance of maintenance and repair is clearly shown such that the number of failed decks constructed prior to 1950 was well less than that of the 1970s.

The majority of the existing decks was structurally adequate. Repair and maintenance was an important factor to maintain the level of adequacy.



Critical Sources Influencing Bridge Deterioration in Cold Regions

The notable parameters that were correlated to the structurally deficient and functionally obsolete bridges were constructed years, year built, volume of traffics, and the presence of water The negative correlation in the structurally deficient and functionally obsolete categories indicates that an increase in the effect of the variables reduced the deterioration level. It is interesting to note that the correlation between the year built and the deterioration of concrete bridges was almost half than that of steel bridges. It may be concluded that concrete bridges are more durable than steel bridges in cold regions. The geometry of the bridges and the volume of traffic also influenced the deterioration. Some environmental factors such as water and temperature also affected bridge deterioration, and the presence of water was particularly associated with the structural deficiency of the bridges. The contribution of water to the deterioration was more associated with the steel bridges than the concrete bridges. The effect of water might have caused freezing-and-thawing damage, leading to the deterioration of bridges in cold regions. Low freezing temperatures are more related to the deterioration of steel bridges. These observations may support typical laboratory test results such that concrete gains strength and steel becomes brittle under low temperatures.

Summary and Conclusions

- The bridge decks exposed to heavy traffic volumes such as the decks in major interstate highways exhibited significant low ratings compared to other decks. The bridges situated in large cities with large population showed more functionally obsolete levels than other areas.
- The most vulnerable bridge type in cold regions was girder bridges made of steel. Concrete bridges demonstrated well lower structural deficiency than steel bridges. Corrosion was the primary contribution to the deterioration of the bridge components. The deficiency level of slab bridges and culverts was insignificant. Truss systems may not be recommended forcold regions.
- The bridge decks in North Dakota were structurally adequate. The decks constructed after 1974 did not demonstrate a rating of below 5, whereas the bridges constructed near 1975 may approach a poor condition in the next 5 years. Particular maintenance and repair may thus be necessary for such bridges.
- The most contributing parameter to bridge deterioration was the year built, followed by the volume of traffic and structural systems. The presence of water was critical to the deterioration in cold regions, which could cause negative effects for the bridges.

Ref:	Title:	Author:	Date:
1.08	Sea ice in the Baltic Sea	M. Granskog H. Kaartokallio H. Kuosa	2006

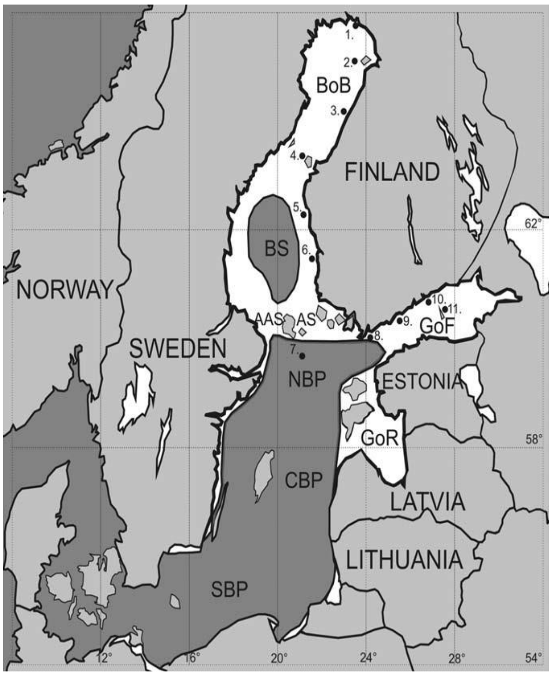
Summary:

Relevance to Thesis

Baltis sea environment, ice conditions, ice regimes

Introduction

The Baltic Sea is one of the world's largest brackish water basins with a surface area of 422,000 km2 and volume of 21,000 km3. The mean depth of the Baltic Sea is only 55 m, and in the Gulf of Finland and the Bothnian Bay less than 40 m. The Baltic Sea is heavily influenced by river discharge, and the sea has a positive water balance. Seasonal sea ice plays an important role in heat budget in the Baltic Sea as well as contributing to salt and freshwater budgets. Annually, sea ice covers a mean of 40% of the Baltic Sea and the median maximum ice extent is 157,000 km2 in average winters. Typical ice-covered areas are presented in the figure. there is a large inter-annual variability in the date freezing begins, thickness, extent, and break-up date. Despite the brackish nature of the parent water, sea ice in the Baltic appears to be structurally similar and comparable to sea ice formed in Polar waters



Large-scale atmospheric circulation patterns are significantly correlated with the ice conditions in the Baltic Sea. During average and mild winters, warm air masses associated with westerly moving cyclones from the Atlantic dominate the Baltic climate, while in severe winters blocking anticyclonic patterns dominate.

Sea ice in the Baltic Sea

Ice forms first in the inner skerries and bays where the water is often fresher and shallower, thus has a lower heat content, and where the ice cover can be anchored to islands and hoals. The land-fast ice cover usually extends to the outer skerries, where the water depth is typically between 5 and 15 m. Sea ice formation in any brackish water,such as the Baltic Sea, resembles more the ice formed in freshwaters than that which takes place in the oceans. Even though the northern Baltic Sea has low surface water salinity, the ice formed resembles that of sea ice, with preferred horizontal c-axis, jagged grain boundaries, and a substructure within the grains associated with brine layers.

Studies have shown there are large variabilities in ice structure and the contribution of different ice types to the total ice thickness. Dynamic thickness growth, i.e. ridging and rafting, play an important role. Dynamic growth conditions may prevail, and the thickness

growth and development of sea ice in the open areas of the Baltic Sea may resemble that of Antarctic waters. The land-fast ice grows more statically than the ice in the open sea. Dynamic thickness growth is therefore less important and thermodynamic growth, both at the ice/water and ice/snow interfaces, is the main contributor to ice thickness growth. The level land-fast ice cover can generally be divided into a two layer medium. The upper layer is partly composed of snow-ice or
superimposed ice and the remaining is frazil-ice. Occasionally a third ice type is present, namely transition ice. The contribution of snow-ice and/or superimposed ice to the thickness growth of land-fast sea ice in the Baltic Sea can be substantial, and is far greater than in the high Arctic.
The relatively thin ice sheet in the Baltic Sea readily supports snow-ice formation. A relatively small amount of snow deposited onto the ice cover can result in flooding of the ice cover with seawater potentially resulting in snow-ice formation.

Bulk salinity is a fundamental and routinely measured sea ice property. The brine trapped into the sea ice lattice is important for several reasons. The volume of the liquid brine, which depends on the bulk salinity and temperature, governs the permeability of the ice cover, and is important for the geophysics, biology and remote sensing of sea ice covers. The thermal conductivity, mechanical, electrical, optical, and acoustical properties are in many cases a function of the sea ice porosity, i.e. brine volume. The bulk salinities in the northern Baltic Sea are generally less than 2, and even lower depending on the ambient water salinity, growth conditions and thermal history of the ice. The low ice salinity is also reflected by relatively low brine. The permeability of the ice is affected by the interaction of temperature, brine salinity and brine volume.

Atmosphere to ice interactions
The mild ice climate conditions in the Baltic Sea are not only responsible for the superimposed ice formation, but also for the rapid changes in ice properties, such as the temperature and the salinity, and thereby in porosity. The thin ice cover responds quickly, usually within hours, to changes in atmospheric conditions, whether it is changes in air temperature or snow accumulation. The Baltic Sea has substantial input of river water. Not only is river inflow into the Baltic one of the main sources for freshwater, nutrients and contaminants in coastal areas, but also the freshwater increases the stability of the water column thereby promoting ice formation. Sea ice also enhances the dispersal of river water since the impermeable cover decreases water mixing and allows river water plumes to spread underneath the ice. Processes that control the under-ice flow of river waters strongly influence the winter oceanography and transport pathways.

Conclusions and future outlook
The seasonal sea ice cover is a distinct feature of the Baltic Sea, although its extent may be mainly limited to the northernmost parts of the Gulf of Bothnia at the end of this century if climate changes as predicted. These include changes in the water balance of the whole Baltic catchment area, and substantial increase of mean temperatures with the predicted changes being most pronounced during the cold season. Recent observations indicate that the total ice volume in the Baltic might be larger than previously thought. It is speculated that sea ice cover in the Baltic may have critical role in the overall nutrient and carbon cycling of the Baltic Sea.

Possible useful references
Granskog, M.A., Martma, T., Vaikma¨e, R. : Development, structure and composition of landfast sea ice in the northern Baltic Sea.
Website
http://portal.liikennevirasto.fi/sivu/www/baltice/ice_forecast

Ref:	Title:	Author:	Date:
1.09	Simulation of currents, ice melting, and vertical mixing in the Barents Sea using a 3-D baroclinic model	K. Stble-Hansen D. Slagstad	1991
Summary:			

<ins>*Relevance to thesis*</ins>
Ice regimes in the Barents Sea, modeling of ice, environmental effects on ice properties

<ins>Introduction</ins>
The general feature of the circulation pattern in the Barents Sea is well known through hydrographical studies combined with a few current measurements. The Barents Sea is characterised by relatively great vertical and horizontal density gradients, which are closely related to the processes of freezing and melting of the ice and freshwater input from land. It is aimded to use the measured density distribution from the autumn as an initial field and create the vertical and horizontal distribution of temperature, salinity, and ice for the spring and early summer season. The developed model described is a 3-dimensional, baroclinic, finite-difference "level model" that is defined by a 'sequence of fixed but permeable levels. Each level has a fixed thickness, except the level near the surface and the one next to the bottom.

<ins>Thermodynamics and ice</ins>
The flux of energy from the atmosphere to the surface water mainly consists of four elements.

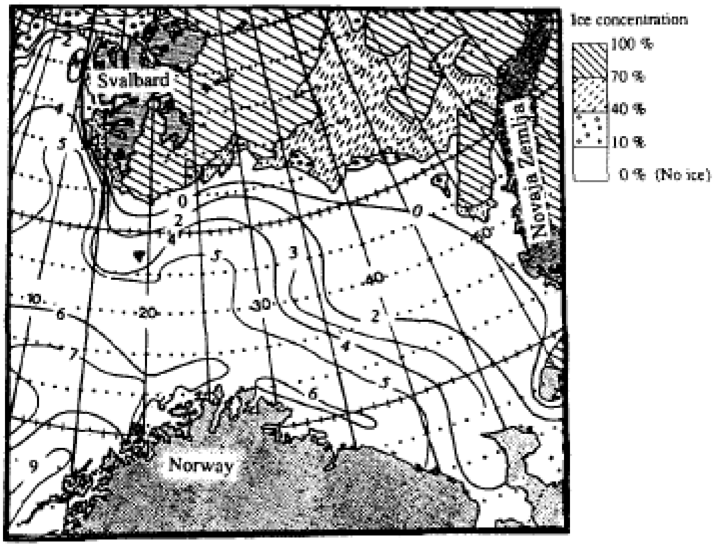
Energy flux = Fh + Fe + Fi + Fq
Fh (sensibleheat)
Fe (latentheat)
Fi (infraredflux)
Fq (solarradiation)

Depending on the sign of the energy flux and the water temperature, freezing or melting processes will take place. The ice model and the processes related to freezing and melting of ice are described.

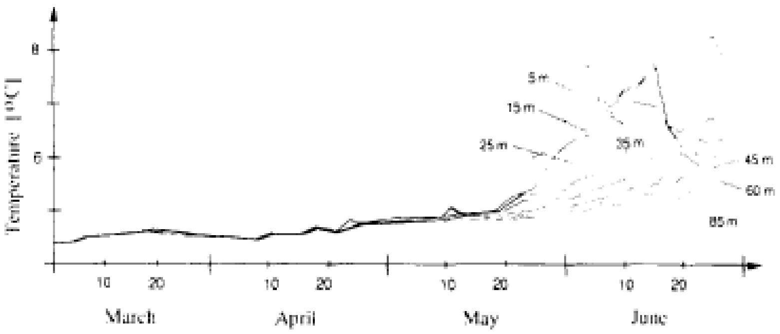
<ins>Ice transport</ins>
The transport of ice is not a trivial problem. The ice is not homogeneous and it may be firmly attached to land or other ice masses. Ideally, acceleration of ice is a result of several forces such as drag from wind and water, the Coriolis force, and gravity due to the sea surface slope. The drag
from wind and water is proportional to the area of the ice, and independent of its thickness. Thus,
when the ice cover is thin and there are strong wind or water forces, the acceleration may become quite high.

<ins>The freezing period</ins>
The main purpose with the present hydrodynamical model is to simulate the physical environment and to use the data as input for a model of plankton growth. The most active biological period is from March to mid-summer. Ice formation will therefore first take place in the water masses that were exposed to ice the previous year, in shallow areas and in the southeastern part of the Barents Sea. Wind and variable cooling, however, may change the ice distribution considerably from month to month and year to year. After the cooling period there has been an increase in temperature near the bottom which is due to the advection of Atlantic Water from the southwest. During the cooling period the stability of the whole

water column is broken down. Further cooling would have increased the salinity due to brine rejection during the freezing process and probably contributed to the formation of bottom water.



One of the characteristic processes during sea ice formation is the release of salt to the surface layer. The surface salinity gradients are generally smaller after the freezing period. This is one of several structural changes in the density during the freezing period which should imply changes in the current patterns.



Discussion and conclusions

This paper does not attempt to give a detailed reconstruction of the current fields and physics from the period we are simulating; rather it presents a study of the mechanisms concerning the melting and freezing of ice and vertical mixing in the water column.

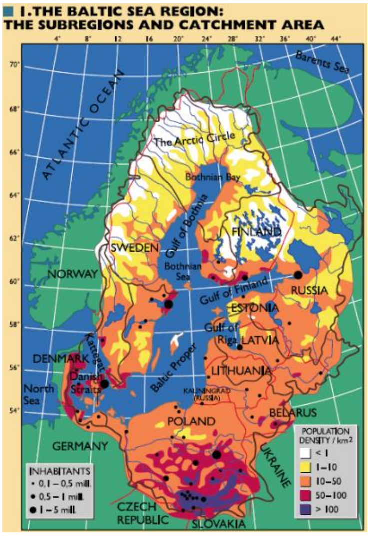
One of the main aims of this test is to discover whether the model can actually produce density gradients and not annihilate them as time passes. Another aim of importance is how the model handles the freezing of ice, and whether the different density gradients appear geographically in the correct position. The latter property is of course highly dependent on the distribution of the ice cover. Examination of the vertical profiles of temperature and salinity reveals that they seem to be typical compared to what is observed and assumed. In the Atlantic Water the mixed layer is about 30-40 metres before cooling (autumn) and 100-150 metres after the cooling (winter). In the Arctic waters the mixed layer is more shallow before the cooling, but deeper (almost permeating the entire water column) after the cooling.

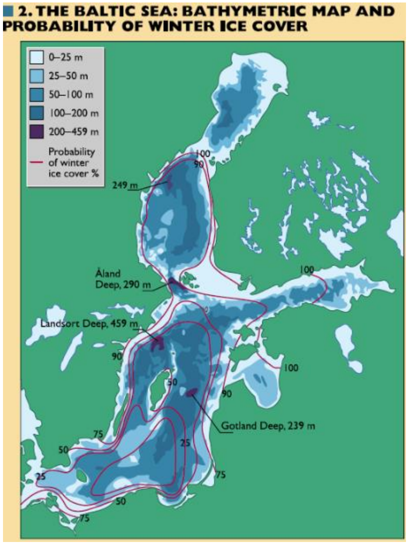
Ref:	Title:	Author:	Date:
1.10	The Baltic Sea – Environment and Ecology	E. Furman H. Salemaa	2004

Paper Summary:

<u>Relevance to thesis</u>
Global description of Baltic Sea climate, environment and ecology, relevant figures

<u>Figures</u>





<u>The Baltic Sea: zonation, bathymetry and ice cover</u>
Unlike most other seas and oceans, the Baltic Sea is located entirely on one continental plate instead of lying on a continental divide, which explains why the sea is so shallow compared to other seas. The average depth of the Baltic Sea is only 60 meters. The deepest part of the Baltic, the Landsort Deep, which is situated in the Baltic Proper off the Swedish coast northwest of the island of Gotland, is 459 meters deep. The bathymetric profile of the Baltic Sea can be divided into three zones. The coastal zone stretches from the mainland to the outer limit of the islands, where they are present. There is a transitional zone extending from the coastal zone to where the depth reaches 50 metres and the open sea zone begins.

The interaction between ice cover and brackish water that is typical of the Baltic Sea is a rare phenomenon elsewhere in the world. The probability and duration of ice cover increases towards the northern and eastern parts of the sea. During normal winters the ice cover lasts 4–6 months in the Bothnian Bay and 2–4 months in the Bothnian Sea and the Gulf of Finland, whereas in the Baltic Proper it lasts less than a month and even then there are areas of open water present. Only exceptionally cold winters can cause the entire Baltic Sea to freeze over. The presence of ice affects the currents, sedimentation processes and the species inhabiting the shores, coastal waters and the open sea. The ice also causes difficulties for maritime traffic. In the spring a layer of freshwater forms between the ice and the brackish water in areas of coast that are influenced by freshwater inflow from rivers. The freshwater originates partly from the inflowing river water and partly from the melting ice, and has a profound effect on the species living close to the surface.

Ref:	Title:	Author:	Date:
1.11	Meteoric Ice contribution and influence of weather on landfast ice growth in the Gulf of Finland	J.Uusikivi M.A. Granskog E.Sonninen	2011

Summary:

<u>Relevance to thesis</u>

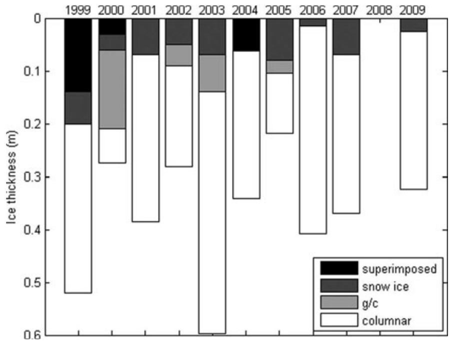
Ice properties in the Gulf of Finland, environmental and meteorological effects on ice properties, land-fast ice accumulation.

<u>Introduction</u>

Sea ice covers large areas of the Baltic Sea every winter, and the ice-cover season lasts for 5–7 months in the northernmost parts of the Bay of Bothnia. The ice cover has a large impact on navigation and biology, and sea-ice texture and icegrowth mechanisms are important factors controlling key ice parameters such as mechanical strength, and chemical and biological properties. Snow-ice and superimposed-ice layers accumulate at the sea-ice surface and are referred to as meteoric ice because of the role of snow and rain in their formation. Snow ice is a
mixture of snow and sea water. Superimposed ice is completely or mainly composed of snow meltwater and/or frozen rain. In the Baltic Sea, depending on season and year, meteoric ice may contribute almost half of the total thickness and up to 35% of the total mass of landfast ice.

<u>Monitored Ice Thickness</u>

There was considerable interannual variation of ice thickness, from 22cm in 2005 to 60cm in 2003 There was no ice in 2008. All ice cores were composed of a granular ice layer overlying columnar ice. Some cores had intermediate g/c layers sandwiched between granular and columnar layers. Granular ice layer thickness ranged from 1.5 to 20 cm. Columnar ice layer thickness ranged from 7 to 46 cm. Intermediate g/c ice thickness varied, when present, from 3 to 15 cm.



<u>Influence of weather on ice thickness and composition</u>

The NAO correlated with weather observations in the study area, and a higher NAO resulted in warmer, wetter and windier winters. The measured temperature, precipitation and wind-velocity anomalies were well correlated to the NAO index. Early-winter average NAO has strong correlation to average early-winter precipitation Total ice thickness was dependent on the mean NAO index, i.e. high--index winters had lower mean ice thickness. Ice composition was also well correlated with the NAO. The contribution of meteoric ice to the total ice thickness was correlated with the early-winter mean. The intermediate g/c ice contribution was also correlated with the mean NAO, ie. g/c ice made a much higher contribution to the total ice thickness in years with high NAO values. Ice-thickness variation was largely due to freezing degree days in early winter. Ice thickness correlated negatively with average winter temperature, precipitation and wind. Precipitation and wind are strongly positively correlated with temperature, which explains the relationship to ice thickness. The contribution of meteoric ice to maximum ice thickness was strongly correlated with early-winter precipitation. The snow fraction in meteoric ice layers was
well correlated with wind speed, but not to precipitation or temperature. Winters with higher windspeeds also had thinner meteoric ice layers. Superimposed ice formation, which occurred only in some years, wasassociated with colder and wetter than average years.

<u>Comparison of Results</u>

In Santala Bay, ice stratigraphy showed typical Baltic Sea landfast ice characteristics, with a granular layer on top and intermediate g/c and columnar ice layers at the bottom. The meteoric ice contribution (average 19.3%) to the ice thickness was typical of the Santala Bay area, but considerably smaller than the 31.6% reported in Bay of Bothnia fast ice. The results also show that the contribution of meteoric ice to fast ice growth is at least as important in the Baltic Sea as in the Arctic Ocean and the Okhotsk Sea, where meteoric ice averages 10% of pack-ice thickness. However, meteoric ice is not as significant a factor in the Baltic Sea as it is in Antartica, where it contributes 24–27% of the total ice thickness. The snow fraction of meteoric ice was highest when superimposed layers were observed, as it efficiently turns snow into ice. The average snow fraction of the total ice thickness, 8.8%, was less than the 18.3–20.7% reported in Bay of Bothnia fast ice. This difference in snow fractions could be explained by higher superimposed-ice production in the Bay of Bothnia area. The thicker the Santala Bay ice cover, the smaller the contribution of snow ice. Although snow ice contributes significantly to the ice thickness, the overall effect of snow on ice is to reduce the level-ice thickness because the insulating effect of the snow outweighs the consequences of snow mass and snow-ice formation.

High winter NAO values are typically associated with windy, warm and moist weather in the Gulf of Finland. A thinner ice cover and larger granular/meteoric ice contribution to total ice thickness are a logical consequence of high-NAO weather patterns. Higher temperature means lower basal freezing rates and less columnar ice growth, while higher precipitation creates suitable conditions for snow-ice accumulation after flooding and/or superimposed-ice accumulation due to melting in the snow cover or percolation of rain through the snow to the ice surface. Of all the weather parameters, Freezing Degree Days had by far the greatest influence on total ice thickness. Neither meteoric ice thickness nor its contribution to total ice thickness was well correlated with temperature or FDD. The thickness and mass of the snow cover also depend on the wind. Higher wind velocities resulted in smaller ice and also thinner meteoric ice layers. These effects relate to snow transport and the accumulation or deflation of snow and thus whether there is sufficient mass of snow to cause flooding and snow-ice formation.

Conclusions

In the Baltic Sea, the 82.0% contribution of columnar and intermediate g/c ice to the total landfast ice thickness indicates that thickening is dominated by downward thermodynamic ice growth at the bottom of the ice cover. Snow ice, which contributes 12.4% of the total ice thickness, is the second most important thickening process. The snow entrained in the snow-ice and superimposed-ice layers combined makes up 8.8% of the total ice mass. The thicker the ice cover is, the lower the contribution of meteoric ice growth to ice thickness, indicating that, although meteoric ice is a significant contributor to the ice thickness, the overall effect of snow on the ice is to decrease the total ice thicknesses due to insulation and reduced basal growth rates. Superimposed-ice formation was connected to certain weather patterns, with cold, wet
winters more likely to produce superimposed ice than average or warm winters. Higher wind speeds appear to lead to less snow being entrained in meteoric ice and thus a smaller snow contribution to total ice mass.

Future climate in the Baltic Sea area is expected to be warmer and wetter This will lead to thinner ice covers with a higher proportion of meteoric ice, However, in sufficiently warm weather, landfast sea ice will not form at all on the southern coast of Finland.

Ref:	Title:	Author:	Date:
1.12	Geophysics of sea ice in the Baltic Sea	T. Vihma J. Haapala	02-2009

Summary:

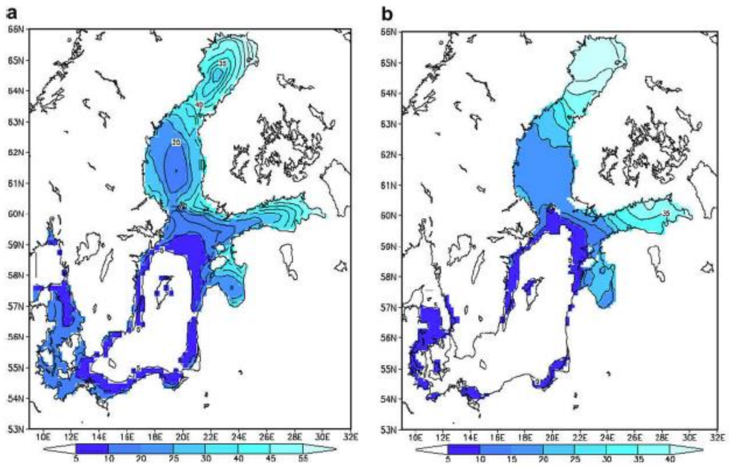
<u>Relevance to thesis</u>
Ice regimes in the Baltic Sea, modeling of ice, environmental effects on ice properties

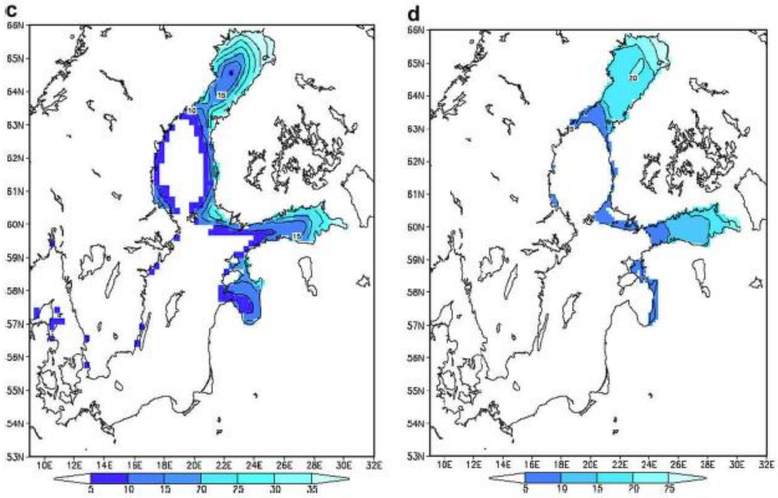
<u>Introduction</u>
Through various mechanisms sea ice is an important factor in the climate system of the Baltic Sea region. First, sea ice has a high albedo. Second, sea ice and its snow cover act as good insulators between the ocean and the atmosphere reducing, or even preventing, the air–sea exchange of heat, water vapour, CO2, and other gases. Third, the ice cover acts as a mechanical barrier between the atmosphere and ocean. Below land-fast ice this prevents the air–sea momentum flux, and below drift ice the momentum flux may be either increased or decreased. Fourth, the ice pack stores and advects fresh water, heat, atmospheric settling, and sediments, and may release them far away from their original source.

<u>Baltic Sea ice climate</u>
In recent decades, research on the Baltic Sea ice conditions has become increasingly active.

Considering the ice climate, the main findings can be summarized as followed:

- A change towards milder ice winters has been detected from the time series of the maximum annual extent of sea ice and the length of the ice season. On the basis of the ice extent, the shift towards a warmer climate took place in the latter half of the 19th century.
- The MIB generally decreases with increasing indices of AO and NAO, but the MIB can be very large even in winters with a positive seasonal NAO index. At least in the northern Baltic Sea, NAO affects the length of the ice season via its influence on the break-up date, but it does not correlate with the freezing date.
- Data on the ice thickness mostly originates from the landfast ice zone, and basically do not shows clear trends during the 20th century, except that during the last 20 years the ice thicknesses have decreased. In the northernmost Bothnian Bay, the ice thickness showed an increasing trend until 1980s.





Considering physical processes related to sea ice:

- The atmosphere, sea ice, and the sea are closely coupled via thermodynamic and dynamic processes. Studies have demonstrated the high variability of thermodynamic surface conditions, which cannot be described by two surface types (such as ice and open water) only. From the point of view of the surface fluxes, however, the temporal and spatial variations in the cloud cover are often even more important than the spatial variations in the surface conditions.
- Sea ice thermodynamics and dynamics are closely interrelated. Sea ice dynamics results in opening and closing of leads, while thermodynamics results in ice formation, growth, and melt. Ice dynamics depends on the ice thickness distribution, and in turn redistributes the ice thickness via rafting and ridging.
- The structure, physical properties, and thermodynamics of sea ice are closely interrelated. The penetration of solar radiation into snow and ice has importance for sub-surface melting. The formation of granular layers of superimposed ice and snow ice has been better quantified, both ice types being common in the Baltic Sea. Observations have indicated the importance of snow and ice thickness as well as the diurnal cycle of snow/ice metamorphism on the surface albedo.
- Observations have demonstrated the stabilizing effect of river discharge and ice melt on the oceanic boundary layer below the ice. This strongly reduces the oceanic heat flux to the ice bottom.

Perspectives on the future research can be summarized as followed:

- The snow cover on sea ice deserves more attention. Snow-ice and superimposed ice are essential for the total ice thickness in the Baltic Sea.
- The snow/ice surface albedo is a critical parameter for climate modelling. In addition to its dependence on the state of the snow and ice cover, the snow/ice albedo interacts with the cloud radiative forcing, and the multiple reflections between the snow/ice surface and the cloud base.
- Two important ice variables are missing from the ice-monitoring activities, namely the ice velocity and the thickness of drifting ice.
- Coupling of operational models is assumed to yield better forecasts, at least in cases when large sea areas are rapidly opened or closed due to ice formation, advection, or melt. Even if in the coming decades the ice cover in the Baltic Sea will be strongly reduced, the experiences obtained in the Baltic Sea will be very useful for research and operational activities in the Arctic and Antarctic.

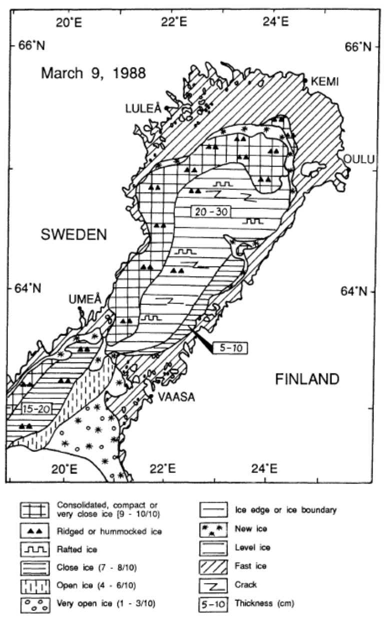
Ref:	Title:	Author:	Date:
1.13	Statisctical properties of sea ice surface topology in the Baltic Sea	John E. Lewis Matti Lepparanta	09-1992
Summary:			

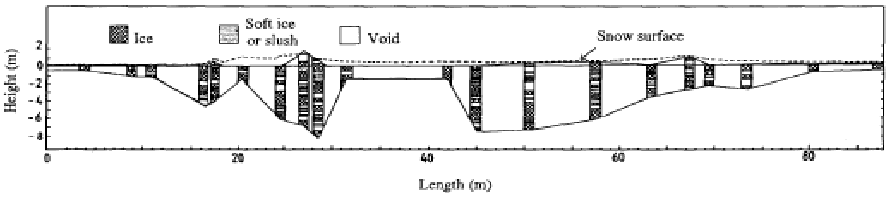
Relevance to thesis
Ice geography in the Baltic Sea, ice regimes, ice drift

Introduction
In the northern part of the Baltic Sea ice forms every year. Depending on the location, the average ice season is 3-6 months and the maximum annual ice sheet thickness 10--120 cm. Frequent storms induce mechanical deformation. The deformed ice has fairly rough surface topography and appears as rubble fields and as ice ridges, with thick but long and narrow accumulations of ice blocks. The thickness of ridges is typically 5-15 m and over large areas their mass accounts for up to one-third of the total ice mass. Only 1st-year ice occurs in the Baltic Sea.

Ice ridges are a major obstacle to winter navigation and when in motion cause the largest forces on offshore structures in the Baltic Sea. In sea ice geophysics knowledge of ridging characteristics greatly aids the understanding and modeling of large scale ice mechanics. However, for the Baltic Sea quantitative information on this subject is relatively limited. Research work includes detailed field investigations of the geometry, internal structure and strength of individual ice ridges and the large scale mapping of the ice surface topography. Airborne laser profiling is presently the best method for ice surface topography mapping on a large scale.

Measured Ice conditions
Throughout December the drift ice fields were small and relatively thin (less than 10 cm), producing only rafting and jamming in the pack ice. By early January the maximum thickness of undeformed drift ice had increased to 30-40 cm and the first ridges began to appear. A deformed ice patch, around 100 x 50 km, developed in the northern basin during January. Easterly winds dominated and ridging was frequent in a 20--30 km wide zone in the western basin extending along a southerly track. After the 20th of February, ridging was also reported from the central and southern parts of the Bay of Bothnia. Within the ice field, the thickness increased to 10--30 cm by the beginning of March and the ice movement was substantial. The thickness of the undeformed ice was 10--60 cm. Not much is known about thicknesses of the parent ice which participated in the ridging processes. The ice compactness was 90 to 100% in the observation areas.





Ridge heights greater than 200 cm are rare which is to be expected since the highest sail height (of floating ridges) ever recorded in the Baltic was 350 cm.

The data were first stratified into 5 groups representing different ice conditions. The length of combined profiles within each group was 30-200 km. The average surface elevation with respect to the water surface level ranged from 16 to 22 cm, the root-mean-square value was 7-14 cm, and the correlation length of the surface was about 50 m. The surface elevation spectra were red (slope -1.5) for wavelengths from 4 to 100 m. Ice ridges were identified using the Rayleigh criterion with a 40-cm cutoff height. The mean ridge heights were from 52 to 59 cm, the standard
deviation of the ridges from 12 to 20 cm, and the maximum ridge was 197 cm. The mean ridge density ranged from 1.4 to 9.5 km -1 in the main ice pack and 17.4 km - 1 in the shear zone. The distribution of ridge heights both for the entire sample and for each of the individual ice groups was exponential. Ridge heights and spacings showed poor correlation for the Baltic Sea data. A minimum set of three parameters (cutoff height, mean ridge height and ridge density) is needed to describe the ridge intensity. Ridge density is the most important factor in describing ice ridging variability.

The volume of mechanically deformed ice was estimated from the data. Ridges accounted for 1-18 cm of equivalent ice thickness. The proportion of rubble was extrapolated from the ridge distributions indicating that rubble fields accounted for 2-10 cm of equivalent ice thickness. The thickness of deformed ice (ridges and rubble) was 15-40 % of the total ice volume.

Ref:	Title:	Author:	Date:
1.14	Baltic Sea Ice Season in the 20th Century	S. Jevrejeva V. V. Drabkin	2004
Summary:			

Relevance to thesis
Ice regimes in the Baltic Sea, evolution of sea ice seasons, seasonal trends

Introduction
The Baltic Sea is located in the seasonal sea ice zone. The maximum annual ice extent is 10 to 100% of the Baltic Sea area, the length of ice season is 4 to 7 months and the maximum annual thickness of landfast ice is 50 to 120 cm. The long-term evolution of the Baltic Sea ice conditions is of high concern to the Baltic Sea countries, as it is expected that even small climatic changes will show up drastically in the ice conditions. The information of the past ice seasons is a key for the prediction of how the coming ice seasons will be.
The observation program included information about the dates of the first freezing, the formation of the permanent ice cover, end of the permanent ice cover, the final disappearance of the ice, and the thickness of the ice. Air temperature measurements were also made. Ice conditions in the Baltic Sea have been examined by time-series analysis in order to study the natural variability of the ice conditions. The ice conditions over the whole region and their evolution in the 20th century are examined using a joint data set, and the local variations around the general development are found for several parts of the Baltic Sea.

Probability of ice occurrence
The probability of ice occurrence in the Baltic Sea varies drastically from 32% along the German coast to 100% in Bothnia Bay. The probability of ice occurrence is also dissimilar for the open areas and shallow inner waters; even along the German coast the probability is confined between 32 and 92%. For the northern part of Bothnia Bay there are no changes in probability of ice occurrence, since the basin has frozen annually throughout the 20th century.
German and Polish measurement stations show statistically significant decreasing trends in probability. However, the Gulf of Finland station demonstrates a statistically significant increasing trend, which can be explained by missing data in the earliest part of century and an increase in the freshwater influx to the gulf during recent decades. Results for the open area of the Baltic show that the decrease in probability of ice occurrence is partly explained by the increase in winter air temperature.

Ice Season
The mean date of freezing in the Baltic Sea is confined to between 10 November in Northern Bothnia Bay and 25 January along the coast of Germany.
The mean date of ice break-up occurred between 20 February along the German coast and 21
May in Northern Bothnia Bay. The influence of large-scale atmospheric circulation on the date of ice break-up was analyzed. Correlation coefficients between the time series of the North Atlantic Oscillation (NAO) winter index and time series of date of ice break-up are small.

Ice thickness
An increasing trend in ice thickness measurement in the northern Baltic Sea was found. Ice growth depends on snow thickness and is linked to an increasing trend in winter precipitation in the northern part of Finland. In the Gulf of Finland, trends showing a decline in the maximum annual ice thickness were found.

Discussion

The decreasing trend in probability of ice occurrence found at most sites is in good agreement with a warming trend in winter air temperature over Europe. The opposite tendency in the Gulf of Finland and Gulf of Riga can be explained by increasing freshwater influx to the shallow semi-closed basins. The date of freezing is characterized by a low standard deviation, and the probability of ice occurrence is close to 100%. The relation between the probability of ice occurrence and standard deviation illustrates the decrease in the standard deviation with increasing probability. The freezing date is related to the sea-surface temperature, which mainly depends on the mixed layer depth, radiation balance and the turbulent heat exchange between sea and the atmosphere.

The trends toward earlier ice break-up in the northern Baltic Sea can be explained by an increasing winter air temperature, with weather conditions dominated during the past years by westerly circulation related to a positive NAO index. Large scale atmospheric circulation patterns represented by NAO teleconnections have significantly controlled ice conditions in the Baltic Sea during the last 30 years. In the southern Baltic the tendency for a later breakup is related to the decreasing probability of ice occurrence. The combination shows less winters with ice, but ice is mostly observed with more and more severe winters.

Conclusions

The long-term time series of date of freezing, breakup, number of days with ice and maximum annual ice thickness of landfast ice in the Baltic Sea were examined by statistical methods.
The conclusions may be summarized as follows:

The probability of ice occurrence is confined to between 32% in the southern part of Baltic Sea and 100% in the north and along the Finnish and Russian coasts.

- In the northern part of the Baltic Sea, there has been a change in the probability of ice occurrence. In the south Baltic Sea and central areas, there is a statistically significant decreasing trend.

- Break-up in the north is characterized by a statistically significant decreasing trend showing earlier break-up. In the south, trends are insignificant but have a tendency for a later date of ice break-up.

- Most sites show a tendency for shorter ice periods.

- There is no general conclusion concerning maximum annual ice thickness. Some sites around Bothnia Bay show an increase, however, most time series are characterized by a decreasing trend.

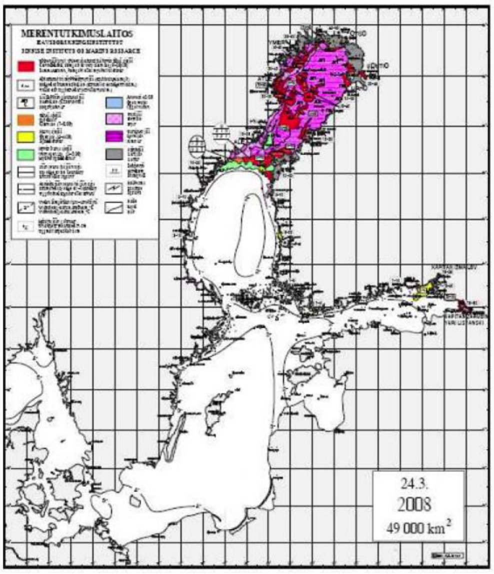
Ref:	Title:	Author:	Date:
1.15	Baltic Sea Ice Breaking Reports 2007-2010	Baltic Icebreaking Managment	2007-2010

Summary:

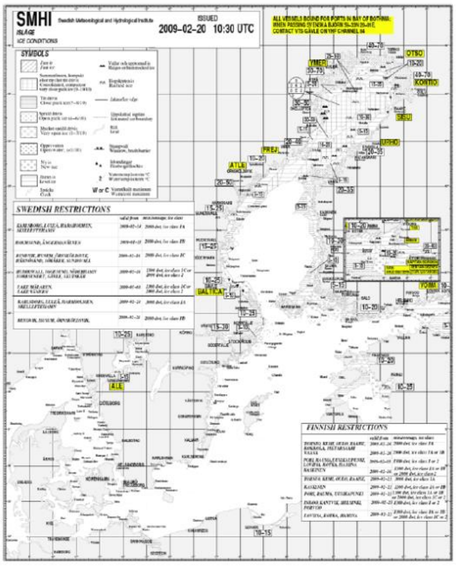
<u>Relevance to thesis</u>
Ice management in the Baltic Sea, seasonal trends of ice season, ice properties

Since these reports contain information on all regions comprising the Baltic Sea, the focus of the summary was put on the coast of Finland, as this is the proposed site of the thesis.

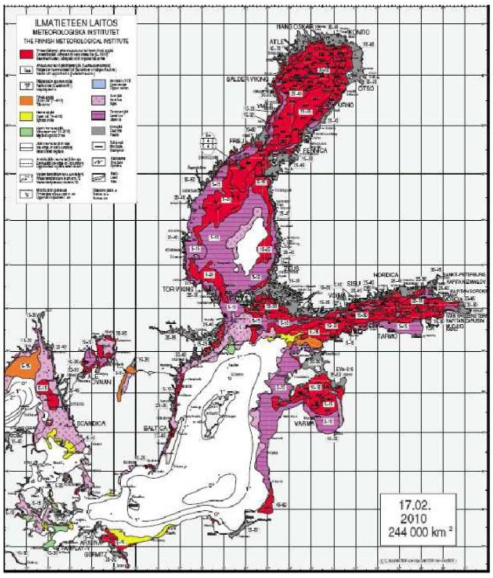
<u>Overview of ice extent per season</u>



2007-2008



2008-2009



2009 - 2010

Ref:	Title:	Author:	Date:
1.16	Simulating the Baltic Sea ice season with a coupled ice-ocean model	J. Haapala M. Lepparanta	1996
Summary:			

Relevance to thesis
Baltic sea ice modeling, ice properties, ice drift

Introduction
The seasonal sea ice cover is an essential feature of the Baltic Sea. The ice season normally lasts 5-7 months, from November to May. In the northern parts of the Baltic the ice covered period is even longer than the ice-free season. Ice largely modifies or even eliminates the ocean-atmosphere heat, radiation and momentum fluxes. An essential difference between ice dynamics and ocean and atmosphere dynamics is that drift ice shows a nonlinear plastic behavior with a large part of the mechanical energy consumed in irreversible internal deformation processes like ridging and rafting. The atmosphere and ocean are always in motion but an ice field may be static. The main problem is to determine the internal ice stress, which arises from ice floe interactions.

The evolution of the ice season is driven by the atmospheric and oceanic forcing and radiation. The ice drift is mainly driven by the wind, while the air temperature basically determines the ice growth. The role of the Baltic water masses is to store heat and consequently delay freezing, and to provide the friction for the ice motion. On a seasonal scale the ice and ocean are highly coupled. The evolution of the ice conditions depends on the heat which was stored in the sea during the previous summer and autumn. In turn, the ice pack modifies the momentum, heat and salt balance of the sea.

The Baltic Sea is situated at latitudes where strong annual variations in all climatic quantities are typical. Observations of the thickness, extent and duration of the ice in the Baltic Sea also indicate a large inter-annual variability between the ice seasons. The ice season evolution is driven by the weather, ice/ocean interactions and the ice field internal processes. The main reason for this large natural variability is the sea's location between the North-Atlantic and Eurasian continental weather systems. The North Atlantic Oscillation (NAO) winter index has been widely used for describing large-scale air circulation patterns and has been related to sea ice characteristics. Basically, large positive NAO indexes (NAO> 1) imply strong westerlies and mild ice winters and correspondingly large negative values (NAO < -1) weak westerlies and severe ice winters. The NAO index gives only a rough estimate of the winter severity in the Baltic, but the specific air circulation patterns around the Baltic Sea are the determining factor in the evolution of the ice season.

The aim of the present model simulations is to examine the model's ability to reproduce the observed ice season evolution. Beginning from the same initial conditions and using the observed meteorological forcing, the normal, severe and mild ice seasons were simulated. The effect of the initial temperature and salinity fields on model results is always problematic in long-term simulations.

Model results were compared to the observed sea surface temperature, freezing date, ice thickness, compactness, and ice break-up.

Quantity	Winter 1983/84 obs.	Winter 1983/84 mod.	Winter 1986/87 obs.	Winter 1986/87 mod.	Winter 1991/92 obs.	Winter 1991/92 mod.
maximum ice extent (10^3 km^2)	187	156	405	331	66	64
occurrence of maximum ice extent	23 Mar	5 Apr	16 Mar	18 Mar	20 Feb	4 Mar
Kemi						
freezing date	4 Nov	11 Nov	2 Dec	5 Dec	18 Dec	14 Dec
max ice thickness (cm)	76	87	92	102	50	46
occurrence of max. thickness	17 Apr	3 Apr	14 Apr	20 Apr	10 Mar	18 Apr
break-up date	8 May	28 May	25 May	28 May	5 May	18 May
Utö						
freezing date	25 Jan/7 Mar[a]	11 Mar	3 Jan	8 Jan	no ice	no ice
max ice thickness (cm)	20–40[b]	27	69	34	–	–
occurrence of max. thickness	20–27 Mar[b]	25 Mar	7 Apr	6 Apr	–	–
break-up date	11 Apr	21 Apr	20 Apr	10 May	–	–

[a] The first freezing occurred 25 January 1984 and the formation of permanent ice occurred 7 March 1984.
[b] Ice thickness measurements were not made in Utö, these values are based on the nearest measurement sites.

The evolution of the ice season has been simulated for three particular seasons, normal (1983/84), severe (1986/87) and mild (1991/92). The model results were compared to the observed sea surface temperature, freezing date, ice thickness and compactness and ice break-up, as available from the published ice charts and tables.

It has been shown that the main characteristics of the ice season could be reproduced by a moderate resolution ice-ocean model. Beginning from the same initial conditions and using the observed meteorological forcing, the model simulated realistic annual cycles of sea surface temperature, ice thickness and coverage and described the inter-annual variability of the ice season well. The most important factor controlling the ice edge and initial freezing in the model is the proper modeling of the ocean surface layer. It determines the heat content of the surface layer and hence the freezing date. To solve this problem the ice model should be coupled to an eddy-resolving three-dimensional ocean model, and the coupling should probably be handled with a boundary layer model for calculating more accurate fluxes between ice and ocean.

The ice growth was simulated realistically. However, the maximum ice thicknesses were slightly larger than observed. The overestimation may be due to an underestimation of snow thickness and oceanic heat flux. The beginning of the ice melting was delayed, which led to about two weeks delay in the ice break-up date. The delayed ice melting may be due to the parameterization of the surface albedo and also because the penetration of the solar radiation into the ice was not taken into account. Dynamic produced ridged ice thickness fields were qualitatively correct.

Ref:	Title:	Author:	Date:
1.17	Ice Dynamics in the Bothnian Bay inferred from ADCP measurements	G. Björk C. Nohr	09-2007

Summary:

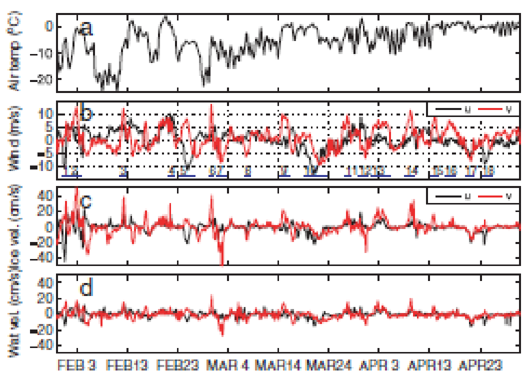
Relevance to thesis
Ice dynamics in projected area, ice properties and typology

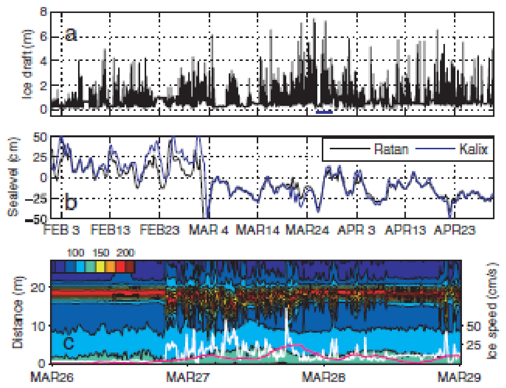
Introduction
In this article a summary and analysis of observational data of sea ice drift, currents and ice thickness is described for a full ice season in the central part of the Bothnian Bay. The main objective with this study was to investigate how the ice motion responds to wind forcing from different directions and how the response changes due to variations in thickness and compactness over the ice season. Another aim is to obtain an estimate of the ice thickness distribution with focus on the amount of very thick ice in the form of pressure ridges.

The drift of sea ice is mainly controlled by a balance between drag forces by the atmosphere and ocean, and internal stresses acting in-between ice floes and between ice floes and solid boundaries. Ice dynamics controls the deformation of the ice cover which in turn generates pressure ridges and open water. Pressure ridges are primarily formed on the windward side of the basin and leads are formed at the upwind side.

Typically level ice becomes 50–120 cm thick. The Bothnian Bay is large enough for the wind forcing to overcome the ice strength and the ice cover deforms therefore during strong wind events and pressure ridges are formed, typically 5–15 m to a maximum of about 30m.

Observations
A persistent ice cover was observed from half of January until the ice broke up in May. The winds were generally moderate with just a few occasions with speed above 10 ms−1 and there was a clear correlation between southerly winds and high air temperature. Significant ice movements occurred in events with high velocities correlated with strong wind velocities and nearly motionless periods in-between. The maximum ice speed recorded was about 50 cm s−1. Currents 2 m below the ice had generally similar direction as the ice motion, but current speeds were lower indicating that the dominating forcing on the ice cover came from the atmosphere rather than from the sea.





Ice thickness and ridge draft
Ice draft of more than 1m occurred frequently representing pressure ridges passing over the instrument. The maximum draft obtained by this method is about 7m. Most of the ice was thinner than 1 m, as expected in this area where the level ice rarely becomes thicker

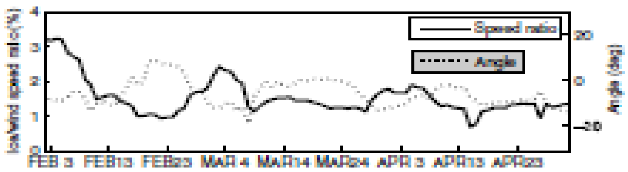
than 1 m. Ice thicker than 1m represents pressure ridges. The ridges constituted a large proportion of the total ice volume. The results suggest that between 30 and 60% of the ice volume in the central Bothnian Bay consists of ridges at least during this particular ice season.

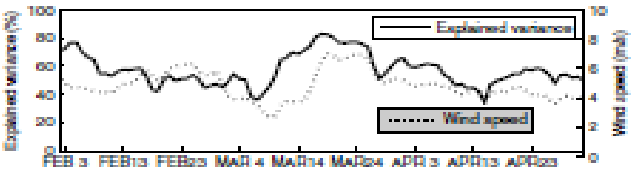
	February	March	April	Total
Hm (Mean ice thickness) (m)	0.43	0.99	0.77	0.73
VR (Ridge volume fraction)	0.32	0.61	0.45	0.49

<u>Ice dynamics</u>

The Bothnian Bay is large enough so the accumulated wind force across the basin can overcome the ice strength during most circumstances and the ice will move even if the basin is completely ice covered. The ice was nearly stationary for wind speeds less than about 5 ms$_{-1}$. The ice speed was small (<10 cm s$_{-1}$), for about 70% of the observations. Extensive ice motion occurred in all events throughout ice season. Typical translations were 10–30 km during the events corresponding to 5–20% of the basin scale (about 150 km). Since the basin was almost completely ice covered during the entire winter each event must have caused substantial ice deformation and ridge building.

It is possible to obtain a rough estimate of the compressive ice strength from the internal ice stress and the wind fetch over the basin. The maximum ice stress during event 10 with near zero velocity was about 0.3 Pa which multiplied with a fetch of about 150 km gives a force of 4.5 × 104Nm−1. In order to obtain an ice strength this should be divided with an ice thickness, which is rather uncertain, but using 50 cm which was the maximum level ice thickness in the area according to the ice chart gives an ice strength of 9 × 104Nm−2. This is actually much larger than the 2.5 × 104Nm−2 that has been used as a working standard in ice models of the Baltic. This difference by a factor of three is somewhat surprising since 50 cm should be about the thickest level ice present in the basin during this season. If thinner ice had to take up the wind load the difference would have been even larger. Another possibility is that the ice cover was heavily ridged in the area for maximal ice stress so that the effective load up-taking thickness was larger than 50 cm.





<u>Discussion</u>

The single fixed instrument in the central part of the basin provides some basic information of the dynamic response of the ice cover to wind forcing, but it gives certainly not the full picture. It is well known that the motion field varies in space. It would be interesting to have observations at several locations in order to quantify spatial variations of the ice motion.
The present study has some implications on ice models for the Baltic and likely also for other semi-sized basins with perennial ice cover such as the Great lakes, the White Sea and the Hudson Bay. With semi-sized is meant here that the basin is large enough to have moving ice but small enough so that the atmospheric forcing is nearly uniform. The size of this area is a critical quantity to reproduce by ice models.

Conclusions

ADCP observations showed that:

- Pressure ridges, defined as ice thicker than 1 m, occupied 10% of the ice cover in February, 40% in March and 22% in April.
- The estimated ridged ice contribution to the total volume was 30–60%.
- The ice speed was small (<10 cm s−1) for most of the time (70%) and stationary (<0.5 cm s−1) for only 3% of the time. High speeds (20–50 cm s−1) occurred in relatively well defined events. These events make up a major part (70%) of the total drift distance.
- The wind/ice speed ratio was about 3% for the initial thin ice cover in early February, and the ratio was significantly lower (1–2%) during the rest of the season.
- There is a general tendency that the ice is more mobile in events characterized by a large shift in wind direction.
- A rough estimate, based on wind fetch and motion data, gives a compressive ice strength of 9 ×104Nm−2, which is more than three times larger than the 2.5 × 104Nm−2 regularly used in dynamic ice models.

Possible useful references:

Ice charts where ice types are localized and categorized, including level ice thickness, are published regularly from the Baltic Sea and Bothnian Bay Swedish Meteorological and Hydrological Institute SMHI, www.smhi.se).

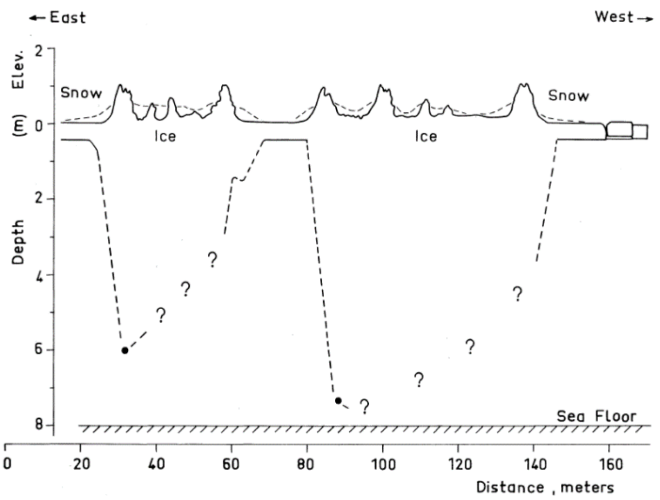
Ref:	Title:	Author:	Date:
1.18	Ice Ridges in the Coastal Area of Finland	E. Palosuo	1971
Summary:			

Relevance to thesis
Ridge properties, ice properties, ridge formation

Introduction
The coastal area of Finland is rather low and there are many islands where the ice can be attached. The following conditions seem to be necessary for the formation of an ice ridge in the coastal areas:

- Wind velocity must exceed a minimum value, which depends on the thickness of the ice and the distance between the islands
- Most ridges will be formed from a rather even ice sheet by pushing the flaps of one sheet over or under the next sheet.
- The thickness of the ice must exceed 7 to 10 cm.
- A part of an ice ridge is very often grounded or attached to an island
- In the floating part of a ridge the ice blocks close to the surface eventually froze together, although the degree of bonding between ice blocks at a depth of about 0.5 to 1. 5 m below the free water level remains low.

The effect of wind on the formation of ice ridges
As seen before, the ice in the coastal area attaches itself to the islands and shoals. It seems obvious that there is a correlation between the ice thickness and the wind velocity necessary to break the ice. The critical factor is the maximum local wind velocity. The wind velocity needed for breaking up the ice cover showed an almost linear relationship with the thickness of the ice. This was valid when the ice was hard. Similar comparisons of wind velocity and thickness of the ice have been made at successive points. When the ice in the inner skerries has reached a certain thickness it does not break easily. But in the outer skerries it breaks even when it is rather thick. In the central part' of the Gulf of Bothnia the ice may move even when it is thick. A short distance between the islands seems to be an important factor in preventing the ice from breaking up.



Ref:	Title:	Author:	Date:
1.19	Physical Oceanography of Baltic Sea	K. Myrberg	2008

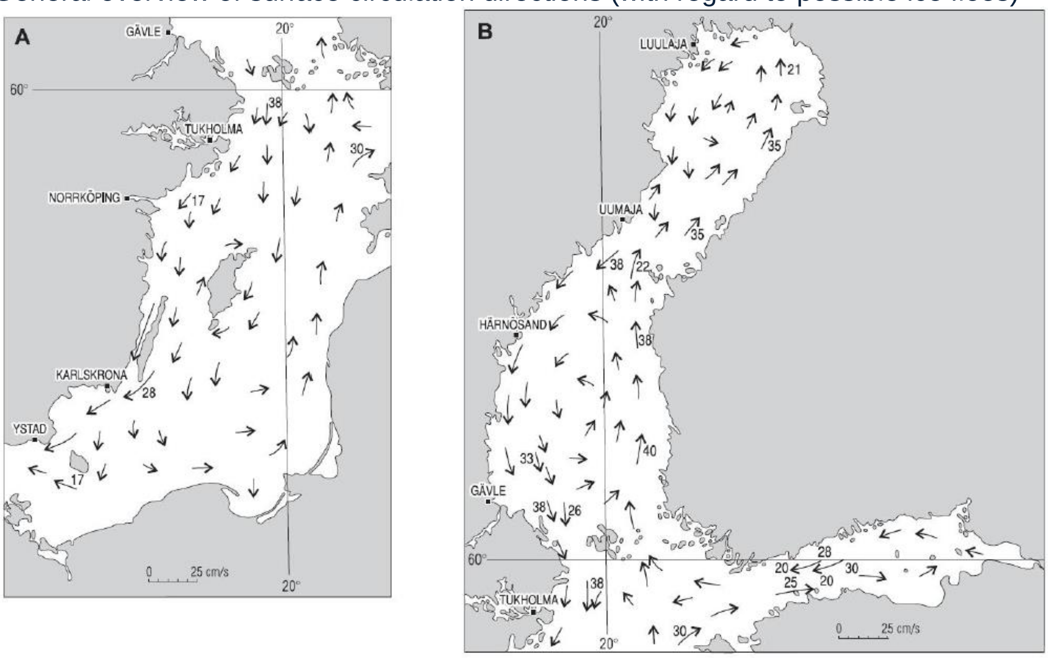
Summary:

<u>Relevance to thesis</u>
General information regarding the Baltic Sea basin, powerpoint sheets

<u>Bathymetry</u>
General overview of Baltic Sea bathymetry

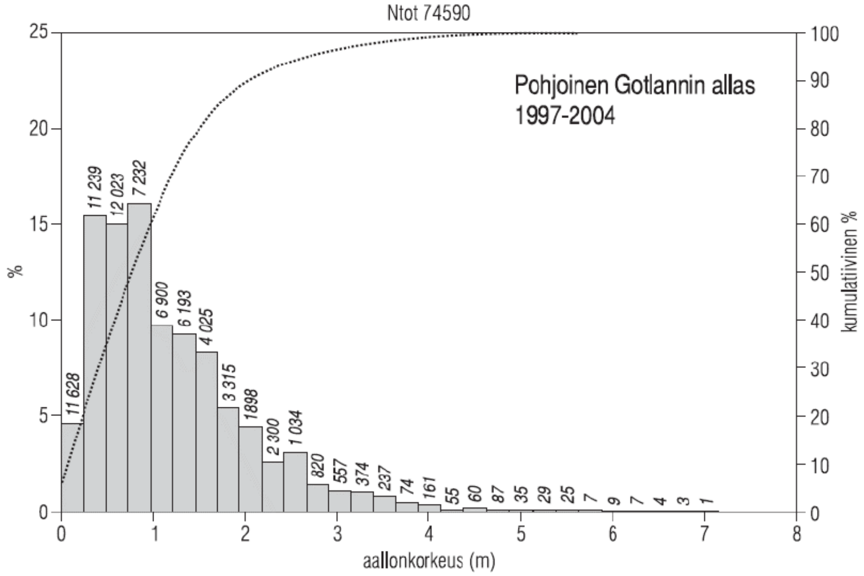
Kuva 4.2. Itämeren pohjatopografian pääpiirteet ja sen suhteen tärkeimpien paikkojen nimet. (Piirretty Fonseliuksen [1996] kuvasta.)

<u>Surface Circulation</u>
General overview of surface circulation directions (with regard to possible ice floes)



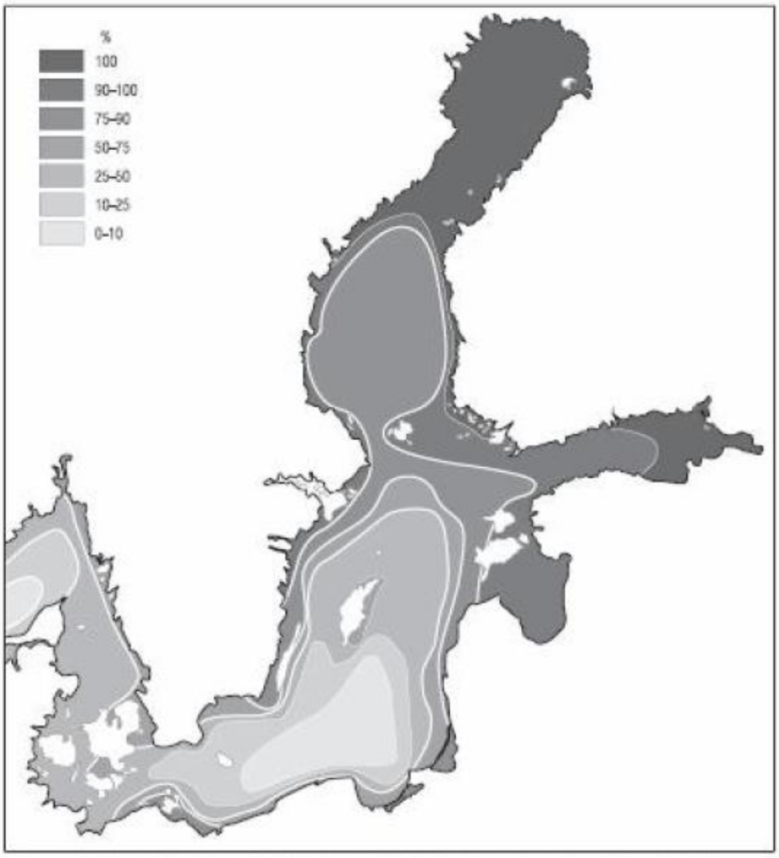
Wave height

General overview of wave height measurements



Probability of Ice Cover

General overview of ice probability every winter



Kuva 7.1. Jäätymisen vuotuinen todennäköisyys Itämerellä. (SMHI ja Merentutkimuslaitos 1982)

Ref:	Title:	Author:	Date:
1.20	Numerical modelling of thermodynamics and dynamics of sea ice in the Baltic Sea	A.Herman J. Jedrasik	04-2011

Summary:

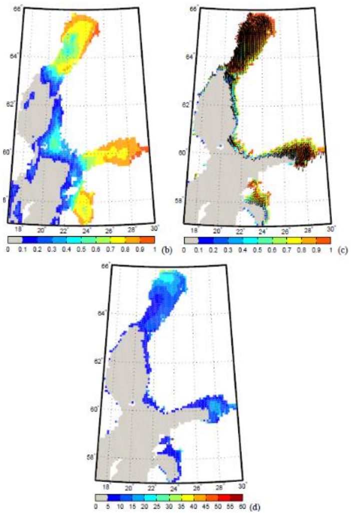
Relevance to thesis

Baltic Sea Ice dynamics, sea ice properties, environmental aspect, wind properties

Introduction

Sea-ice phenomena constitute an important component of the physical and biochemical environment of the Baltic Sea. In the Bothnian Bay as well as in the inner parts of the Gulf of Finland and in the Gulf of Riga, sea ice develops every winter. The specific nature of the Baltic has important consequences for the understanding and numerical modelling of the Baltic Sea ice thermodynamics and dynamics. In most situations, the sea ice covers only a part of the total water surface and is a mixture of ice types differing in structure and properties – level, rafted and ridged ice, possibly with cracks and leads.

This study has two objectives. First to provide a systematic, quantitative validation of the sea ice model performance. The second objective is to analyze interactions between synoptic-scale atmospheric forcing and freezing, melting and (re)distribution of the sea ice in the sub-basins of the Baltic Sea.



Sea ice model

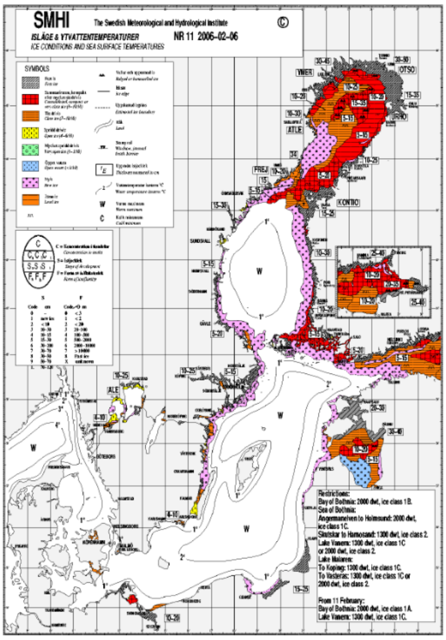
The sea ice model developed in this study describes the spatial and temporal evolution of the following four variables: ice concentration, mean ice thickness, mean ice temperature and ice velocity. The sea ice model and the hydrodynamic model are coupled at each internal time step by means of air-ice-water heat and momentum flux.

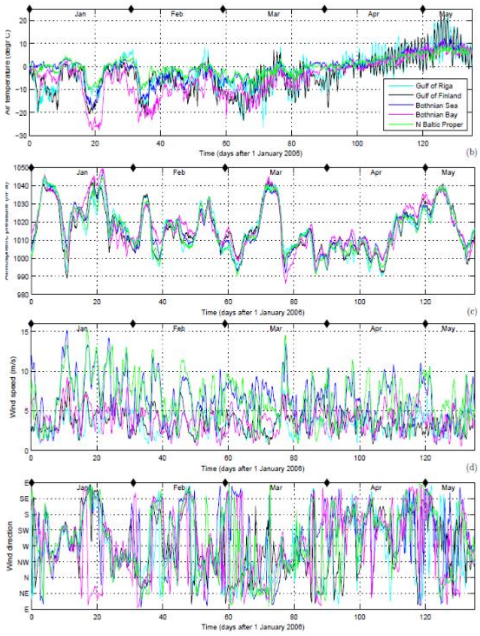
Meteorological conditions

The meteorological conditions over the northern part of the Baltic Sea during the winter were typical of the region at that time of the year. A number of synoptic-scale low and high pressure systems, fronts, ridges and troughs passed over the study area, leading to a high variability of wind speed and direction, which resulted in the advection of air masses with different temperature, humidity, and cloudiness.

Generally the winds were strong, particularly in the Baltic Proper and the Bothnian Sea, where about ten events with wind speed over $10ms^{-1}$ were recorded. Crucial for the sea-ice development was the period in mid-March. The total ice-covered area in the Baltic Sea reached its seasonal maximum that period.

Not surprisingly, the ice concentrations in the Baltic Sea depend strongly on the atmospheric forcing. The influence of the wind is much more pronounced in the larger basins (the Bothnian Sea and the Baltic Proper) than in the smaller ones. Strong winds and wind-induced currents tend to break and fragment the ice cover. In the large basins, typically only partly covered with ice, the ice broken by winds tends to disperse over large, previously ice-free areas. In smaller basins, with ice covering most of their area, the change is shifted towards higher ice concentrations. Moreover, in the smaller basins, the wind direction seems to be more important for the correlations analyzed: in the Bothnian Bay the N-S wind component has an understandably stronger influence than the W-E component.





The ice in the Baltic Sea is relatively thin and thus can be easily deformed by dynamic processes such as winds, currents, waves, and water-level variations. During strong wind events, even areas with a consolidated ice cover are prone to the influence of the dynamic factors. Generally, dynamic processes lead to a higher variability of ice concentration and mean ice thickness. Moreover, although no ice is produced or melted due to the dynamics alone, the dynamic redistribution of ice indirectly affects the temporal evolution of the total ice volume due to the modified surface fluxes and the total stress experienced.

The modeling results obtained with and without the ice dynamics differed in some important aspects. If the dynamics is ignored, the ice cover acts as a “lid” on the sea surface, cutting off the momentum flux from the atmosphere. As a consequence, the surface currents under the ice are very weak and the influence of the ice edge on the water circulation can be clearly seen. If the ice dynamics is included, the surface currents form a more uniform system encompassing the whole basin and the currents in the ice-covered zone are stronger.

<u>Conclusion</u>

The study demonstrated strong relationships between the ice cover variability and the external forcing on the synoptic time scale. Another important aspect of the sea-ice phenomena in the Baltic Sea discussed in this paper concerns the role of ice dynamics. It was shown to influence not only the ice cover itself, but also the thermal regime of the surface water layers and the three-dimensional circulation patterns in the basins affected.

Ref:	Title:	Author:	Date:
1.21	Design Ice Load Level in the Baltic Sea	S. Hänninen	2003
Summary:			

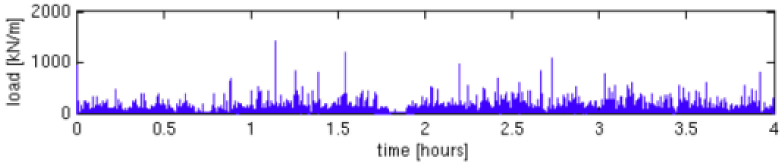
<u>Relevance to thesis:</u>
Ice loads in the Baltic, ice properties, Baltic Sea ice design

<u>Introduction</u>
This article concentrates on ice load towards a ship's bow frame. Total ice load and loading length are excluded. The purpose was to study the use of statistical methods when defining long-term ice loads on ship hulls. The measured data consists of load maxima from different periods of time. It is at interest that in every ship measured frame load maxima are much higher than design ice loads. Ship lifetime load maxima are approximately two times higher than design ice loads. When measured stresses on the frame are compared to those on plating, it can be noticed that at least in two cases frame is stronger than the plating. A correlation between average ice thickness and ice load level was found. With the help of speed and ice thickness information it is possible to develop an ice load prediction system.

<u>Measurements</u>
The long term measuring systems on Baltic Sea ships were designed so that they would automatically collect distributions of load peak amplitudes and load maxima for certain periods of time. The ice load was evaluated by measuring shear strains at the neutral axis of the frame. The latest ice load measuring systems are built so that loads are continuously recorded.

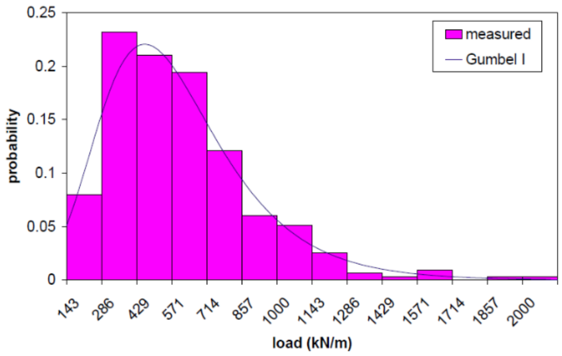
For icebreakers, ice rules requirements are also calculated. Naturally icebreakers are built much stronger. In all cases frames are built considerably stronger than ice class requires. Plate thickness, on the other hand, is not that much thicker. Ships are differing in size and they have different hull forms and propulsion power. An icebreaker naturally exhibits the optimum hull form for operation in ice, which certainly has an effect on load level on the frame. Design ice load level according to ice rules depends mostly on ship size and propulsion power. Current design ice loads for the ships are from 800 kN/m to 1200 kN/m.

<u>Results</u>
A typical loading history is shown in the figure below. The probability distributions are similar in all cases. Ice loading is assumed to be a weakly stationary stochastic process, which is essential to prediction of future ice loads.



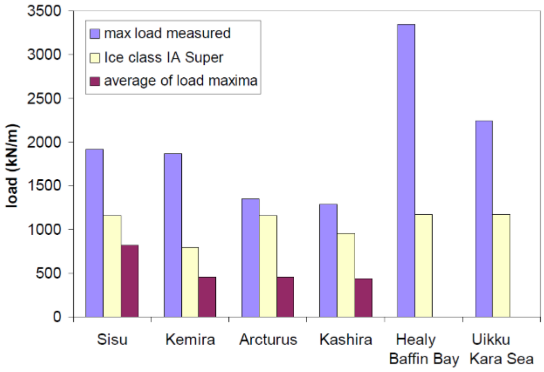
These measurements give quite a clear picture of the load level that different ships encounter in these areas, because measurements have been conducted over several years. Highest load amplitudes, which are of most interest in relation to ice rules, do not follow the same distribution model as those by the lower loads. More information is needed to clarify in which operational situations these highest loads have occurred and also for resetting design ice load level.

It can be seen from figure that the design ice load level, which basically corresponds to the first yield of the frame, is consistently exceeded. Return period, i.e. time in ice after which load maxima will probably exceed design ice loads is only four days. So it seems very likely that ships built according to Finnish-Swedish ice rules and which operate in ice in the Baltic Sea will often be damaged in ship-ice contact. In reality this is not the case.



Comparing results

Measured load maxima are presented in the figure below. It can be seen that design load were exceeded during every measurement. MT Uikku and USCGC Healy operated in arctic waters. Those load maxima are naturally higher than in the Baltic Sea, because these were in thick first year ice and also multiyear ice. Design ice load level based on these measurements should be about 2000 kN/m for each ship. According to ice rules the design ice load value is only half of that value. It seems more or less that the ice load level depends more on sea area and exposure time in ice.



Stress levels

Load responses i.e. stresses on the frame and plating, are needed for design. Response of the shell structure was measured using strain gauges which were mounted on the plating at the midpoint of an area restricted by two frames and two stringers. Response of the frame was measured at the mid-span of the frame. Ice rule equation is calculated using real dimensions and material strengths of the ship. Because the frame is built stronger than required, the yield stress is not achieved at the load level of 1163 kN/m, but at 1600 kN/m. On the other hand plate is a bit thinner than required. It can be seen that stresses on the plating are larger than those on the frame.

Conclusions

Long term ice load measurements in the Baltic Sea have been made on board four different ships. These measurements combined with latest measurements in arctic waters form a good basis for data bank of ice loads. Measured load maxima on studied ships are considerably higher than design ice loads of Finnish-Swedish ice rules, which is basically first yield load. However, structure has some amount of plastic stress reserve. Stress reserve of ship frame and plating are different.
Response of the structure depends on load shape, size and magnitude.

APPENDIX B – SUMMARY OF ARTICLES RELATED TO ICE MECHANICS

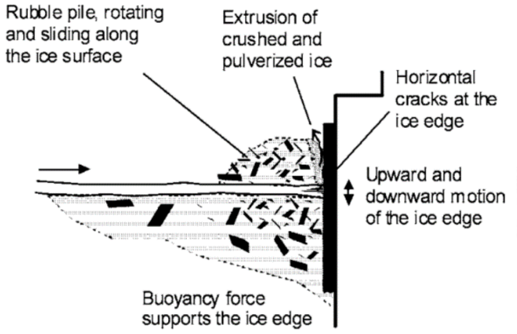
Ref:	Title:	Author:	Date:
2.01	A Spectral Model for Forces Due to Ice Crushing	Tuomo Kärnä	05-2007
Summary:			

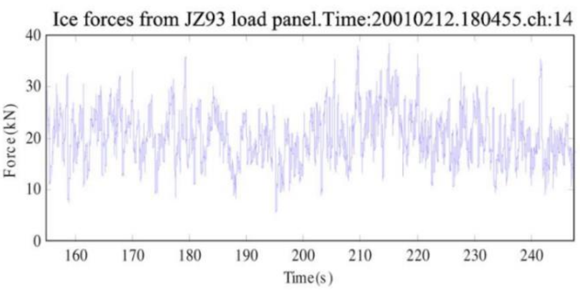
Relevance to thesis
ice forces, ice crushing, vibrations, spectral model

Introduction
This article presents a model of dynamic ice forces on vertical offshore structures. The model concerns a loading scenario where a competent ice sheet is drifting and crushing against the structure. Full scale data obtained on two offshore structures were used in the derivation of a method that applies both to narrow and wide structures. The model provides a tool to consider the non simultaneous characteristics of the local ice pressures while assessing the total ice force.

A simulation of the dynamic ice–structure interaction process is very complex if the feedback effects due to the structural displacements need to be considered. Direct force measurements made recently on two offshore structures show that this feedback effect can be neglected if the ice velocity is moderate to high and if the structure's displacements at the waterline are only a small fraction of the ice thickness. Many offshore structures are operating under these conditions.

Ice Excitation as a Stochastic Process
The article addresses dynamic ice actions in conditions where a sheet of level ice is drifting against a vertical offshore structure and is failing by a failure mode known as continuous crushing. The figures below shows the main phenomena of continuous ice crushing. The rubble pile that evolves in front of the structure contains ice fragments of variable size.

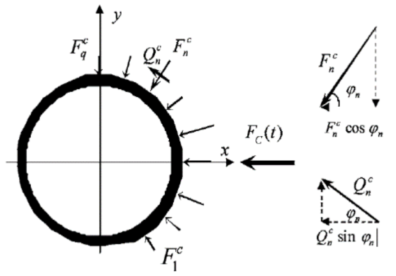




Experimental Data
The results of this paper are largely based on the full-scale data that were measured at the lighthouse Norströmsgrund and a small diameter structure named JZ9. The lighthouse is located in the Northern part of the Gulf of Bothnia. The waterline diameter of the basic structure is 7.2 m and about 7.5 m with the additional force measuring panels. The structure JZ9 is used as a mooring pole and is connected to an oil platform. The diameter of the pole is 1.5 m. The overall height is 18 m including a 8 m high underwater part.

Long-term visual observations that were made on the lighthouse Norströmsgrund show that more than 60% of all loading events occurred in the crushing failure mode if the ice was thicker then 0.20 m and if the diameter of sheet ice was at least 50 times the structure diameter. Flexural and mixed failure modes were common for thin ice and small ice floes usually failed by splitting. Dynamic buckling and creep buckling were also seen occasionally. A variety of ice failure modes were observed when ice ridges were encountered. The occurrence of ice crushing did not show any preference with regard to the time or environmental conditions within the winter season. Characteristics of the ice crushing process changed if the ice was very warm or inhomogeneous. The highest static forces are expected to arise due to actions of ice ridges.

<u>Model of Continuous Crushing</u>
The figure below illustrates the local ice forces acting on a structure. In a dynamic situation the total force has an additional component in the y direction. Due to this component the dynamic response of the structure always has a two-dimensional character in each level of the structure.
The figure indicates that the local forces have two lateral components. Each local force varies about a positive mean level. The ice forces have traditionally been studied with a main emphasison the maximum peak values that can be identified from force records.

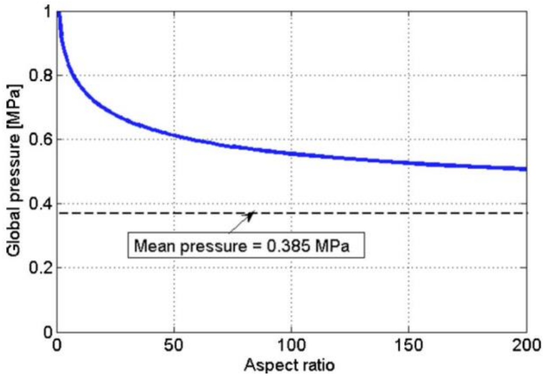


$$F_C(t) = F_{CM} + F_{CD}(t)$$

$$F_{CM} = (\mathbf{C} + \mu_k \mathbf{B})^T \mathbf{F}^{\text{mean}}$$

$$F_{CD}(t) = (\mathbf{C} + \mu_k \mathbf{B})^T \mathbf{F}(t)$$

<u>Applications</u>
The theory derived above was used to study characteristics of the global pressure. The results of example calculations are shown in the figure below. The global pressure decreases as the width of
the structure increases. This is an inherent feature of the ice crushing process. The mean level of the global pressure does not change when the width of the structure increases. However, the intensity of the time-varying total force decreases with an increase of the width. Therefore, the global pressure of a wide structure approaches the mean level of the local pressure.



This phenomenon is one of the reasons for a size effect that should be considered in the design of offshore structures. Another feature of the results shown in the figure above relates to the dynamic action effects due to ice crushing. A decrease in the crushing intensity leads to a reduction in the dynamic response of the structure.

Discussion

Two pieces of new information on the crushing process arise from the full-scale data used for this paper. First, forces due to continuous crushing that were measured in the field exhibit slowly varying fluctuations at frequencies around 0.1 Hz and lower. Such force variations are usually not seen in laboratory tests. This difference has consequences in the prediction of the global pressure as a function of the aspect ratio. Second, local and global ice pressures did not show any significant increase at a range of low ice velocities. The phenomenon of alternating ductile to brittle crushing was absent in ordinary conditions when steady-state vibrations did not arise. The observation is made showing that the global ice pressure increases with the compliance of the structure. Global pressure due to continuous brittle crushing becomes almost independent of the aspect ratio w/h in the range of w/h8. The results obtained by the present model show that the global pressure continues decreasing with the aspect ratio even at w/h100.

Conclusions

A spectral model was derived for a dynamic analysis of vertical offshore structures. The model concerns conditions where a competent sheet of level ice acts on the structure and fails by continuous, brittle crushing. The main input parameters of the model include the mean value and the standard deviation of the local ice forces.

The model has two limitations. First, the phenomenon of self-excited vibration is not incorporated. Second, the model does not apply for conditions where a compliant structure is interacting with the ice sheet and creates an ice failure mode known as intermittent crushing or alternating ductile-brittle crushing. This restriction should be noticed because it is deemed that the ice force will increase if the waterline displacement exceeds a level where the continuous crushing mode changes into intermittent crushing.

Ref:	Title:	Author:	Date:
2.02	Estimation of Local Ice Pressure Using Up-Crossing Rate	Chuanke Li Ian J. Jordaan	08-2010

Summary:

Relevance to thesis
probabilistic methods, ice load estimation, ship-ice interaction, offshore structures, local ice pressures

Introduction
Estimation of global and local ice pressures is of great importance to the design of ice-resistant ships and offshore structures. The global ice pressure is the global ice load divided by the global interaction area. Local ice pressure is the local ice load over the local areas of interest within the global interacting area. It is a well-recognized fact that local ice pressures can be much higher than the global ice pressure. This results in the requirement of local structural reinforcement within the ice impacting zone of a structure. This article focuses on local ice pressure estimation methodology, based on up-crossing rate theory. This method treats the local ice pressure measurements as a continuous process.

Probabilistic Model Using Up-Crossing Rate
The ice pressure during ice-structure interaction is a stochastic process. For any given time, the value of local pressure is a random variable. For a given structure, the probability distribution of interest is that the probability of first passage of a given load level. This is because the structure will not survive after the first passage of the external load over its resistance. Therefore, the probability of the first excursion of a specific load (such as the resistance of the structure) is equivalent to the probability of the structural failure during its design life. Only up-crossing of a load trace is investigated.

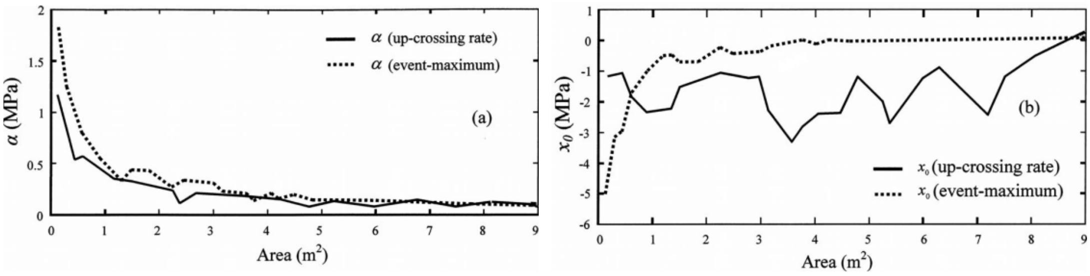
Data Analysis With Up-Crossing Rate Method
In order to obtain the up-crossing rates for different combined areas, the data are reformatted to account for both spatial and temporal exposures. Applying the routine described below the up-crossing rates for different areas under different pressures are obtained.

- Obtain the pressure traces on a combined area of interest for each event.
- Link all the pressure traces (the time history of the pressure) on a specific area within the strain gauge panel for each event.
- Link all event pressure traces obtained from Step 2 into a single trace for the given combined area of interest.
- Use different thresholds of pressure to cross pressure trace obtained from Step 3.
- Count the number of crossings for each threshold and the total duration of the pressure trace obtained from Step 3. The up-crossing rates at a given threshold can be obtained by the number of crossings over the duration for an area of interest.
- Repeat the above procedures to get the up-crossing rates at different threshold levels for all the areas of interest.

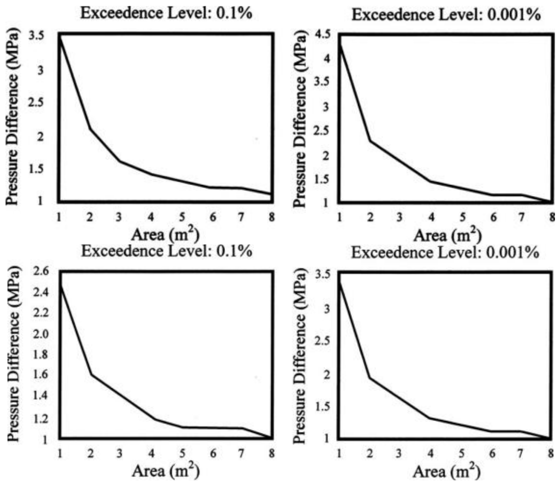
A linear relationship between the natural logarithm of up-crossing rates and pressures is evident for any area analyzed.

Comparison of Methods
A comparison can be made between the traditional method which treats each event discretely and considers peak pressures on a given area from each event. The method established in this article is based on up-crossing rate theory and treats the pressure trace

data as continuous data. This method includes the variations of pressures and is considered more mathematically rigorous. Comparisons are given in the figures below



It can be seen that the values from the up-crossing rate method are lower than the values from the event-maximum method. The difference between the two approaches decreases with increasing area. The x0 values obtained using the event-maximum method were observed to be larger than the x0 values found using the up-crossing rate method for areas between 0.6 m2 and 9 m2. It may be clearly observed that for a given probability of exceedence, the up-crossing rate method gives lower extreme pressure estimates than are found using the event-maximum method. This difference is more pronounced for smaller areas. It may also be observed from the figure below that the pressure-area curves follow a decreasing trend for any confidence level, regardless of which method is used. In ice mechanics this is termed the pressure-area scale effect.



The figures clearly indicate that using the event-maximum method for design is conservative, particularly for smaller areas.

Conclusions

The event-maximum method of local ice pressure estimation was developed based on ship ramming data from the 1981. Up-crossing rate analysis is not applicable to those data, since this method requires time history data. The applicability of this method will depend on the suitability of the available data. Up-crossing theory provides a promising approach for local ice pressure data analysis and design load estimation. For suitable data, the up-crossing rate method can serve as a valuable evaluation tool. The event-maximum method provided similar results to the up-crossing rate approach for areas larger than 2 m2 and more conservative estimates for smaller areas.

Ref:	Title:	Author:	Date:
2.03	Wind Induced Static Ice Forces on Offshore Structures	J.V. Danys	1977

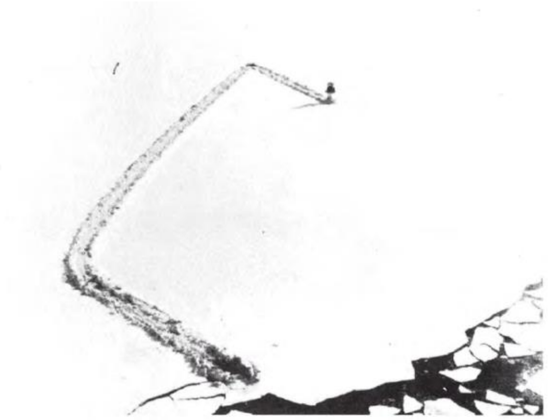
Paper Summary:

Relevance to thesis:
wind induced ice loads, ice sheet flow, ice failure modes, ice properties

Introduction
Wind blowing along an ice surface induces a force which tends to move the ice cover. As long as the ice cover is anchored at the shore or on the shoals, no movement occurs, and there is no force on offshore structures. However, an ice cover may get loose for various reasons, and then the wind induced force or pressure will be felt by the structure. Early in the sixties it was concluded that ice impact force would be much larger than wind induced static ice force and, therefore, the latter force is not important in design of offshore structures. This article shows otherwise.

Observations
A rather unique movement of the ice cover is show in the figure below.

Prolonged strong winds blew for approximately 20 hours from the South then for several hours from the West and finally from the North. The ice cover on the lake had been lifted and broken off the Southern shore by the rising water level. The loosened ice cover was pushed against two lightpiers in the middle of the lake and the narrow lightpiers cut "u" shaped narrow channels in the ice sheet



Ice failure mode
An ice sheet in ice-structure interaction may fail by crushing, bending, shearing or buckling. Vertical faces of the structures cause failure by crushing and inclined surfaces failure by bending. Failure of an ice sheet against conical surfaces is a complex failure. Studies have shown that friction between ice and surface of the structure and angle of a cone have great influence on the failure mode.

Observations of ice sheet failure against the lightpiers caused by the wind induced static forces showed that it was predominantly a failure by crushing. The cut-out channels left behind the lightpiers were with straight sides and were about the same width of the lightpiers at the water line. The ice sheet was not fractured in segments, as it is characteristic for a failure of an ice sheet in bending against a conical surface. Another reason for failure mode by crushing is likely the very slow motion by the wind induced forces. Ice rubble in front of a structure would induce ice sheet failure in bending.

Wind Induced Forces
Wind blowing over the surface of an ice floe or a floating ice cover exerts a tangential force against the ice surface. This force depends, among other factors, on the degree of coupling between the air and the ice because the transfer of momentum through the boundary layer is related to the aerodynamic quality of the surface. In a fully developed turbulent boundary layer, when the effect of buoyancy on the turbulent motion is negligible, the flux of momentum is constant throughout the layer.

The estimated surface area of the ice sheet which was moved by the winds changing their direction and which left "u" shaped cut-off channels was 120 x 106 m². The total wind induced force from the following equations:

$$F = 0.132\ C_{10}\ U_{10}^2\ A,$$

where $C_{10} = 1.6 \times 10^{-3}$, for average texture of ice sheet covered with snow,

$U_{10} = 11$ m/s, average maximum wind speed,

$A = 120 \times 10^6$ m², area of the loose ice sheet,

is $F = 3{,}067 \times 10^3$ kg ($6{,}762 \times 10^3$ lbs).

Then, the ice force on the two lightpiers per lineal meter of the structures, 25 cm below the water level, is:

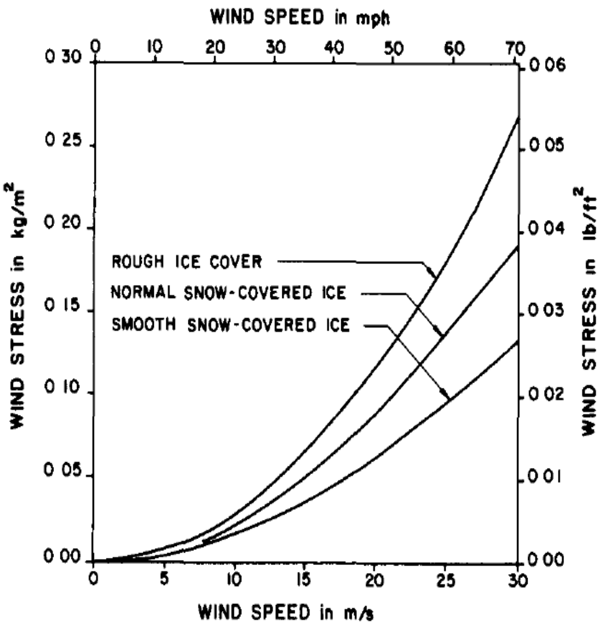
$$p = \frac{F}{B} = \frac{3{,}067 \times 10^3}{6.86} = 447 \times 10^3 \text{ kg/m } (300 \times 10^3 \text{ lbs/lin.ft }),$$

where B = 6.86 m is total width of the two lightpiers at the water line.

Total ice force on the Yamachiche Bend Range rear lightpier, 3.66 m wide at the water line, is:

$$P = 447 \times 10^3 \times 3.66 = 1{,}636 \times 10^3 \text{ kg } (3{,}607 \times 10^3 \text{ lbs}).$$

In design of the lightpiers, it was assumed that maximum effective ice thickness would be 91 cm, the design crushing strength of the ice 17.6 kg/cm² and the overall safety factor of the structure 1.9. The average thickness of the solid ice sheet upstream from the 1ightpiers was 50cm. The ice sheet in contact with the lightpier failed in compression but it is impossible to estimate the actual failure stresses. The wind induced ice stresses could have been as high as 89.4 kg/cm2 (1,271 1b/in2) for 50-cm thick ice sheet. However, the ice sheet of 50cm thick had to fail before compressive stresses reached 33.4 kg/cm² as otherwise the lightpier would have failed. Thus, the wind induced a static ice force well exceeding the crushing strength of the ice.



<u>Conclusions</u>

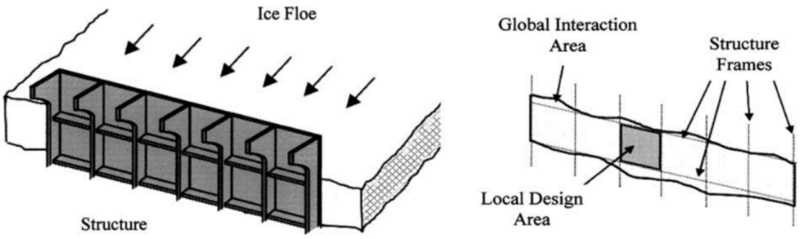
Wind can induce considerable large static ice thrust on the offshore structures if the loosened ice sheet has a large surface area. This thrust should be taken into consideration unless the structure is designed for the failure stresses of ice.

Ref:	Title:	Author:	Date:
2.04	Local Design Pressures for Structures in Ice	R.S. Taylor I.J. Jordaan	08-2010

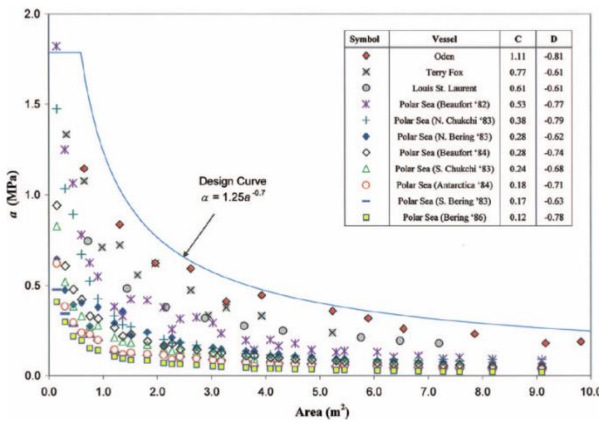
Summary:

Relevance to thesis:
ice load estimation, ship-ice interaction, offshore structures, local ice pressures

Introduction
Increased global energy demand has stimulated increased offshore industrial activity in arctic and subarctic regions around the world. The estimation of local pressures represents an important input in the design of structures for ice environments. The two key areas of interest are the global interaction and local design areas. The global interaction area can be determined from the shape of the ice feature and the shape of the structure. For design purposes, one also needs to consider the local design area, which is typically the area of a plate between frames, a panel, or substructure that is considered in the design. Global ice pressures are an important consideration in the assessment of the required foundation resistance, as well as the overall strength and stability of the structure.



Methodology
Each data set consists of a series of interaction events containing local pressure measurements recorded on an instrumented section of the ship hull. For each ship ram event within a particular series, the maximum pressure on a given area was identified. Maxima for each event in the series were extracted. Ship-ice interaction data from the CCGS Louis S. St. Laurent, USCGS Polar Sea, Swedish Icebreaker Oden, and the CCGS Terry Fox have been considered. Local ice pressures were obtained mainly from strain gauge data. For some vessels, global loads were also obtained using sensors, strain gauges, and accelerometer data. Parameters measured from the tests included impact forces, impact area, ship motions with six degrees of freedom, ship forward speed, and ambient environmental factors.



Data analysis using the event-maximum method of local pressure estimation was performed for the data sets described above. The results are plotted in the graph below. The local pressure design curve has also been included in this plot. These results show that the calculated values fall below the design curve for all data considered. It may be observed that the pressures follow a decreasing trend with increasing area, and each data set has a distinct, well-defined curve. This suggests that the pressure is dependent on some physical characteristic of the interaction, such as the ice type, thickness, or temperature. Coefficient C appears to be most influenced by the ice type. Thicker and stronger ice types (multiyear and iceberg ice) correspond with the higher C values, while lower values correspond more with first-year ice conditions. This is a logical result, since multiyear ice and glacial ice are expected to produce higher pressures than first-year sea ice. For the thinner first-year ice events, flexural failure may be more dominant, resulting in lower pressures.

Exposure

In assessing the extreme loads on a structure, exposure is an important consideration. Exposure is treated differently for data analysis than for design. Exposure effects are removed during data analysis to give a standardized design curve, corresponding to single panel exposure. For the design, local pressure estimates based on the design curve are then adjusted to reflect the exposure corresponding to the design scenario. Not including the exposure adjustment during data analysis will result in a more conservative design load estimate. The length of the interaction duration for individual events, as well as the number of events that occur within a given time period are important aspects of exposure. The greater the exposure to ice impacts, the higher the extreme load a ship must be designed to withstand. The position of the panels on the structure is also important, since panels on the bow of a ship will be more exposed than those on the side. Similarly, panels within the ice belt region of a structure will have greater exposure to heavy ice loading than other regions of the structure. An alternative approach is to use an exposure factor to account for the increased probability of impacts in a particular region of the structure.

Conclusions

The results suggest that the pressures from each set of data may be dependent on some physical characteristic of the interaction, such as the ice type, thickness, or the dominant failure processes during the interaction. Linking the physics of ice failure processes with the observed local pressure behavior is an important direction for further study. The treatment of exposure was also explored in the context of data analysis and design. Approaches to adjust for exposure during data analysis were presented. For design, expressions to account for the effects of panel exposure, the frequency of impacts, interaction duration, and the position of the panel on the structure were provided.

Possible useful references:

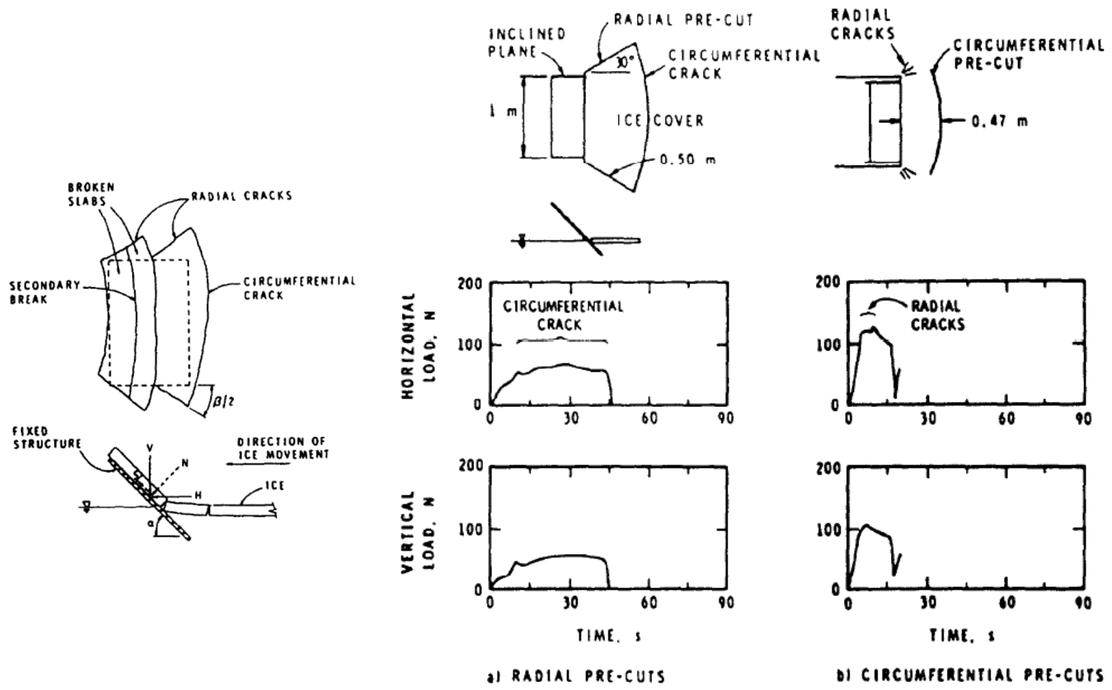
- *Jordaan, I. J., Taylor, R. S., and Bruce, J. "Velocity Effects on Ice Pressures," in preparation.*
- *Jordaan, I. J., Frederking, R., and Li, C., 2006, "Mechanics of Ice Compressive Failure, Probabilistic Averaging and Design Load Estimation," Proceedings of the 18th IAHR, Sapporo, Japan, Vol. 2, pp. 223–230.*
- *Jordaan, I. J., Maes, M. A., Browne, P. W., and Hermans, I. P., 1993, "Probabilistic Analysis of Local Ice Pressures," ASME J. Offshore Mech. Arct. Eng., 115, pp. 83–89.*
- *"General Requirements, Design Criteria, the Environment and Loads," Canadian Standards Association, Paper No. CAN/CSA-S471-04.*
- *Jordaan, I. J., Li, C., Mackey, T., Stuckey, P., Sudom, D., and Taylor, R., 2007, "Ice Data Analysis and Mechanics for Design Load Estimation, Final Report," prepared for NSERC, C-CORE, Chevron Canada Resources, National Research Council of Canada, Petro-Canada, and Husky Energy.*

Ref:	Title:	Author:	Date:
2.05	Ice Sheet Failure against Inclined and Conical Surfaces	M. Kaldjian	1987

Summary:

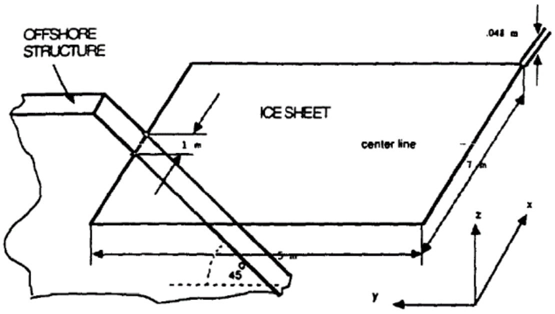
<u>Relevance to thesis:</u>
ice sheet failure modes, inclined surfaces, ice bending, ice mechanics modeling

<u>Introduction</u>
Arctic offshore structures and ships have to be designed to withstand the forces produced by the floating ice cover as it presses against the structure, crushes, breaks and drifts away. The interaction between the ice cover and a structure is very complex. Many forces are at play at a given moment, crushing and flexural failure, translation and rotation of the ice pieces, buoyancy, gravity and ice friction to lift, move and slide the broken ice pieces around the structure. An economic and safe structural design requires a thorough quantitative understanding of the loads involved in the ice/structure interaction. During ice/structure interaction the maximum breaking load is associated with the formation of radial cracks in the ice-sheet in front of the inclined plane, rather than circumferential cracks as shown in the figure below.



The presence of built-in circumferential cracks is insignificant, while the built-in radial cracks reduces the maximum breaking load by half as shown. Firing high pressure hot water jets to these
spots (or possibly building sharp ridges forward of the structure at these points), or using a mechanical device will precipitate formation of radial cracks and thereby reduce the value of the maximum breaking load that an offshore structure has to withstand without causing environmental side effects. This article presents in part the effects of the following parameters, namely offshore structure geometries (slopes and sizes of inclined planes and conical surfaces, displacement boundaries, sharp forward ridges), friction, geometric and material nonlinearity, and artificially induced cracks on the ice/offshore structure load interactions.
<u>Numerical approach</u>

Experimentally obtained data on ice/structure interaction loads are few in number and costly to obtain. To extend this data bank, mathematical models were prepared and analyzed numerically. The study covered loads and displacement boundaries to accommodate inclined planes, conical surfaces, sharp forward ridge effects, and mechanically induced pre-cracks.As a slow moving, floating ice-sheet encounters an offshore structure, interaction loads throughout the contact area cause stress field build-up in the ice sheet. When these stresses are high enough, the ice sheet cracks, breaks, and causes the ice-sheet to advance.



Mathematical models of the floating ice sheet as a large, rectangular, continuous plate supported by springs (equivalent buoyancy) were prepared. The plate was held at the far edge and a displacement boundary condition of an inclined plane or conical surface applied statically at the middle of the near edge. The displacement boundary condition was that of the contact surface edge geometry of the offshore, or ship structure.

The mathematical models were analyzed using finite element techniques which are well suited for boundary displacement loads.

<u>Results</u>

The following general observations can be made from this study:

- Most of the upper surface of the ice sheet is subjected to compression and lower surface to tension.
- Near the vicinity of the offshore structure, flexural stresses in the x-direction were dominant because of large bending moments in the ice sheet, whereas away from the structure, the axial stresses in the x-direction were more prominent. It was noticed that bending moments around both axis were of equal magnitude and importance.
- Near the offshore structure the stresses in the x and y-directions were positive (tension) on the lower surface. Since ice is weak in tension and the surface is more rugged at the lower face this will help initiate cracks faster. The presence of radial precuts made the ice sheet deflect more and caused larger stresses.
- The assumption of uniform edge pressure on the ice-sheet due to contact with the inclined plane structure was not justified.
- The most highly stressed elements were those in contact with the offshore structure and the precut.

<u>Conclusion</u>

This article has shown that the finite element technique is indeed a very useful and powerful tool to study ice/structure interaction. Ice/structure interaction is a boundary displacement contact rather than a boundary edge load problem.

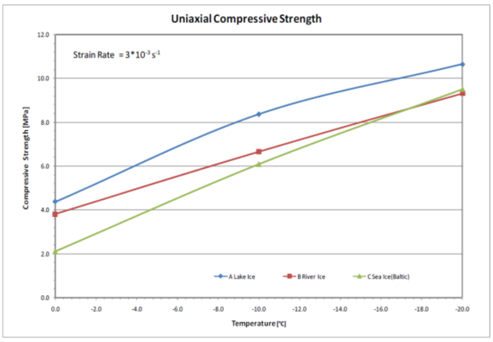
Radial precuts using hot water jets, mechanical ditchers such as Ditch Witch, or some other mechanical device, placed at strategic locations look very promising.

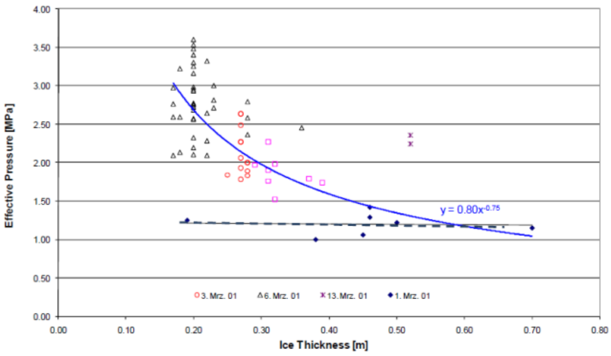
Ref:	Title:	Author:	Date:
2.06	Ice Forces affected by Temperature and Thickness of the Ice	J. Schwarz P. Jochmann	06-2009

Summary:

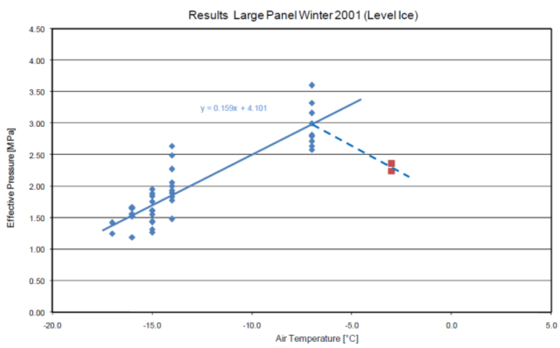
<u>Relevance to thesis:</u>
ice forces, ice temperature, ice thickness, Gulf of Bothnia

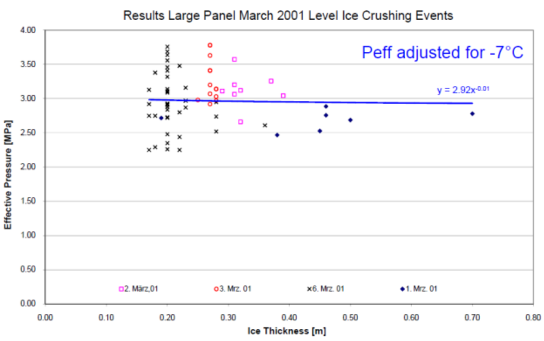
<u>Introduction</u>
Most of the existing formulae for the determination of ice forces on structures consider the mechanical properties of the ice, the structure width and the ice thickness. The mechanical properties may be the compressive strength in case of vertical structures or the bending strength for inclined structures. Both strengths depend on the brine volume, the temperature, the strain or loading rate, and the crystal structure. The compressive and bending strength data as obtained by sample tests show an increase as the temperature decreases.





<u>Temperature Effect</u>
Like in the various graphs of the effective pressure vs. ice thickness in the previous research reports the figure above shows a strong decrease of the effective ice pressure with increasing thicknesses. However, the maximum effective pressure measured on March 1st, when the air temperature was about constant, is independent of the ice thickness. In order to evaluate the effect of the temperature the original effective ice pressure data were plotted versus the air temperature as shown in the figure. The figures shows the surprising result, that the effective ice pressure of level ice as measured in the ice crushing mode has a maximum at air temperatures of approximately –7°C. This phenomenon is most likely due to fact that the highest effective compression strength of ice does occur at the transition from ductile to brittle deformation





The temperature, at which the ice pressure in the ice-structure interaction case has precisely its maximum, will depend also on the total porosity of the ice and the velocity of the ice-structure interaction.

Ice Thickness Effect

The figure above shows that the effective ice pressure data depending on ice thickness are strongly influenced by the temperature, at which the measurements were carried out. Therefore the effective ice pressure data of need to be temperature-corrected. The effective pressure of level ice interacting with a vertical structure is independent of the ice thickness. The zero or small effect of the ice thickness on the effective ice pressure is in agreement with other model and full scale measurements.

Conclusion

The present investigation was concentrating on the effect of the temperature and of the ice thickness on the effective ice pressure. It was found that the effective ice pressure has a maximum at air temperatures of approximately –7o C. When the temperature decreases further the crushing ice pressure also decreases due to the more brittle failure of the ice. This result is new and different from the up-to-date knowledge in ice engineering. When the effective ice pressure data were corrected for the –7° C air temperature, the effective ice pressure was independent of the ice thickness. This result is of major importance for the design of offshore structures in ice regions, because presently the design procedures are using ice pressure data decreasing significantly with the ice thickness.

Possible useful references:

- *Blanchet, D. and DeFranco S.J. 1996. Global first-year Ice Loads: Scale Effect and Non-Simultaneous Failure. Proceedings of the 12th International Ice Symposium (IAHR), Beijing*

- *Hirayama, K.; Schwarz, J.; Wu, H.-C. 1974. An Investigation of Ice Forces on Vertical Structures", Iowa Institute for Hydraulic Research Report No. 158.*

- *Jochmann P., Schwarz J, 2005. The influence of individual parameters on the effective pressureof level ice against lighthouse.(POAC'05). Potsdam, NY, USA, Vol. 3.*

Ref:	Title:	Author:	Date:
2.07	Refined Ice-Structure Interaction Model based on Observations in Gulf of Bothnia	A. Engelbrektson	1997

Summary:

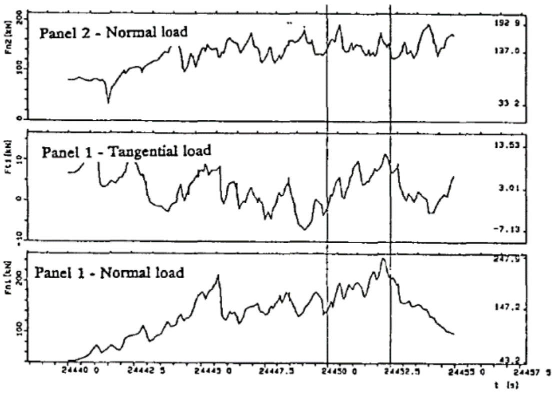
Relevance to thesis:
ice forces, ice-structure interactions, Gulf of Bothnia

Introduction

In a report to POAC 89 a model for characterization of "static and dynamic" ice forces was presented based on experience from studies of ice-structure interaction in the Gulf of Bothnia.
A generalized ice force time-history for design of offshore structures with respect to resonance vibrations due to periodic ice-structure interaction was suggested. It was also observed that the identified mechanism of interaction could provide explanations of other phenomena such as the size-dependence of effective ice pressures on offshore structures.

Crushing of Drifting Ice against Rigid and Flexible structures

When the drifting ice is being indented by a stiff structure, brittle failures occur at local contact areas distributed over the gross contact area along the interface between the structure and the ice. Over a large contact area the "global" ice force time-history will be smooth, if the ice is homogeneous, and approach the sum of the time-averaged local forces. The smaller the contact area is, the more will the global ice force fluctuate, depending on the random composition of the local time-histories. The probability of coincidence between local peaks increases with time and the maximum value of the global force increases accordingly. The predominant period is set by the drift speed and the particular structure of the ice. The fluctuation of the pressure between an elastic flexible structure and an indented ice cover induces vibrations of the structure. Generally, in the case that no significant interaction between the ice and the structure takes place, the vibrations can be regarded as composed of a mixture of free vibrations of the eigen-modes of the structure and vibrations forced by the fluctuating ice pressures.

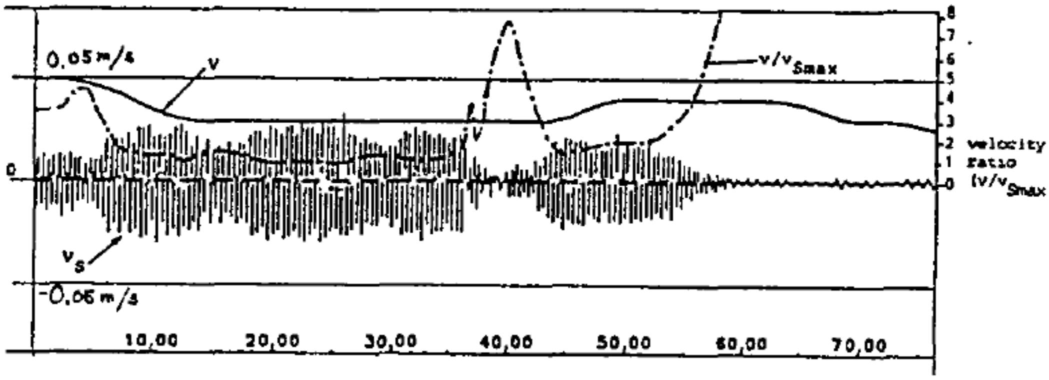


An example of local ice force time-histories is shown in the figure above. The records are from a system of ice force sensing steel panels, on the lighthouse Norstromsgrund in the Gulf of Bothnia. The following features are observed:

- The periodicity of the local ice force is clearly affected by the vibrations of the structure.
- When the structural vibrations start to influence the periodicity of the ice forces, the phases of the local ice force fluctuations are coordinated.
- Due to the coordination of the local ice force fluctuations, the fluctuation of the sum of the local forces also increases. However, the time-history of the sum of the local forces is smoothed, since the peaks are not completely simultaneous.

There is always a tendency of periodic interaction and as this tendency becomes more pronounced, the more the respective natural frequencies of the predominant structural modes and the ice crushing modes approach each other. This is based on the speed of the ice relative to the structure during the course of indentation and it is certainly also based on the magnitude of the relative displacements and the properties of the ice.

As shown in the next figure, interaction between the structure and the ice, leading to resonance vibrations, is greatly favored if the speed of the ice is of the same order as the maximum velocity of the structural vibrations of the ice level. However, resonance has been observed within a fairly large range of relative velocities and relative displacements.



Obviously, flexible structures such as the Norstromsgrund lighthouse have a strong tendency to interact with drifting ice which is crushed against the structure in a failure mode that can be characterized as "powderizing" of the ice along the interface.

Fully developed resonance vibrations

The following characteristics of fully developed self-induced resonance vibrations are observed:

- When the vibrations have reached a state, where the energy absorption due to structural damping equals the energy input from the ice, the vibrations are very regular and the amplitudes change smoothly. The power density spectrum shows, that the sine components of the motion time-history are essentially those with the predominant displacement frequency of the structure and multiples thereof.
- The predominance of the sine components with frequencies which are multiples of the fundamental frequency of the structure indicates that the vibrations are essentially forced by corresponding load sine components so that other load components can be neglected.

Analysis

Since the response of each structural mode of vibration can be coupled to each load component distinctly, the sine components of the response can be transformed to load sine components with a much better precision, if the analyses is limited to fully developed resonance vibrations than in the general cases towards which previous analysis procedures were directed. As a tool for the transformation process a finite element model was used, the mechanical characteristics of which were calibrated based on measured load-deflection properties and modal eigen-frequencies.

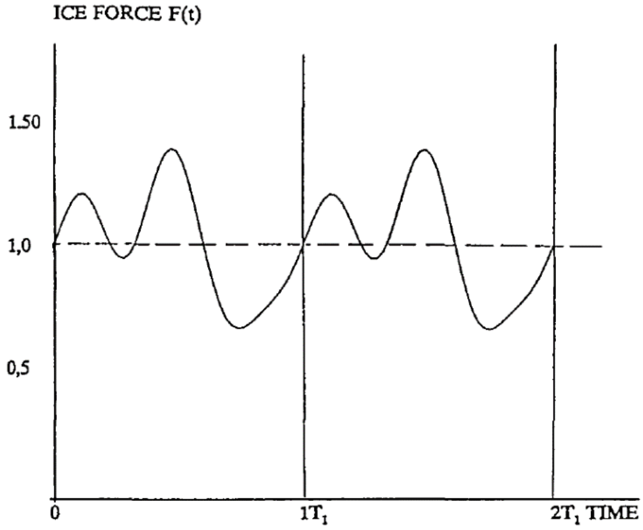
Modified Ice Force Function

Based on the results of the improved analysis the generalized ice force formula can now be adjusted. The improved accuracy of the process for transformation of response data is taken advantage of, resulting in a reduced uncertainty as regards the amplitudes of the dynamic components as well as the shape of the ice force time function.

Basically, the global ice force is still expressed by means of one "static" and a number of "dynamic" components:

$$F = F_o + \Sigma F_{n\,max} \cdot \sin(n\omega_1 t + \theta_n)$$

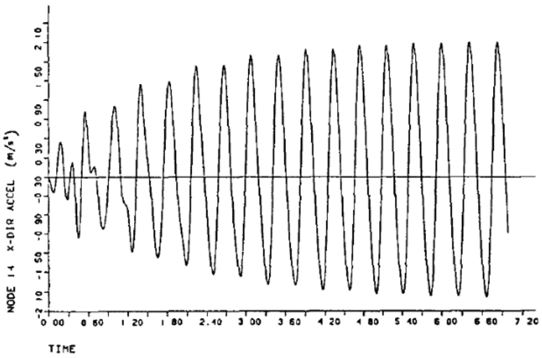
n	$F_{n\,max}/F_o$	θ_n (rad)
1	0.23	0.55
2	0.16	0,65
3	0.09	2.38
4	(0.05)	4.26
5	(0.05)	2.84



The resulting generalized ice force time history is displayed in the figure below. However, in the case that structures and equipment are sensitive to resonance at higher frequencies, load components with frequencies higher than 3 times the fundamental frequency should also be included.

Calculated response to the generalized dynamic ice load

The acceleration response of the lighthouse model to the derived dynamic ice force was calculated in order to demonstrate the suggested response calculation procedure and also to check the appropriateness of the procedure for deriving the ice load by going backwards from the calculated load to the measured response. The computed acceleration time history is displayed in the figure below.



This time-history may be compared with the recorded accelerogram displayed earlier. As expected, there are some peaks, even up to 0.27 g, in the record. Allowance for such occasional effects can be made within the frame of the safety-factoring of the design load.

Quantification of the ice force function

The anchor parameter for the generalized dynamic ice force function is the "static" ice force component which is obtained by averaging the fluctuating ice force during a time period of sufficient length not to give rise to any dynamic response of the affected structure. This average force known as the "effective pressure over the gross area" that has to be related to the specific ice conditions, for which the ice force is to be predicted. This "time-averaged effective ice pressure" can be related to the various ice strength parameters, the size of the contact area, the ice thickness, etc. From the observations of ice forces acting on the ice force sensing panels, it shows that the effective ice pressure, defined as above, will be less sensitive to the geometry of the contact area than the peak pressures. By superposition of simultaneous time-histories from two or three panels we can see, that the peak values of the effective pressure vary considerably with the size of the total contact area.Considering the mechanism of more or less random local failures over the gross contact area, this is what can be expected.

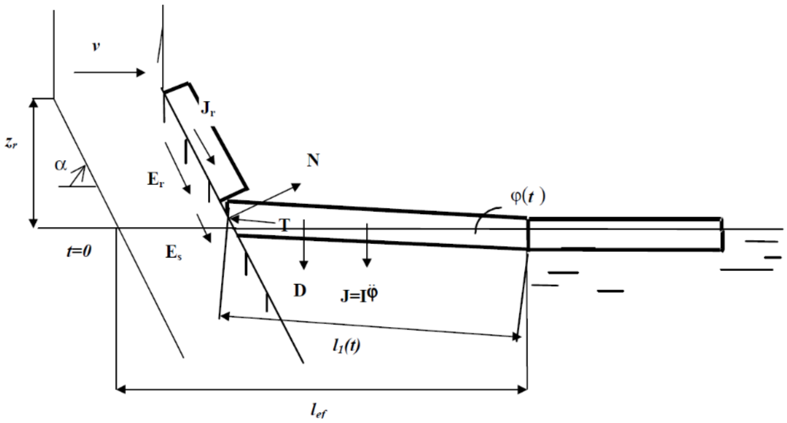
Ref:	Title:	Author:	Date:
2.08	Dynamics of the Ice Sheet interaction with a sloping structure	K. Shkhinek E. Uvarova	2000

Summary:

<u>*Relevance to thesis:*</u>
ice mechanics, ice-structure interaction, sloping structure, ice dynamics

<u>Introduction</u>
It is assumed that use of slopes for offshore structures is especially effective because they reduce the ice load. Many experimental as well as analytical investigations deal with the problem of ice interaction with slopes or sloping structures. But still even in static analysis there is no unique approach to define loads. All these works consider the quasi-static solution, but this solution can be considered only as a first approach. The effect of dynamics can be significant. Ice sheet in static analysis can slide along the slope without longitudinal deformation. So it will easily bend and fail by flexure. But the sheet inertia, friction, rubble on the slope will restrict sliding speed of the sheet edge in dynamics. Therefore if the ice sheet moves with relatively great speed and if the slope inclination to the horizon is high then the sheet will be additionally compressed in longitudinal direction. This phenomenon leads to load increase and can change the failure mode from flexure to compression.

<u>Problem Statement</u>
The process of interaction of consists of several stages. Radial cracks are caused by limited penetration of the structure in the first stage. The cracks confine the investigated part of the ice sheet. This part is considered later as a strip that is pushed on the slope by the whole ice sheet. It is assumed that the strip can undergo bending and longitudinal deformation. The next stage of interaction is the formation of circumferential cracks, connected with bending of the strip during its sliding up the slope. The third stage of interaction is subsequent division of the strip in pieces
during the interaction. Initially the strip is long and easily can fail by bending on the two rather long pieces. The loads corresponding to this process are quite small. Later the piece in contact with the structure breaks into smaller pieces which form rubble near the structure and at its surface.
Longitudinal deformation of the sheet at the contact with the strip is assumed to be much smaller than longitudinal deformation of the strip itself. So the sheet is considered as incompressible whereas the strip compressible. Change of the form of the strip due to bending is neglected but all forces that induce bending moment and corresponding failure mode are considered. A reversion motion is investigated.



The initial length is not a constant and can change its value depending on several parameters, for example, of mass of rubble on the structure slope, ice speed, etc. The initial length as the first approach can be defined from the static solution.

Main stages of Dynamics of Ice-Slope interaction

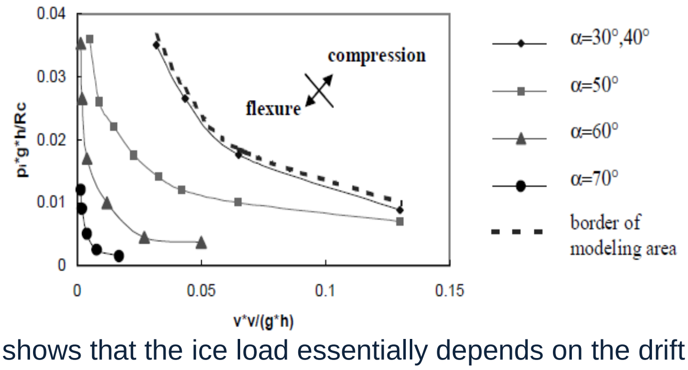
During of ice to slope structure interaction the following stages were considered:

- The initial stage of interaction when the strip moves against the slope and due to bending failure is divided on two pieces. The time moment, when the maximal stress in some section of the ice beam becomes equal to the compressive or tensile ice strengths, defines the failure instant.
- Subsequent motion of ice, rotation and sliding of the nearest to the structure pieceof the strip and its division on smaller pieces.
- Rubble formation on the slope and the ice piece interaction with rubble.
- The inertia of the ice strip (or its piece) rotation.
- The deficit of buoyancy force due the strip (piece) moving up.
- The longitudinal force induced due to the strip (piece) compression during the structure motion. This force consists of two parts: one is connected with projection on the longitudinal direction of the ice weight excess (due to deficit of buoyancy) and another with the piece compression.
- The damping of the ice strip (piece) oscillation.
- The force, exerted by the ice strip edge on the structure surface.
- The inertia of rubble located on the sloping surface.
- The forces due to the rubble and the ice sheet edge friction along the structure surface.

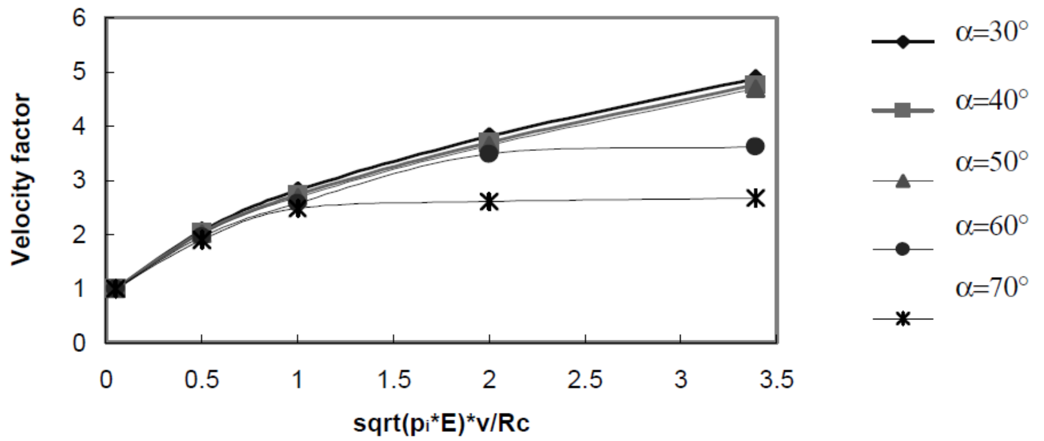
Determination of the mass of the ice rubble on the structure surface is connected with some difficulties: when the ice piece reaches the construction neck, it rotates and falls down, loading part of the ice beam near the structure. The scheme described above was used for all stages of interaction. Subsequent the ice strip division, sliding, pushing the rubble, etc. repeated several times.

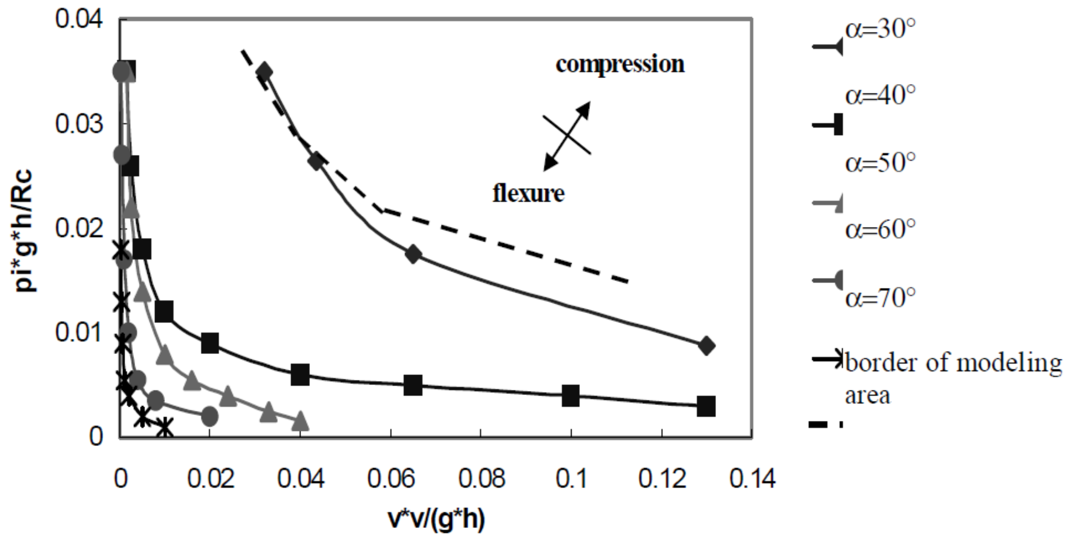
Calculation Results

A special computer program was developed based on this theory. This program gives possibility to determine the mode of ice failure and value of the maximal horizontal (vertical) load on the slope during all stages of interaction. The ice properties and the structure form were varied. Increase of ice thickness or ice velocity leads according to this figure to transition ice failure mode to compression instead of flexure for the same other parameters. The more is the angle of structure inclination to the horizon the more is the probability of ice failure by compression.



The figure below shows that the ice load essentially depends on the drift velocity, and can increase several times at high velocities. Usually value of the velocity factor changes significantly when failure by flexure is replaced by compressive failure. Significant increase of the velocity factor is connected with influence of the longitudinal compression. Due to this compression resistance to flexure failure increases. Great longitudinal compression in these situations enlarges the limit of flexure failure but do not change the limit of the compressive one. Therefore the whole pattern and the load remain the same independently on the ice speed.





Existence of the rubble on the slope essentially influences ice failure mode and ice load value. The zone of failure by compression increases for the same combinations if rubble is considered. Presence of ice rubble on slope also leads to the increase 1.5-2.0 times of the velocity factor.

<u>Conclusion</u>

Dynamics of ice / inclined plane interaction is reviewed in this article. The analytical solution is obtained and wide numerical experiments are carried out. The results demonstrate possibility of transition ice failure mode from flexure to compression at high ice speeds and some of angles of slope inclination. This transition leads to loads increase. Loads increase significantly if rubble is located on the slope. Influence of dynamics is characterized by the velocity factor equal to dynamic/static loads ratio. Results of the suggested solution are in a good correlation with physical experiments.

Ref:	Title:	Author:	Date:
2.09	Simulation of Ice Pile-Up process in FEM	J. Paavilainen J. Tuhkuri	2009
Summary:			

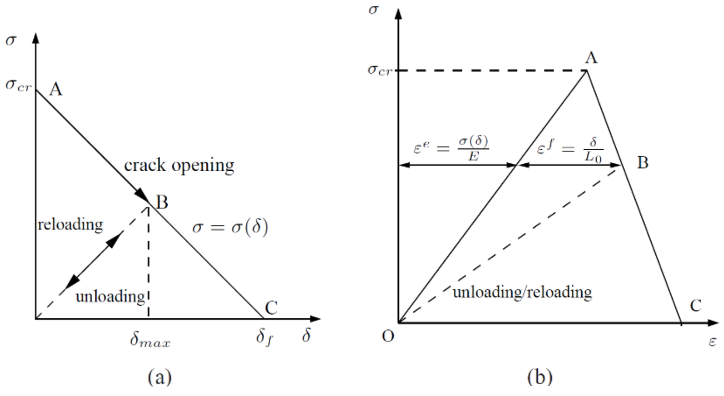
<u>Relevance to thesis:</u>
Ice pile-up, ice mechanics, ice interaction modeling

<u>Introduction</u>
The failure of ice cover against an inclined structure is a fragmentation process where an initially intact ice sheet breaks into discrete ice blocks which then accumulate in the ice-structure interface and thus affect the failure process. For design and safe use of marine structures in ice covered waters, the understanding of this fragmentation process and the calculation of the ice load on structure are important challenges. It is believed, that in order to understand the failure of ice and ice loads on structures, the ice-structure interaction should be studied as a process and simulated.

One method to simulate the ice failure processes is the discrete element method (DEM), which has previously been used in analyses of ice pile-up. Another method used in determining the ice forces on structures from piles is finite element method (FEM). This article presents a 2D combined finite-discrete element method to model the multi-fracture of beam structures and an application of the method to an ice-structure interaction problem. In the method, elastic beams and their fracture are modeled according to finite element method by using non-linear Timoshenko beam elements and cohesive crack model.

The ice pile-up simulation is made by using combined finite-discrete element method. The method can be divided into three parts, namely the continuum, the failure and the contact model.

<u>Continuum and failure models</u>
Intact ice sheet and the pieces that are broken from it are modeled with non-linear Timoshenko beam elements. The basic kinematic assumption of the Timoshenko beam state that the cross sections remain plane but not necessarily normal to the mid surface during deformation. In addition, small strain assumption, large displacements and a viscous damping model are utilized in the model. The failure of the ice beam is modeled with the cohesive crack model. Of the two types of cohesive crack models, the quasi-brittle model is used as it is more appropriate for sea ice.



$$F(\sigma, \delta_{max}) = \sigma - \sigma_{cr}(1 - \frac{\delta_{max}}{\delta_f}) = 0 \quad \text{with} \quad \sigma = \sigma_x + \frac{\sigma_{cr}}{\tau_{cr}^2}\tau^2$$

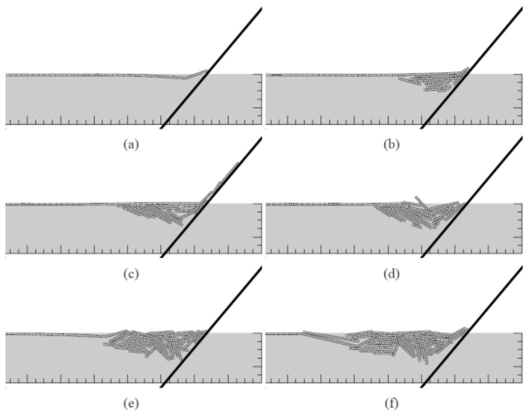
If a crack has formed and the stress state is such that F < 0 and σ x _ 0, the unloading or reloading case is active. This is shown in figure ‘b’ with a dashed line BO. In the case of crack closure, i.e. F < 0 and σ x < 0, the stress σ is evaluated as if the material would be intact and the crack opening displacement is equal to zero, $\delta = 0$. Again, the δ max has a constant value as in the cases of unloading and reloading. In summary, the value for δ max changes only in the crack opening phase and it is an increasing function to make the failure process irreversible.

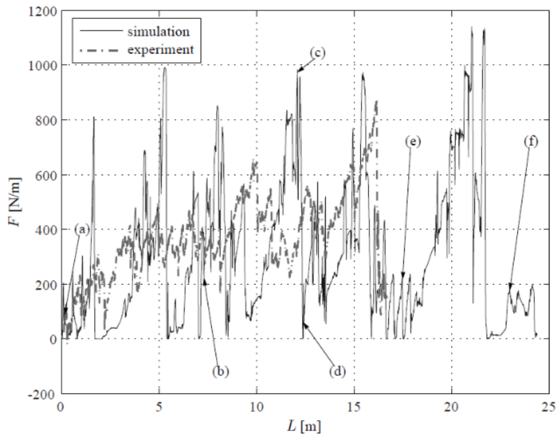
Contact model and time stepping

Failure of intact ice results in creation of smaller ice beams which at later stages of the simulation
can collide with other ice beams in the model. These interactions between ice beams are simulated by using the discrete element method. In addition to finite elements, interacting ice beams are also composed of one or more discrete elements. The contact detection and the calculation of the contact forces are handled by using these discrete elements. The elastic contact forces are based on the overlap area and the rate of change of the overlap area of contacting elements. Inelasticity is modeled by using a plastic limit for the material.

Ice Pile-Up Simulation and Conclusion

In the simulation, an ice beam was pushed at its left end with a constant velocity of 0. 02 m/s against an infinitely rigid structure, as shown in the figure. Both ends of the structure were supported and the inclination angle was 50∘. The first figure shows snapshots of the simulation and the second digure gives the horizontal force acting on the inclined structure as a function of the length of pushed ice L.





Initially, the ice sheet fails against the inclined structure by bending and started to form a pile which grew both vertically and horizontally. After a pile was formed, the ice sheet either slides on top of the pile to the inclined structure and rode-up along the plate or failed against the pile. A collapse is a process where the pile fails under the load from the ice sheet ride-up or pile-up in front of the structure. Collapse resulted a movement of the pile down and left and a decrease of the horizontal force. The cycle, growth of the pile against the plate and collapse of the pile, occurred several times during the simulation. In the simulation these collapses of the rubble pile caused the force to drop to zero as the contact between the sheet and the structure was lost. Another phenomenon observed in the simulations was a clockwise rotational motion of the rubble pile. the average forces of 310 and 370 N/m obtained correlate with physical experiments.

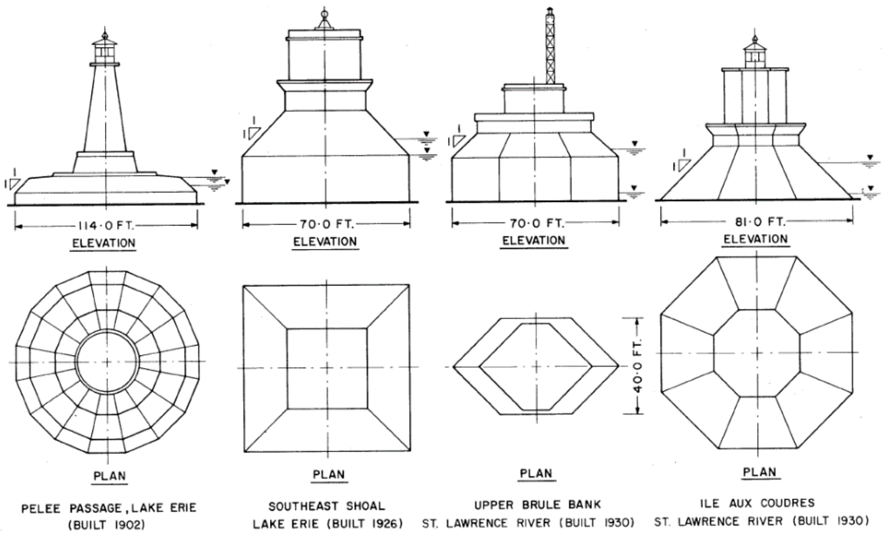
Ref:	Title:	Author:	Date:
2.10	Effect of cone shaped structures of impact forces of ice floes	J. V. Danys	1971

Summary:

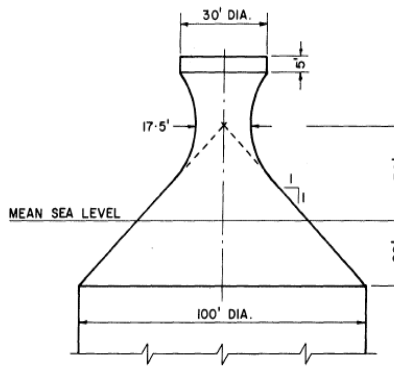
Relevance to thesis:
ice mechanics, ice-structure interaction, sloping structure, ice floe forces

Introduction

Although for a long time the theoretical knowledge about the ice forces was very limited and sometimes non-existent. Design and construction of lighthouses and bridge piers were based on the engineers experience and intuition. Certain features of the structures exposed to ice forces became typical, although there was no good explanation for it, and besides some failures there were ample successful structures. Early in the history of lighthouses construction sloped surfaces became accepted feature to reduce ice thrust on the light piers.



The effect of the ice forces on the cylindrical and conical piers were studied in more detail and it was concluded that the cone-shaped structure had a considerable advantage over the other shapes in reducing the impact forces of floating ice and breaking waves. The stability of the structure with some flat, vertical sides is very unbalanced when ice floes can come from any direction. Then the stability in the direction of the vertical face becomes appreciably smaller than in the direction of the conical section. The final shape is to be designed considering the functional requirements, ice, waves, earthquake and other forces, as well as construction and overall economy.



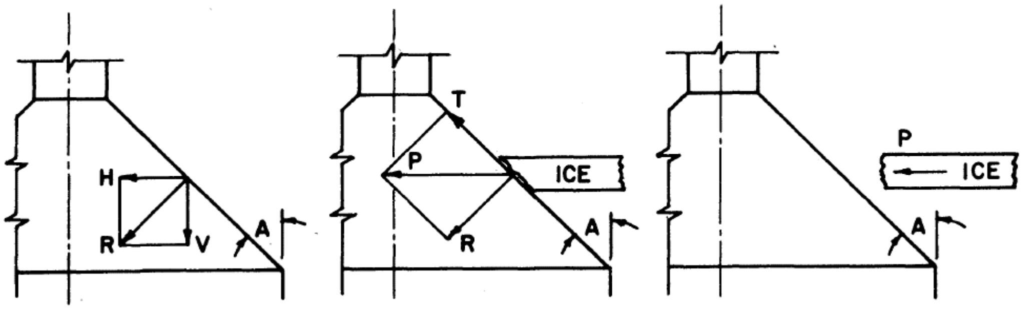
Failure modes of Ice Floes

Four possible modes of destruction of the ice sheet colliding with the structure are: failure by buckling, crushing, shear or bending. The force developed by an ice sheet will depend on which of these modes of failure is taking place.

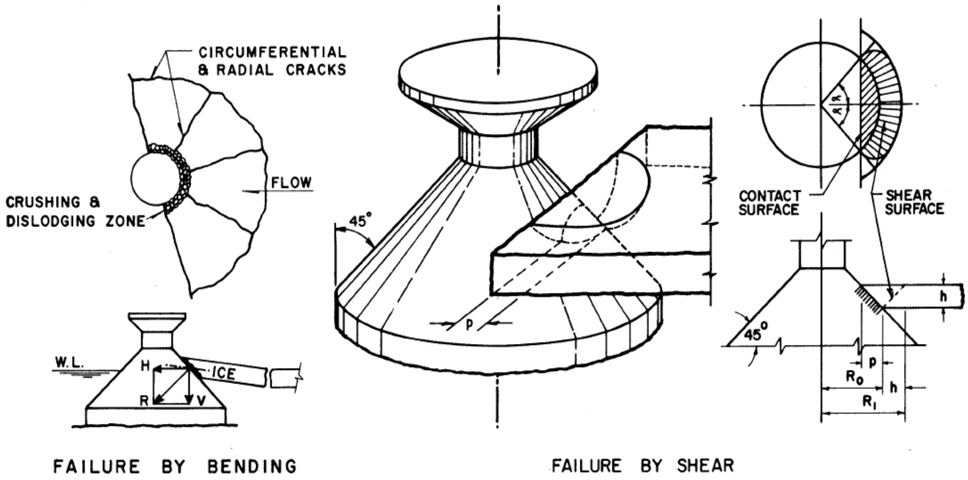
Failure by Crushing

As the compressive strength of ice is much greater than the flexural or shear strength, a failure by crushing, generally, would exert the most severe dynamic load on the structure.

As a result of a collision with a sloped surface, one component of the potential force will act perpendicularly to the surface of the structure, and the other component, tangentially to the surface. The friction between ice and steel plate or smooth concrete is quite small, and the tangential component of the force, generally, may be neglected as being comparatively a small force.



Failure by Shear
After the initial crushing of ice on the structure, the vertical component of the resultant force will induce shear stress in the ice sheet. The magnitude of the shear force depends on the penetration depth of the ice sheet into cone. The area of the shear plane in a simplified way could be calculated as half a frustum of a cone where the small radius is assumed equal to half of the chord corresponding to the penetration depth. Furthermore, the sheared off ice wedge shall be dislodged and this adds an additional force



Failure by Bending
The vertical reaction produced by the cone raises the edge of the ice sheet upwards and induces bending stresses in the ice sheet. The theory of a semi-infinite plate supported on elastic foundation can be applied to estimate the force which would produce the failure along the circumferential crack created by the force acting at the edge of the ice sheet. The model testing indicated a considerable increase in ice load on a structure with the increasing velocity of the approaching floes. Model testing of ice forces showed that the loads recorded subsequent to initial impact were considerably larger than the initial impact loads. This was attributed to the weight of the ice fragments leaning on the structure.

Comparison of Failure Modes
Calculations indicate that the horizontal force on the cone-shaped pier caused by flexural stresses would be about three times smaller than in the case of failure by crushing or shear. It shows that a failure by shear develops smaller forces when the ratio of unit compressive strength to shear strength is 4. If this ratio is smaller, failure by crushing would occur before failure by shear. The vertical forces induce stabilizing moments in case of failure by bending.

For the overall stability of a structure the geometric proportions of the structure, the relation of the height of the application point of the force to the base and the foundation width are important. Generally, the larger the diameter of the base and the closer the acting force to the base, the greater the relative effect of the vertical component of the ice force to the stability of the structure is. The effect of the vertical force is considerably reduced for a relatively tall structure with a small base.

The proposed method of calculating the forces resulting from failure by bending has many shortcomings. The applied Meyerhof is theory was developed for static conditions and for a force acting downwards as a static load. Actually, the floating ice exerts a horizontal and dynamic force and a vertical acceleration force acts upwards and introduces the rise of the edge of the ice sheet and piling of the ice on the structure. Three corrections are made to the basic force calculated according to Meyerhof's theory. First, the force is increased because of the dynamic effect of the moving floe against the pier. Second, the additional load is added because of the weight of the ice fragments piling on the sloped structure. Third, the tensile or flexural strength of the ice sheet is increased because the ice sheet hitting the slope is in a state of compression.

Conclusions

The cone-shaped pier forces the advancing ice sheet to ride up and to break in bending which results in smaller forces on the structure. Part of the load acts downwards increasing the stability of the structure. From the comparative model testing it appears that the horizontal force on a conical structure is about four times smaller than on an equivalent vertical cylindrical structure.

The cone- shaped structure would act differently or its effect would be reduced if the cone slopes would develop a high resistance against an upward sliding of the ice sheet. A possibility for such a case would be formation of high strength ice collars well frozen to the structure. The failure mode by bending would be affected and the ice forces on the structure would be increased to the magnitude of the forces induced by the failure by crushing. Thus the forces calculated from ice failure by crushing would represent the extreme conservative load.

The cone-shaped pier would have a considerable advantage in breaking advancing ice ridges even if the ice sheet was solidly frozen to the structure and so obstructing the ride-up of the ice on the structure.

Ref:	Title:	Author:	Date:
2.11	Failure mode effect on Conical structure under dynamic ice forces	Feng Li Qianjin Yue	06-2007
Summary:			

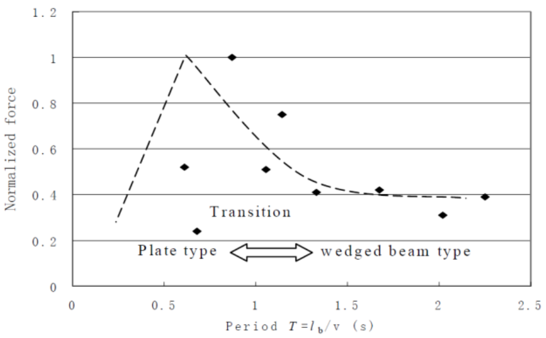
<u>Relevance to thesis:</u>
ice mechanics, ice-structure interaction, sloping structure, ice dynamics

<u>Introduction</u>
A key engineering problem for conical offshore structures is how to determine the worst dynamic ice load function so as to process an effective and dependable dynamic analysis of the structure. As a dominant failure mode during ice-cone interactions, bending is a kind of failure due to development of off-plane displacement of sheet ice. As a result of multi-factor influence, the process of deforming and breaking and failure pattern under ultimate condition possess a variable character. Two basic types of bending failure have been derived, called wedged beam type and plate type and a mode map to distinguish by each other This article summarizes failure mode effect of conical structure ice forces.

<u>Mechanism of Dynamic Ice Forces</u>
When one refers to dynamic ice forces a problem which cannot be avoided is how to treat the velocity effect. It is shown by a great deal of model tests that velocity influences of ice force may represent different phenomenon and regularity for different interacting process, such as change in range of cone angle, friction condition and velocity. When answering such a question of whether or not there exists a velocity effect and what kind of velocity effect, material interaction conditions and the dominant mechanisms must be considered.

Let us consider an ice beam for which the failure force is expressed by effective modulus of elasticity and flexural strength. For bending failure it is reasonable to suppose that it does not depend on strain rate of ice intensively, the inertia effect is generally regarded as a main factor. It is believed that this model is only right when no transition of failure mode takes place. The transition of failure mode puts an upper limit on dynamic magnification of bending loads, and corresponding breaking length of ice tend to be shorter than bending. The alternative mode may be shearing, dynamic buckling, crushing or some combination of different modes. A research on failure mode effect may be a short cut to replace the difficult velocity effect for determining the worst dynamic ice force. The analysis parameters can be substantially reduced but also the dynamic load problem is substituted by a static one with reduced difficulty.

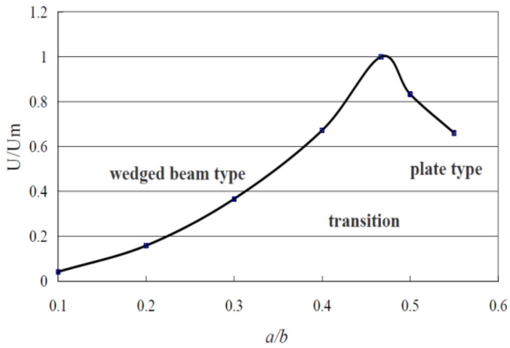
<u>Failure mode effect and mode parameters</u>
A research on failure mode effect deals with the definition and distinguishing of different failure modes and the interrelation between ice force parameters and mode parameters. In the figure the ice force-period interrelation is shown. The average peak value force increases continuously until a certain maximum level, and then suddenly falls down to a very low level. This phenomenon is explained by mode effect with a transitional bending failure instead of velocity effect.



Typical wedged beam type failure is radial cracks appear firstly and extend fully with a big breaking length. Typical plate type failure is a circumferential crack arises before radial ones and with quite small breaking length. Theoretically, circumferential and radial cracks should be arising simultaneously.

Energy analysis of elasticity model

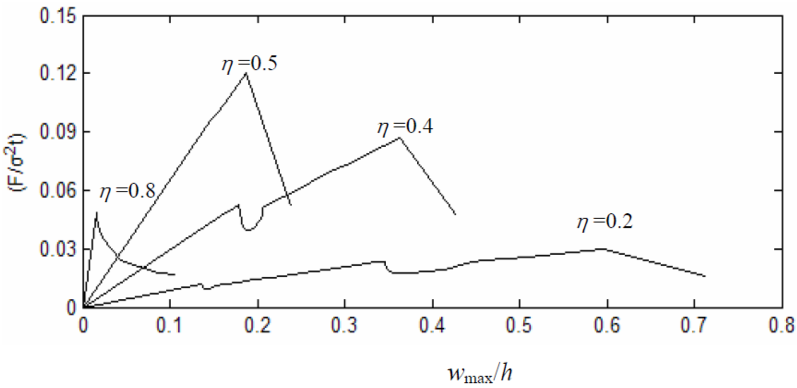
Considerer a model of elastic plate with a semi-cirque region. Suppose an ideal contact between sheet ice and the cone surface is satisfied. When sheet ice deforms in bending under a certain linearly distributed load on the inside boundary, an approximate displacement field and corresponding ultimate failure force are obtained by energy method. The figure shows an elastic deformation energy distribution of the ice plate as a function of the mode parameter η. This curve clearly shows a zenith at the critical point. This result relates transitional bending failure with the worst dynamic ice force.



With the parameters as same as the elasticity model, a non-linear finite element method (FEM) analysis was performed. Different values of mode parameters are considered for stress analysis of each study group. Mode effect is detected by comparing each result in turn with other groups.

Conclusions

The following conclusions are obtained from mode effect research by using a single parameter model for failure process analysis of ice-conical structure interaction, the mode parameter is defined as η=a/b, *a* and *b* are radii of the cone and circumferential crack of ice respectively.The mode parameter, to a great extent, decides ultimate load-bearing capacity of sheet ice under bending. As η increases, the bending stiffness of sheet ice increases but terminal deflection decreases. This shows a brittle trend of failure. When η is small, failure mode is belongs to wedged beam type, the corresponding ice force is low and with a long deforming process. When η is close to 0.5 or so, the transitional failure occurs. Both the peak value force and elastic deformation energy reach a maximum, while deformation during unloading stage falls to minimum. This is taken for the worst failure mode for dynamic ice load. For a higher value of η, plate type failure becomes dominant. With a great bending stiffness and quite low capability in deformation, this kind of failure is quite sensitive to the boundary condition and tends to a local failure with a lower ice force.



Ref:	Title:	Author:	Date:
2.12	Ice Ridge to Structure interaction – Geometry and failure modes of First Year ice ridges	B. Bonnemaire M. Bjerkas	2004
Summary:			

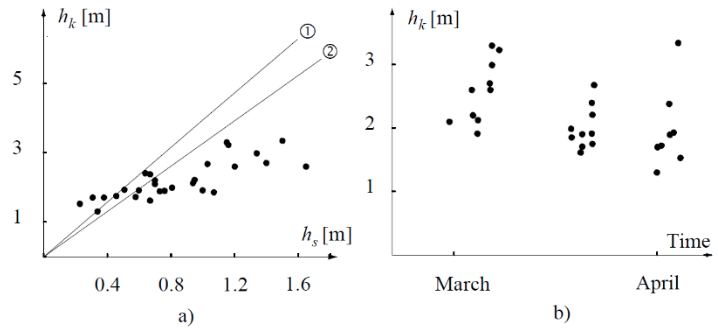
<u>*Relevance to thesis*</u>
ice ridge interaction, first year ice ridge properties, ice ridge load, Gulf of Bothnia

<u>Introduction</u>
This paper addresses the interaction between first-year ice ridges and an instrumented lighthouse in brackish water. Offshore structures have to be designed to withstand environmental loads. In a
environement where only annual ice is present, loads from consolidated first year ice ridges or floating rubble fields often corresponds to the design criteria. The range of first year ice ridge or rubble field loads on Arctic structures is wide. A ridge is an extended pile of broken ice blocks with a sail and a keel extending above and below the water line with a triangular-shaped cross section.

<u>Ridge geometry</u>
The deepest observed keel was 3.3 m. The table below gives an overview of the mean geometrical properties of the ridges. Symbols hk, hs, hc and hi refer respectively to the keel, sail, consolidated layer and parent ice sheet thicknesses. The ridge factor is defined as ψc =hc/hi.

	h_k [m]	h_s [m]	h_k/h_s	h_c [m]	h_i [m]	Ψ_c
Mean	1.87	0.71	3.0	0.69	0.54	1.45
Std. deviation	0.95	0.46	1.16	0.21	0.25	0.46
Max	3.34	1.65	6.67	1.05	1	2.45

The figures below show the measured sail height versus keel depth for the selected ridges, and the ridge keel depth versus time during the measurement period.

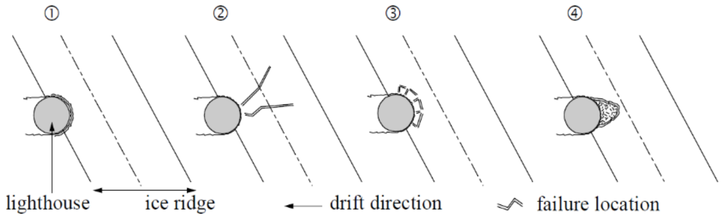


<u>Snow on ice</u>
The presence of snow on the ice will alter the frictional properties of the top surface. This will affect the amount of ice that will accumulate in front of the interaction zone on top of the ice. There seems to be no strong correlation between high loads on the structure and the occurrence of snow cover on the ice.

<u>Surrounding ice</u>
The ice surrounding the ridge could be a rubble field, rafted ice or simply level ice. It is assumed that a ridge within a rubble field will not fail by bending in the horizontal plane (around the vertical axis of the structure). Consequently, the failure of a consolidated ridge within a rubble field represent the dominant failure which will result in the highest load during an ice-structure interaction in a first-year ice environment. However, no significant differences are observed between ridges surrounded by level/rafted ice and ridges surrounded by a rubble field.

Failure Modes

Four different failure modes were observed: crushing, splitting, bending failure and failure on a wedge formed in front of the structure.



1: crushing 2: splitting 3: bending 4: wedge failure

The sequence is the following:

- Level ice is crushing against the structure. The forces are relatively low and of a stochastic nature.
- The ridge starts to fail in crushing; the load presents a saw tooth profile.
- The load in the interaction zone reaches a maximum. The force necessary to develop splitting failure is reached; there is a change in failure mode.
- The fragments from the splitting failure cannot be evacuated; a wedge builds up in front of the structure. The incoming ice fails on the wedge; the load level on the structure is low. The wedge length varies in time; it usually increases till some collapse appears within the wedge that causes its partial reduction.
- The wedge builds up in height and ice accumulates.
- The wedge collapses under the pressure of the incoming ice and the fragments can be cleared around the structure, the ridge event is almost finished.
- The virgin level ice impacts the structure.
- Level ice crushing with some local bending failure restarts.

Crushing failure was observed in all events. Bending (or buckling) and splitting failure was often associated with crushing, these failure modes alternated depending on the homogeneity of the ridge. In some cases, failure on a rubble wedge took place. In these cases, crushing failure takes place first followed by splitting or bending that produce a big quantity of rubble in front of the structure. This ice is compacted in a wedge and the incoming ice fails on this wedge. The length of the rubble wedges were in the range of 1-2 lighthouse diameters before they tend to collapse. The events with pure crushing concern more shallow and slow drifting ridges whereas wedge failure tends to happen more often with deeper ridges. Ridge consolidation is not shown, but is believed to play an important role in the selection of the failure mode that will require less energy. Analysis of all the events showed that the failure mode giving highest forces was pure crushing of the ridge. The maximum forces in that failure mode are limited, as soon as there is enough force in the ice sheet to trigger bending or splitting failure, the failure mode changes and the load drops. If the fragments cannot be cleared then wedge failure appears inducing limited loads.

Conclusion

- The deepest keel found is 3.34 m and the highest sail is 1.65 m.
- From 12 ridge interactions with a segmented panel, the ridge factor based on consolidation are found to be on average 1.45.
- Ice ridge – structure interaction is complex and composed by several failure modes as crushing, bending, splitting and failure on a rubble wedges.
- Snow cover does not seem to influence the ice loads significantly.
- Crushing failure seems to give the highest loads during interaction with ice ridges.

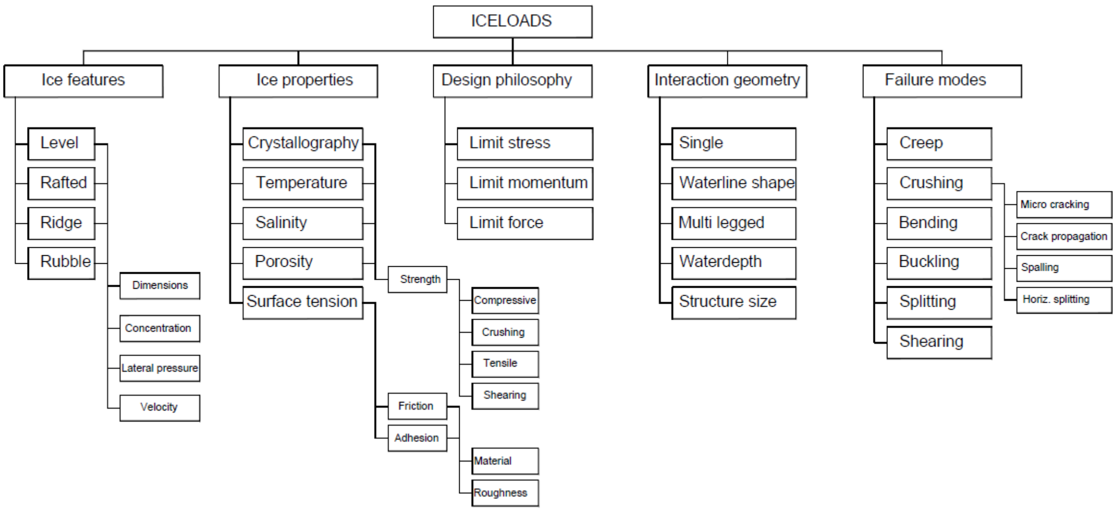
Ref:	Title:	Author:	Date:
2.13	Global Ice load dependency on structure width and ice thickness	K. Shkhinek S. Løset	06-2003

Summary:

Relevance to thesis
ice thickness, ice-structure interaction, global ice loads, ice load parameters

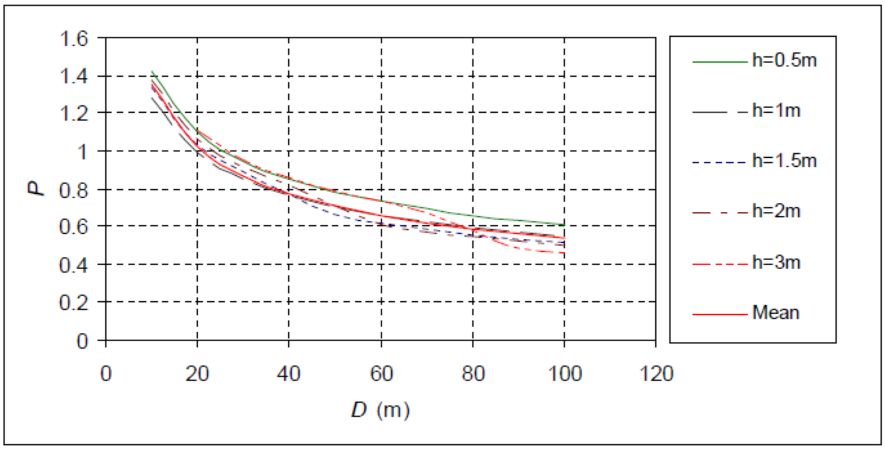
Introduction
The structure width (D), ice thickness (h), strength (σ c) and the ice speed (v) are the major parameters that determine the ice to structure interaction process and ice load. Indentation pressure depends on contact area or aspect ratio. The latter is defined as structure width/ice thickness (D/h). It is difficult to suggest with confidence any load (pressure) dependency on the structure width, ice thickness and their combination. The second problem of estimation of ice loads is how to include ice strength in calculation methods. Ice properties vary significantly through the ice sheet thickness. The third important parameter is the ice speed.

Ice load parameters
A number of parameters affect the ice load acting on structures. The most essential ones are shown the figure below. Some of them should also be considered in combination such as size, strain, speed and thus strain rate.

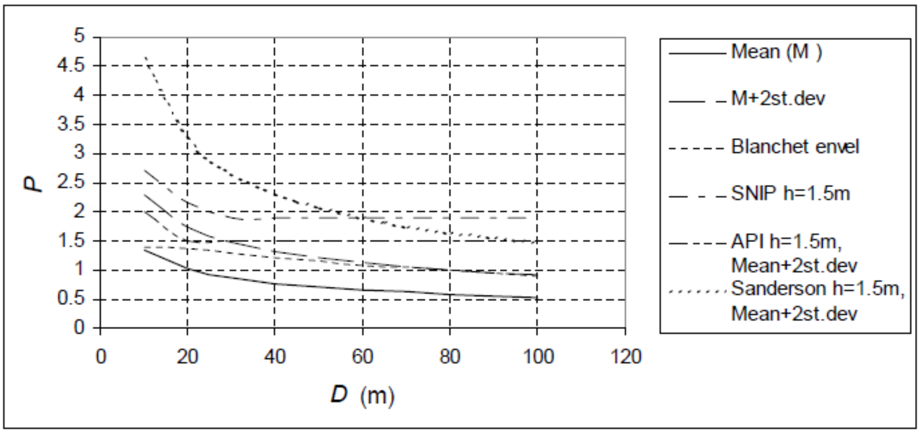


Ice thickness and structure diameter
Usually the influence of ice thickness and structure diameter on the pressure is considered in combinations. The disadvantage of most of the usually suggested dependencies is that they consider pressure dependence on aspect ratio and on contact area independently. It is clear that these parameters reflect different physical processes that exist simultaneously, and neither of them can be used separately. Non-simultaneous failure develops during the ice/structure interaction and this effect can be considered as depending on aspect ratio.

The figure below shows calculation results of non-dimensional pressure $P=p/\ c\ \sigma$ versus structure diameter D for different ice thicknesses h.



For the most common ranges of structure diameters (10-100 m), ice thickness (0.5-3 m) and
aspect ratios exceeding 4, the mean dependence for non-dimensional pressure is proposed in
the following form: $P = 1.35(D/10)^{-0.39}$ $\quad$ *for* $D/h > 4; 10\,m < D < 100\,m$
The figure below shows a comparison of the pressure with the structure width.



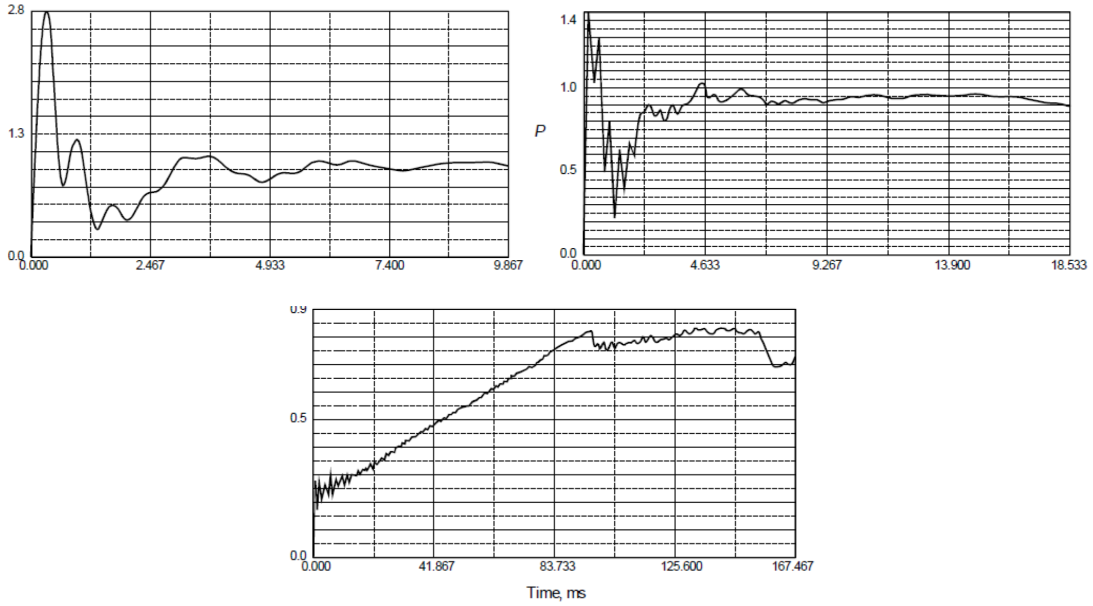
<u>Strength</u>
The ice strength is a crucial parameter. It depends on ice temperature, salinity, porosity, and internal ice structure and strain rate. It characterizes the conditions in each particular area in the particular moment of time. Especially important is the information about the strength distribution and its variation for probabilistic modeling of ice loads. The main disadvantage with the strength parameter is its strong dependence on sample size (the so-called scale effect).

For design purposes it is suggested to divide the sheet into layers. The salinity and temperature are then determined for each layer (depending on air temperature history and ice thickness). These values are used to calculate the present strength of each layer. Later it has been recommended to use a square averaging of different strengths for the determination of the effective strength. In reality, the ice modulus of deformation and strength are distributed non-evenly through the sheet cross-section. Thus the maximal strength in all layers will be reached non-simultaneously and failure will develop stepwise. The load will be redistributed between other layers after failure of the weakest layer. This induces increased stress in adjacent layers and development of failure. As a consequence the sheet will be destroyed at a lower load than is predicted by the strength averaging method.

Speed effects

The ice speed has influence on many parameters such as ice strength, real contact area, failure type and thus the resulting ice load. It was shown that there are practically two different phenomena during the ice/structure interaction: initial the ice sheet hits the structure and the structure penetrates in the ice. In this first process the pressure along the contact area is directly proportional to the ice speed whereas for the second process (penetration), the local speed nearest to the structure zone is not high if the structure is rigid and immovable. Therefore other factors such as non-simultaneous failure, variation of real contact area became more important than speed in this phase. It is assumed that the ice pressure is evenly distributed along the contact area. However, the stress is distributed unevenly during the penetration phase: there are stress concentrations at corners that cause the initial failure. In a later stage areas with maximal pressure move gradually to the center of the contact surface. This is one of the reasons for non-simultaneous failure.

On the figure below results for 3 different speeds is shown. The first graph is for v=1,0 m/s. The second graph is for v=0,5 m/s, and the third graph is for v=0,1 m/s. If the ice speed is low then maximal load corresponds to the penetration phase whereas at high speeds the first term predominates.



CONCLUSIONS

The analysis of experimental data leads to the following conclusions:

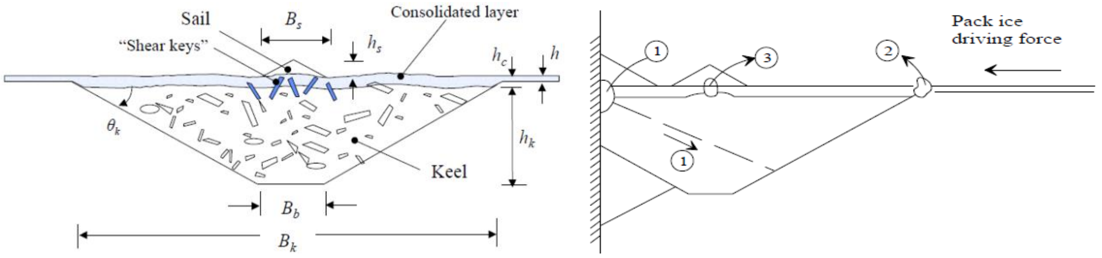
- The mean peak pressure decreases with the increase of both aspect ratio and contact area. The disadvantage of the majority of experimental and theoretical dependencies is that they consider the pressure dependence on these parameters separately, whereas both of them influence the pressure.
- The influence of ice thickness on average pressure is not significant for structure widths and ice thicknesses relevant for design of offshore structures.
- A special method for determination of the effective ice strength is discussed. Based on this method lower effective ice strength is obtained than what currently is used.
- Different phenomena correspond to different speed ranges. If the speed is low then loads corresponding to the penetration process predominate. At high speeds loads due to ice hitting the structure are more important.

Ref:	Title:	Author:	Date:
2.14	Global Loads due to Ice Ridges	T. Karna C. W. Rim	08-2001
Summary:			

<u>*Relevance to thesis*</u>
ice ridge interaction, first year ice ridge properties, ice ridge load analysis

<u>Introduction</u>
First-year ridges are known to produce the highest forces on offshore structures in several ice covered sea areas. In this article a passive failure model that considers both of these near field failure and plug failure modes of the ridge keel is presented. The model developed is intended for deterministic ice load predictions and also for probabilistic ice load determination.

<u>Load Limiting Mechanisms</u>
Analysis of field data shows that ice ridges may assume several different geometrical forms. In the present treatment, we will study ice ridges having a cross section depicted in the figure below. An important feature of the design ice ridge shown is that the rafted and consolidated layer with a thickness parameter *'hc'* is extensive in both directions from the ridge sail. The keel of a first year ridge consists largely of loose ice blocks that will be treated as ice rubble. However, the strength of this keel material may change with the depth. An obvious reason for this is that some ice blocks are frozen into the consolidated layer but extend into the area of the keel rubble. Such ice blocks will have the effect of increasing the cohesion in the uppermost keel layer.



The global load caused by an ice feature is limited by the different failure modes. Three different failure modes are depicted the figure:

1) The consolidated layer crushes against the structure. At the same time, the ridge keel and the rubble accumulation in front of the structure fail along a shear plane.
2) The level ice behind the ice ridge fails.
3) The consolidated layer fails in a weak zone below the ridge sail.

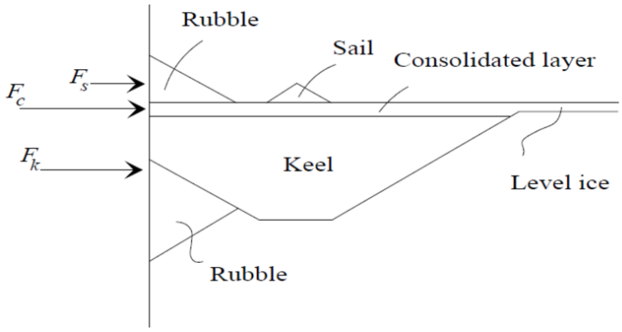
The global load arising due to the failure mode (1) is known as "limit-stress" load whereas modes (2) and (3) produce "limit-force" loads.

The global load acting on the structure is evaluated using the formula:
'*Fg = min{ Fg1, Fg2 }'* where Fg1 and Fg2 are the global loads corresponding to the limiting mechanisms (1) and (2), respectively. We first consider the evaluation of the limit-force loads. The limiting force mechanism (2) yields a global load estimate *'Fg2 = prb h L'* where '*prb*' is the ridge building pressure, *'h'* is the thickness of the level ice that exists behind the ice feature and *'L'* is the length of the ice feature in the direction perpendicular to the ice drifting direction.

Limit Stress Load on an Ice Ridge

The load limited by the failure mode (1) is assumed to be *' Fg1 = Fc + Fk + Fs '*

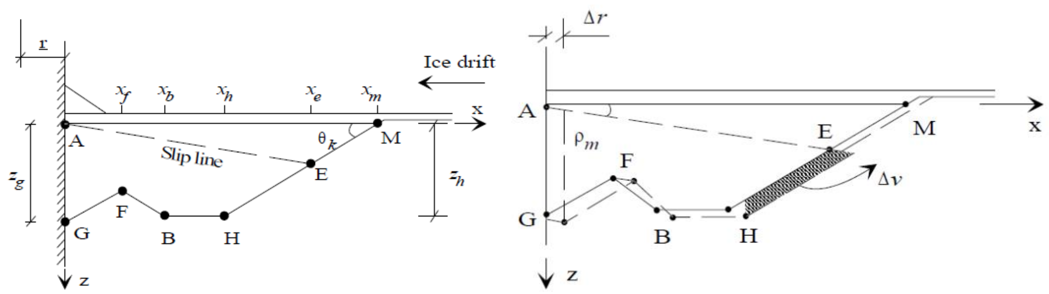
The first component Fc arises from the failure of the consolidated layer and the components Fk and Fs are termed the keel load component and the rubble (or sail) load component.



Keel Load Determination

To determine the load component provided by the ridge keel we need to consider how loading conditions develop after initial impact.

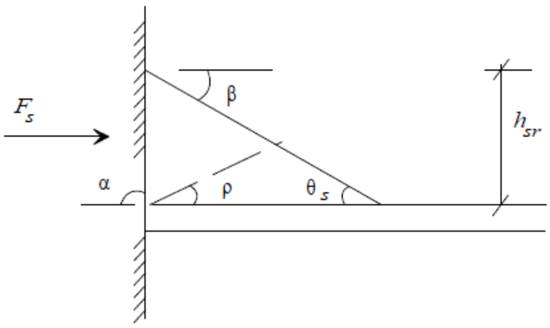
(B) DURING INTERACTION



The interaction process starts when the edge O of the ridge profile impacts the structure. It is assumed that the keel experiences several shear failures along slip lines AE that have an inclination ρ m with the x axis. Accordingly, we assume that the failing block AGFBHE undergoes a rigid body displacement relative to the rest of the keel. The relative displacements at keel failure are large and secondary failures will occur at the line HE. The keel consists of loose ice blocks. Therefore, the shear failures, together with the secondary failures, result in a sequence of changes in the keel geometry while the structure penetrates the ridge. The cohesional resistance of the keel arises as the result of rigid connections between ice blocks. These connections will fail at a relatively small strain level. On the other hand, the development of the shear surfaces (slip planes) within the keel and the mobilization of the frictional force components are associated with large strains. Under these conditions, the combination of the load components as a direct sum of the peak values would lead to an overestimation of the keel load component.

Rubble Pile

The sail of the actual ice ridge is usually not relevant while calculating the global load because the maximum keel load component occurs before the ridge sail meets the structure. But one needs to consider the effects of the rubble pile that develops in front of the structure. The load component due to the rubble pile is small compared with the keel load component. Therefore, the contribution of the vertical slip planes that were considered for the keel can be ignored.



Resistance provided by consolidated layer

We assume that the resistance provided by the consolidated layer is given by the simple formula *'Fc = pcr hc D'*

Where *'hc'* is the thickness of the rafted and consolidated layer, '*D*' is the width of the structure and '*pcr*' is the nominal ice crushing pressure on the total ice-structure interface. Some specific features of the consolidated layer should be taken into account while evaluating *'pcr'*. The consolidated layer is likely to contain macro-scale defects and voids that reduce the ice strength. It shows that a cross-sectional strength of the consolidated layer is reduced by 30% to 40% if the porosity increases from zero at the top to 20% at the lower boundary of the consolidated layer.

<u>Conclusion</u>

A new model was developed for a deterministic prediction of global loads on offshore structures caused by first-year ice ridges. The load caused by a ridge consists of load components arising from a consolidated layer, a rubble pile that develops in front of the structure and of the ridge keel. The ridge keel is considered as a layered accumulation of ice rubble, below the consolidated layer. The uppermost layer of the ridge keel can have a high apparent cohesion strength, due to ice blocks or "shear keys" that are partially frozen into the consolidated layer.

A soil mechanical approach is used to simulate the changes in the keel profile when a structure penetrates the ridge. Both vertical and inclined structures can be considered by the present model. Two load limiting mechanisms are considered. The first is known as limit stress load, wherein a failure takes place inside the ridge. The second load limiting mechanism is known as the limit-force load, which may occur if the level ice behind the ice feature fails at a lower force than the actual ice feature considered.

The present lack of knowledge about the internal friction angle of the ridge keel represents a major source of uncertainty in ice load prediction. The computations also showed that the layered structure of the ridge keel may influence the keel load component considerably. The frictional resistance that develops at the rubble/structure contact area causes an increase in the ice load. Assuming that the volume of the ice rubble below the consolidated layer remains constant, the geometry of the keel cross sections appears to have only a minor effect on the maximum value of the keel load component.

Ref:	Title:	Author:	Date:
2.15	Ice Forces on an Isolated Circular Pile	R. Frederking L.W. Gold	1971

Summary:

Relevance to thesis
ice sheet loads, circular pile to ice interaction

Introduction
This article describes the ice force developed on a rigid circular pile by a laterally-moving ice cover. A method is presented for calculating the load for the condition of continuous contact between the ice and half the circumference of the pile. The model takes into account the strain rate dependence of the resistance of ice to deformation, and the effect of temperature.

Deformation Behaviour of Ice
Under certain loading conditions ice behaves in a visco-elastic manner. If it is deformed at a constant rate of strain, it exhibits an upper yield stress. The strain associated with yield depends on the type of ice being deformed and the rate of deformation. If the stress or rate of strain imposed on the ice exceeds a fairly critical value. crack formation is initiated. This cracking activity causes a deterioration of the ice-structure and contributes to the occurrence of yield or failure. For the loads of interest for design, the deterioration of the structure by crack formation would be so extensive at yield that the ice could not be assumed to have the same deformation properties as in the uncracked state. Failure or yield in an unconfined compression test at the rates of strain under consideration occurs by the formation of a fault zone in which there is a marked increase in cracking activity. This zone is approximately parallel to the plane of maximum shear. For strain rates less than that associated with the ductile -to - brittle transition in behavior, the material in the zone remains intact, but the deformation of the specimen is concentrated in this region. At rates of strain greater than that associated with the ductile-to-brittle transition in behavior, the formation of the zone is abrupt and results in catastrophic failure.

It is necessary to establish the relationship between the strain rate in the ice immediately adjacent to the pile and the rate of penetration of the cover. The shape of the load-penetration curve for approximately constant rate of penetration is similar to that of the stress-strain curve from constant strain rate tests. Comparison of the laboratory results with field observations on load and penetration would give the dependence of the strain rate in this area on the rate of penetration. The assumption of elastic behavior should result in a good proportion of the load build-up prior to yield at the rates of penetration of interest for design.

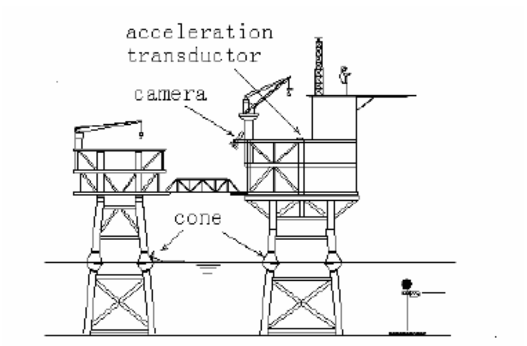
Discussion
It is expected that an ice cover would be in intimate contact with a pile only during the very initial period of its movement relative to it. Once the failure process had been induced, contact between the ice and pile would probably no longer be continuous. It would be expected that stress concentrations would exist at the points of contact from which failure could continue with relative ease. The load resulting from such partial contact conditions would be less than that predicted assuming intimate contact. The normalized load decreases as the pile diameter increases. It might be considered that this is a geometry effect, but it is in reality a strain rate effect. The unit load developed on the pile will not be strongly dependent on rate of penetration and pile diameter in the ductile region.

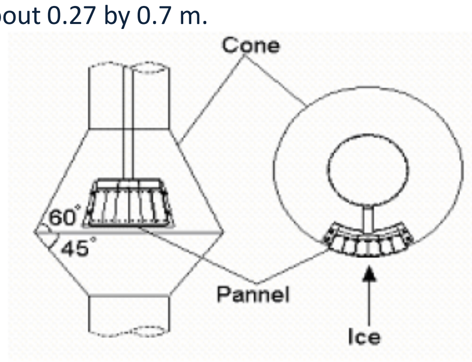
Ref:	Title:	Author:	Date:
2.16	Ice Load Spectrum on Narrow Conical Structures	Y. Qianjin Q. Yan	2006
Summary:			

Relevance to thesis
ice loads spectrum, conical structures

Introduction

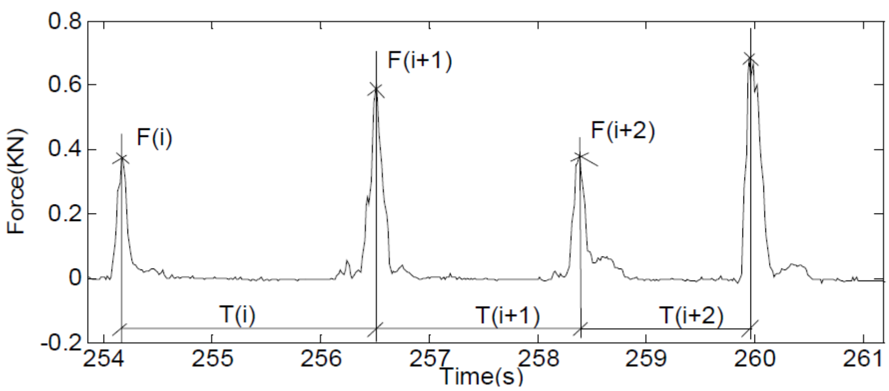
Conical structures are effective to reduce extreme ice force by changing the ice failure mode from crushing to bending. In light of recent dynamic analysis a deterministic ice load function for narrow conical structure was proposed. As known, frequency domain analysis is convenient for the structure under the action of stochastic environmental loads such as gusty wind, sea wave and earthquake, but also for ice loading. In this article, a load spectrum model for ice forces on narrow conical structures is discussed. The results are based on the spectral analysis to ice force time series recorded by load panels installed on JZ20-2 MUQ platform. Ice breaking cones on JZ20-2 MUQ platform (figure 2) are double ward cones. Upward cone angle is 60 degree and downward cone angle is 45 degree. 6 load panels, each covers an area of 8 degree of cone surface, are installed on one of the upward cones. Load area of the panel is about 0.27 by 0.7 m.





Ice failure and Ice forces

Typical feature of the ice failure is broken ice pieces been cleaned up in each circle and those pieces do not pile up before the cone. In the figure below, periods of ice force are defined as T(i), amplitudes are defined as F(i). Determination of the period can be done by using breaking length and velocity of ice.

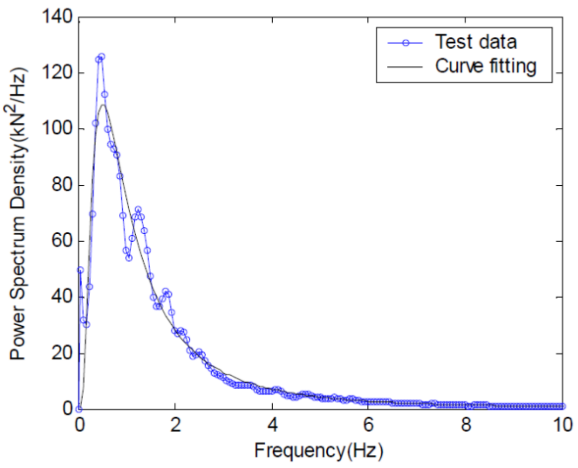


Spectral Analysis of ice forces

Consider the general case where an offshore structure under the impaction of ice sheets, structural response can be estimated by using random vibration theory. The main task of this article is to determine ice force power spectral density of conical structures. To derive power spectral density of ice forces, 54 events from the field test are selected for the analysis. Time durations of those events vary from 3 to 10 minutes. Supposed ice thickness, velocity, strength and water level are constant parameters in this period, ice failure process during this time is stable and thus ice force is a stationary random process. Welch's averaged modified period gram method is adopted to estimate ice forces' power spectral density.

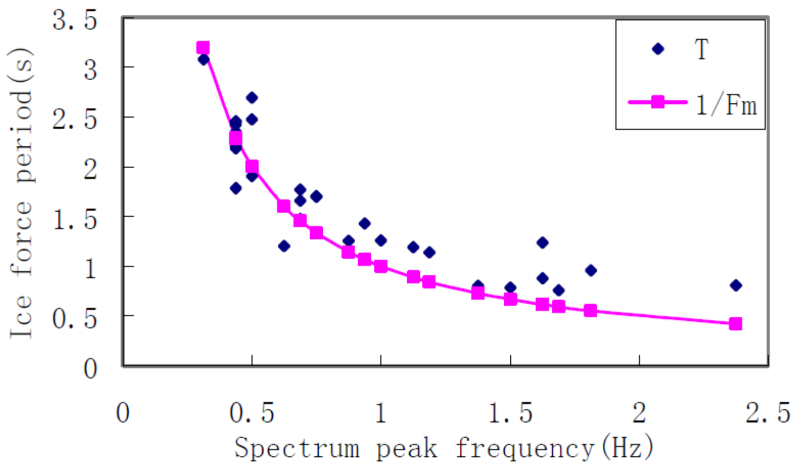
A typical spectral analysis result to ice force is shown in the figure. It can be seen from the figure that the energy of ice force distributed in a frequency range of 0.3 to 3 Hz. The natural frequencies of most jacket leg structures are in this range. Thus those structures are sensitive to dynamic ice forces on the conical structures.

Quite a lot mathematical functions can be used to approximate power spectral density results of ice force. In this article, an expression developed by Neumann which is used to simulate the sea wave spectrum is used.



Parameters of ice load spectrum

To apply ice load spectrum for different structures and ice conditions, parameters of ice load spectrum should be expressed by ice force parameters. Theoretically the relationship between spectrum parameters and ice force parameters could be established by studying the statistical characteristic of ice loads and spectral moments. Higher order spectral moment is difficult to study, thus a simplified method is adopted in this paper to determine load spectrum parameters. The simplified method is based on the study to slope coefficient, peak frequency and 0th spectral moments of the ice load spectrum.



Load Spectral Model with ice force parameters

The load spectral model can be defined as the equation below:

$$S(f) = \frac{9.97\overline{F}_0^{\,2}\overline{T}^{-2.5}}{f^{3.5}} \exp(-5.47\overline{T}^{-0.64}\frac{1}{f^{0.64}})$$

With the parameter Fo defined as:

$$\overline{F}_0 = A_4[A_1\sigma_f h^2 + A_2\rho_w ghD^2]$$

where $g\rho_w$ is the weight density of water, σ_f is bending strength of ice sheet, h is ice thickness, D is the diameter of the cone and A_1, A_2, A_4 are dimensionless coefficients. It should be noted that in this article only breaking ice force is used because the broken ice pieces do not climb up high along the ice breaking cone. T is mean period of the ice force and can be determined by using the breaking length and velocity of the ice sheet:

$$\overline{T} = \frac{L_b}{V} = \frac{kh}{V}$$

where L_b is breaking length of the ice sheet, V is velocity of the ice sheet and k is breaking length-thickness ratio of ice sheet. k = 7 is used as a mean value.

Conclusion

A spectral model was derived based on spectral analysis to ice forces data obtained by load panels installed on JZ20-2 platform. The model can be used in the dynamic analysis of offshore structures with narrow ice breaking cone. It concerns ice failures by bending and the broken ice pieces do not pile up before the ice breaking cone. Relationship between ice force parameters and ice force spectral model parameters was established. Thus the power spectral density of ice forces can be determined by given the parameters of period and amplitude of the ice forces. The ice force period and amplitude can be obtained from related studies.

Ref:	Title:	Author:	Date:
2.17	Stability of Self-Exicted Ice Induced structural vibrations	M. Maattanen	1977

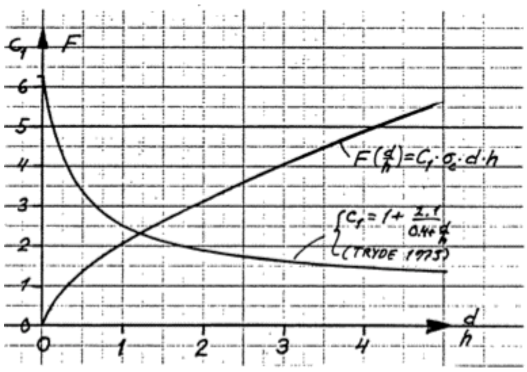
Summary:

Relevance to thesis
ice induced vibrations, ice load dynamics

Introduction

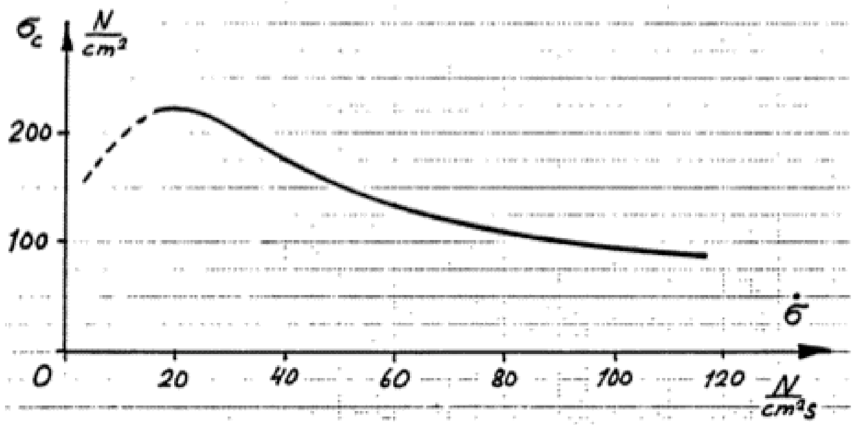
In order to reduce foundation costs of marine structures that have to withstand loads of moving ice fields it is advantageous to minimize ice contact area. In case of single-pile structures the reduction in diameter yields also reduction in ice load, as seen on the figure below, regardless of the increasing "ratio effect" at small diameter to ice thickness ratios. Foundation costs can be dropped 60 to 70% but the structure becomes more flexible and sensitivity to ice-induced self-excited vibrations will increase.

The dynamic ice and structure interaction has been explained to be due to a property of ice. The ice failure oscillations are based on the ice thickness, temperature and loading rate. It is also suspected that it depends on the structures natural frequency, stiffness, mass and damping. A simple formula to interrelate the quantities of ice and structure to yield ice crushing frequency is derived in previous research. The rise of vibrations is explained to be derivable using the theory of self-excited oscillations.



Rise of self-excited vibrations

The physical basis for the rise of self-excited vibrations can be found from the ice crushing strength versus stress or strain rate curve. At the very beginning of a loading cycle the deflection of structure is increasing with the velocity of the ice and the resistance of the structure is increasing almost linearly with time. This will continue linearly until the ice crushing strength is exceeded or un-linearly while deflection rate decreases in relation to the ice velocity causing an increase in strain rate. Then the ice crushing strength is also increasing making even greater ice loads possible and increasing more the strain rate. The process continues until the maximum point in the ice strength curve is achieved after which the crushing will start.



At the point of maximum ice strength the resistance of the structure exceeds the resistance of the ice and the spring back of the deflections starts. This in- creases the strain rate still more, causing now a decrease in the ice crushing strength. The deflection spring back may then continue more easily and faster accelerating thus itself. The deceleration starts when the deflection has become so small that the ice load exceeds the resistance force of the structure even with a great strain rate. The crushing then stops and the next loading cycle may start. Loading cycles will repeat themselves with more or less similarity. The variations of the ice strength are emphasized at the maximum point of the strength yielding to somewhat random frequencies and amplitudes. The descending part of the ice crushing strength curve can be interpreted as a negative damping effect and in case its magnitude exceeds the amount of the internal positive damping of the structure self-excited oscillations will rise.

Parameters affecting the rise of self- excited vibrations are ice thickness, ice velocity, the projectional area of the structure exposed to the ice pressure, structural stiffness, mass and damping distributions. The deflection of structures in this context is supposed to be so great in relations to the elastic deformation of the ice that the latter can be ignored. Depending on the significance of the parameters the deflection spring back of the structure may pass the zero point after which the contact between the ice and the structure may be lost for a short duration before the next loading cycle. With great ice velocities deflections will oscillate usually all the time on the positive side of the zero point.

Results of Stability Calculations

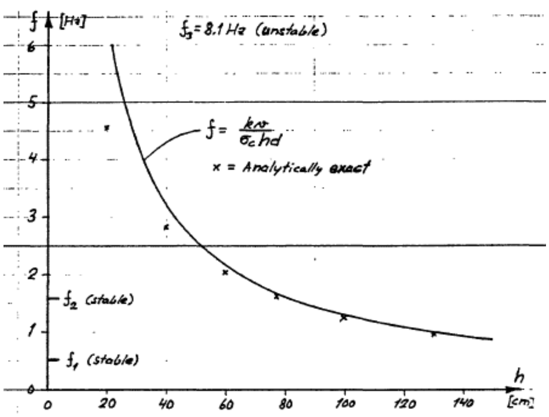
The comparison of stability conditions calculated either solving the roots of the dynamical equations of motion or integrating them numerically gave consistent results. A striking observation after integrating limit cycles in unstable cases was the fact, that quite similar saw tooth deflection and ice force curves were obtained as have been measured in-field. At the beginning and end of crushing section the numerical integration gives out additional force oscillations, partly due to higher harmonics and partly due to temporary loss of contact between the ice and the structure, but the ascending section and all the deflection curve is quite even. As these curves are obtained starting directly from the physical property of ice it is perhaps the best evidence on behalf of autonomous, self-excited vibrations to be the original cause of vibrations in the ice and structure interaction.

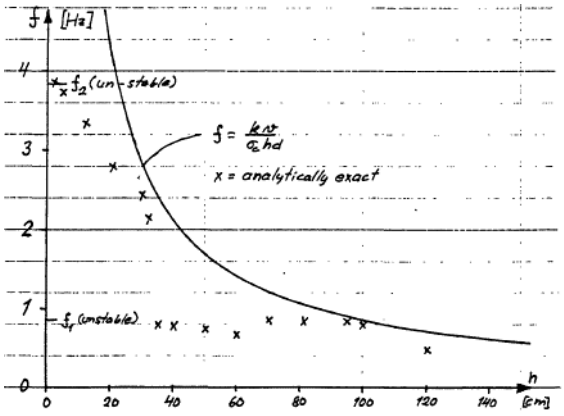
The calculated frequency depends on both the ice properties: thickness, crushing strength and its strain rate derivative, and the structural properties: stiffness, mass and damping distributions, as was assumed to be the case. In case structural inertial effects are small compared to ice forces, the crushing frequency may be calculated using an approximate formula:

$$f = \frac{kv}{\sigma_c hd}$$

Where *'k'* is the spring stiffness of the structure in the direction and action point of ice load, *'v'* ice velocity, *'d'* structure diameter. One exact point coincides with the second natural frequency of that structure in question, but as this mode is stable and its amplitude at the ice action point is very small no divergences occur. Near unstable natural frequencies the equation will not give acceptable results, since the exact frequencies will tend towards the frequency of unstable mode.

The frequency of ice crushing is not dependent on the natural frequency of the structure. Because the equation does not include mass terms there will not be either change in ice crushing frequency in case inertial effects are small and other parameters kept constant. The change of natural frequency by tuning the stiffness would have given different dependence on the natural frequency.





The above figures are valid for 100 cm thick ice. When ice thickness decreases the damping requirement decreases also, linearly. In practice with a 10 cm thick ice the first mode approaches the stability boarder and also in-field it was then observed vibrations only on the second mode. In any case the very high requirements for the stability explain the sensitiveness of steel structures to ice induced oscillations. In concrete the internal damping is greater than in steel but due to more blunt structure hydrodynamic losses are much smaller resulting to modal damping coefficients that are almost the same or only slightly greater than in the steel structure.

<u>Conclusions</u>
The knowledge of the rise of self-excited vibrations gives means to design structures stable or to control vibrations. As possibilities to increase internal damping in fixed structures are rather limited the best way to avoid vibrations is to tune natural modes. The tuning of natural modes is done so that the stability is guaranteed on those modes that will contribute significant amplitudes to the upper structures. This is achieved with suitable mass and stiffness distributions or, of course, making structures very stiff - and expensive. The conventional caisson type structures belong to the latter group. A very promising structure is that which is equipped with a vibration isolation system. Light springs that are supporting the upper structures guarantee very small amplitudes for natural modes at the point of ice action and additionally the suspension system can be equipped with hydraulic shock-absorbers making as high modal damping coefficients possible as required. Calculations show, however, that if for instance rubber elements are used in springs no additional hydraulic shock-absorbers are required.

The self-excited vibrations may of course appear also on other frequencies than natural frequencies, but thence the dynamic response of the structure will not be as severe. As the amount of ice crushing strength vice strain rate data is rather limited there exist uncertainties in the stability calculations. The best way to check the weight of different parameters affecting to the rise of self-excited vibrations would be to conduct a series of laboratory tests.

Ref:	Title:	Author:	Date:
2.18	Ice Load and Structure Vibration when Ice acts on Up-Down Cone	N. Xu Q. Yu	06-2007

Summary:

Relevance to thesis
ice load on conical structure, adding cone to narrow vertical pile, ice dynamics

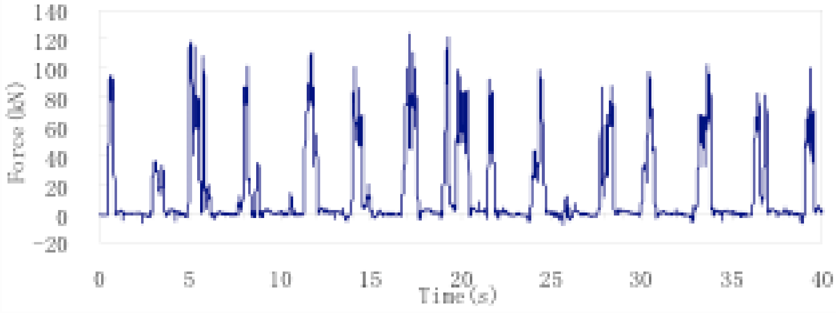
Introduction
The ice forces of ice-structure interaction depend on the failure mode of the ice sheet. When ice interacts with a vertical structure, crushing is the typical failure mode. Similarly, the typical failure mode experienced of ice in collisions with structures with inclined faces is flexural. Since the flexural strength of ice is much lower than its crushing strength, ice forces on structures with inclined faces are lower than those on vertical structures. Due to this fact, the idea of adding an ice-breaking cone onto vertical structures is adopted to reduce the ice load on the structure. The cone should be designed so that the floating ice will act on the inclined face. Also the angle and diameter of the cone should be optimized properly with a small cone angle (small cone angles make flexural failure occur easily, whereas large cone angles increase wave and flow loads). It has been indicated that flexural failure can happen when ice acts on either the up or down portion of a cone. When the tide level is high, ice plates experience upwards flexural failure, whereas during a low tide level the failure direction is downwards.

According to field observations, strong vibration still exists on these structures even after mounting the cone. The most extreme cases of vibration occur when ice acts on the intersection of the up-down cone. Obviously, the ice force on vertical structures is proportional to the leg diameter of the jacket structure, while the maximum diameter of the up-down cone is nearly twice that of the original leg diameter of the cylindrical structure. Once crushing failure occurs, the maximum ice force may even be larger than the force experienced before adding cone. In order to evaluate the effect of adding an ice-breaking cone, the extreme and dynamic ice forces of vertical and conical structures must be compared. This article is dedicated to the failure process when ice acts on different parts of the cone (up, down, up-down), dynamic ice force, and ice-induced vibration.

Ice-induced vibration of vertical structures
Among various failure modes of ice-vertical structure interaction, crushing failure is the most common and most severe phenomenon. The ice crushing failure may cause the largest horizontal force and strongest vibration of the structure. The relative speed between the ice and structure will influence the loading rate of ice sheet and ice failing mode. At a specific range of ice speed, the strong steady state vibration induced by the largest dynamic crushing ice force, causes the most serious disturbance on the field structure. The relative speed between ice and the structure could make ice fail in ductile and brittle while in turn causing the structure to move forward and backward.

Dynamic Ice force on conical structure
The typical ice force variation curve in the figure on the next sheets, was recorded by a load panel and illustrates that the pattern of ice force looks like a series of pulses. In each ice bending failure process of the measured data, the ice crashes regularly act on the upward cone. The faster the ice moves, the more the period of the ice load will approach the natural period of the platform; therefore the displacement of the structure is amplified. According to the observations of the process and the direct measurements of ice loads, the ice load character of the downward cone is similar to the upwards cone. Ice force total unloading happens when ice acts on either inclined surface of the up-down cone. For instance, when the ice begins to contact the cone on the top surface, it will be forced to climb up the cone

and circumferential and radial cracks will occur at almost the same time. While the ice continues to climb the cone, it will break into several wedge-shaped ice slabs and fall down. Because of this, the amplitude of dynamic ice force is the same with the maximum static ice force.

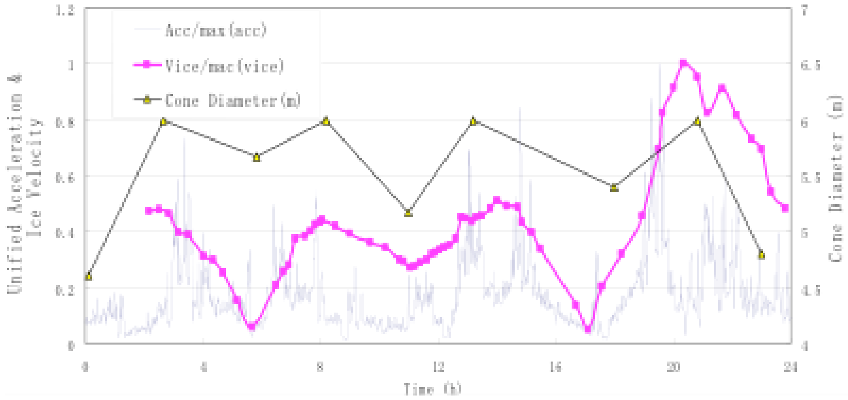


The Failure Process Observation When Ice Acts on the Intersection of Up-Down Cone

Because of the tide ranges, ice sheets will act on the intersection between the up-down cone. The ice force of this condition is considered as a key problem; the ice force might be larger than the force on the original structure or even doubled if the ice failure mode is crushing, since the diameter of the cone is bigger than that of the original vertical pile. Sufficient conditions for crushing failure occur if the vertical surface of the structure is much larger than the thickness of ice sheet. Since the designed up-down cone is a typical corner angle, the thickness of ice is far greater than the height of this angle. Cleavage failure mode could occur but not crushing failure.

Measurement of Ice induced vibrations

According to the analysis of continuous vibration records, it is indicated that the response obviously changes with respect to ice velocity. Varying ice thicknesses will cause most of the response sudden change. The figure below shows the response changing by the position at which the ice acts on the ice-breaking cone.



As can be seen, the abrupt response variations are mainly because of the stochastic ice thickness. The uniform conical ice-induced vibration is varied according to the rule of ice velocity. When the level and uniform ice sheet acts on the up-down cone, the response does not increase abruptly, which means that the ice failure mode is still flexural but not crushing.

Ref:	Title:	Author:	Date:
2.19	Ice Rubble Build-Up on Conical Structures during Ridge Interactions	R.F. McKenna S.E. Bruneau	1997

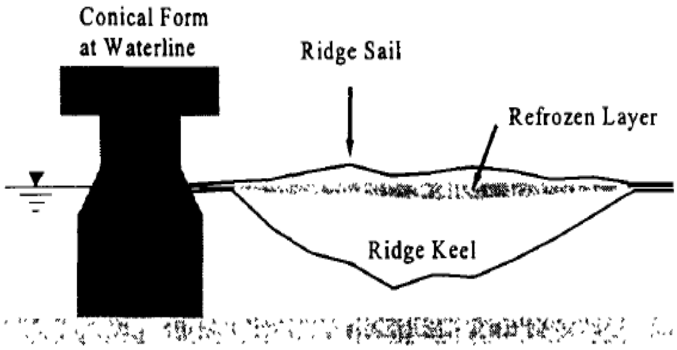
Summary:

Relevance to thesis

ice rubble build up, conical structure, ridge interactions

Introduction

Conical and other sloping forms at the waterline are used to mitigate the large forces associated with ice crushing and to reduce ice-induced vibrations of offshore structures. As the slope of the structure is reduced with respect to the horizontal, level ice loads are reduced but the projected area exposed to ice rubble is increased. This is of considerable concern when such structures are impacted by large first-year ridges and rubble fields.



An upward-breaking conical structure will displace the sail rubble in its path, break the refrozen layer and may displace keel material as well. Because of the slope of the structure, a significant amount of rubble may accumulate on its front face. This article considers the accumulation of ice above the base of the cone and the resulting forces exerted on the structure.

Estimates of Rubble Build-Up for steady state conditions

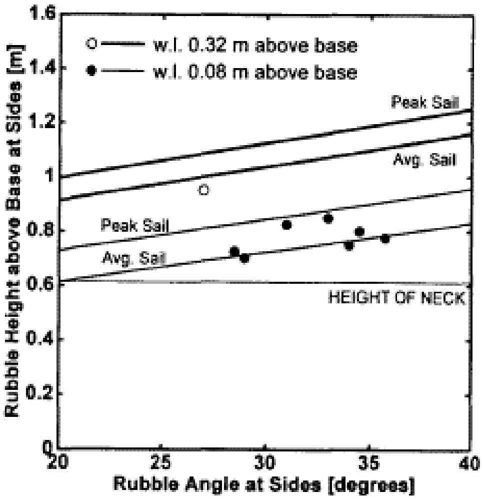
As a first-year ridge moves past a conical structure, rubble builds up slowly on the cone and is shed when the ridge has passed. For a very wide ridge, the ice tends to reach a stable height which is maintained for some distance. In this case, the rubble passing the sides of the cone must be the same as that displaced by the structure. Consider the incoming rubble with height ‘Hr’ above the base of the cone. This is displaced to the sides of the structure, forming an angle ‘e’ with the horizontal and raising to a height ‘He’. As long as the speed of the rubble passing the sides is the same as the incoming rubble, the area of the rubble cleared on the sides is equal to the projected area of the incoming rubble onto the cone:

$$H_R\left(D_B - \frac{H_R}{\tan\alpha}\right) = \frac{(H_C - H_R)^2}{\tan\theta} - \frac{(H_N - H_R)^2}{\tan\alpha}$$

It is expected that the level of the incoming ice should be at least the average sail height (ridge cross-section area above cone base / ridge width) and not more than the peak sail height. The rubble height HR was estimated for each of these cases by calculating average values for the larger ridges (W = 3.5 m and 4.0 m). Very steep structures would not tend to lift as much rubble onto the conical face. As well, it should be noted that the refrozen layer in the present experiments was thin and was not a significant factor in the rubble accumulations.

Conclusions

Ice tank experiments were conducted to address the interaction between fixed upward-breaking conical structures and first-year ice ridges. Fifteen scale model tests were conducted on six ice ridges with depths ranging from 0.6 m to 1.2 m, to address the forces and mechanisms of first-year ridge failure against a 45° upward-breaking conical structure. The experiments are unique since they address the behavior of first-year ridges modeled in a realistic manner and at a large scale. Horizontal and vertical loads were measured on the upward-breaking conical structure which had a neck diameter of 0.6 m, a slope of 45° and a base diameter of 1.8 m. Clearing forces on the cone were isolated by subtraction of the cyclical breaking forces for the refrozen layer. Extensive measurements were made of the properties of the blocks forming the ridge and of the shear strength of the rubble in situ. The parameters addressed in the test program were ridge size, water level and structure speed. The clearing forces on the conical portion of the structure were found to depend on ridge size and water level, and scaling relations were obtained to describe them. Observations were made of the rubble buildup around the structure and these can be predicted using a steady-state model of the process.



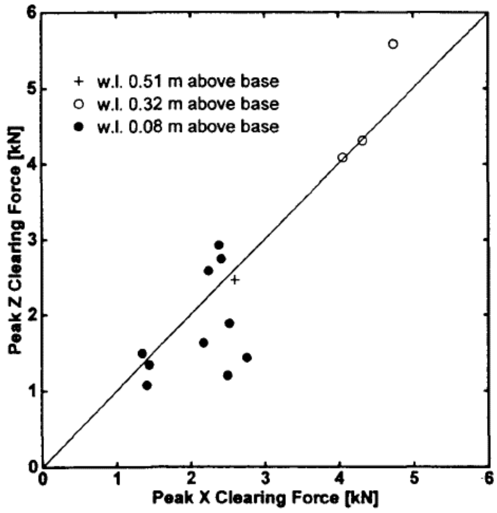


TABLE 3	Forces on cone including interpreted clearing and breaking forces						
Ice Sheet	Run	Mean X Breaking Force [N]	Mean Z Breaking Force [N]	Peak X Clearing Force [N]	Peak Z Clearing Force [N]	Peak X Total Force [N]	Peak Z Total Force [N]
4	1	964	770	4326	4310	5290	5080
4	2	1016	730	2764	1430	3780	2160
5	1	769	581	2421	2739	3190	3320
5	2	759	457	2531	1883	3290	2340
6	2	0	0	2600	2460	2600	2460
7	1	661	515	2179	1625	2840	2140
7	2	725	483	2505	1197	3230	1680
7	3	494	375	1416	1075	1910	1450
7	4	561	431	1449	1339	2010	1770
8	1	562	353	2248	2577	2810	2930
8	2	1227	694	4063	4086	5290*	4780
8	3	692	555	-	2585	-	3140
8	4	654	508	1356	1492	2010*	2000
10	1	1294	986	4736	5584	6030	6570
10	2	722	589	2388	2921	3110	3510

*estimated values based on test 4, run 1 and test 7, run 4 for similar conditions

Ref:	Title:	Author:	Date:
2.20	Ice ridges interaction with Confederation Bridge piers	M.O. ElSeify T.G. Brown	2006

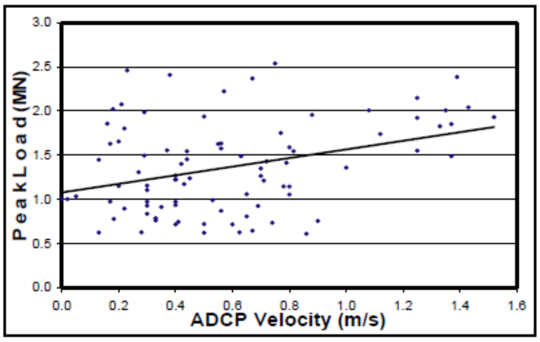
Summary:

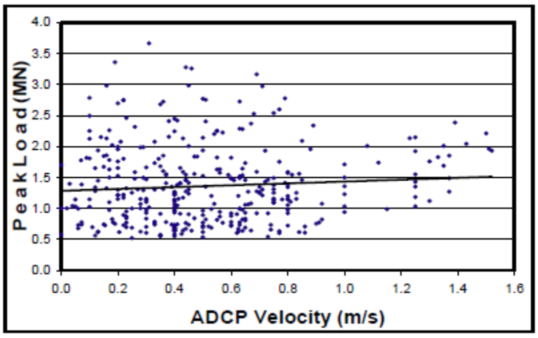
Relevance to thesis
Ice ridges; keel, geometric properties, velocity influence

Introduction
Sea ice is composed of a wide variety of different forms of ice features. Further from shore, strong wind conditions and ocean currents often force ice floes to collide creating rafted ice, ice pressure ridges, hummocked ice and ice shear ridges. Due to their size, first year ice ridges represent one of the most hazardous threats to shipping, navigation, pipelines and offshore structures. Therefore, offshore structures must be designed to withstand the loads resulting from the interaction with first year ice ridges.

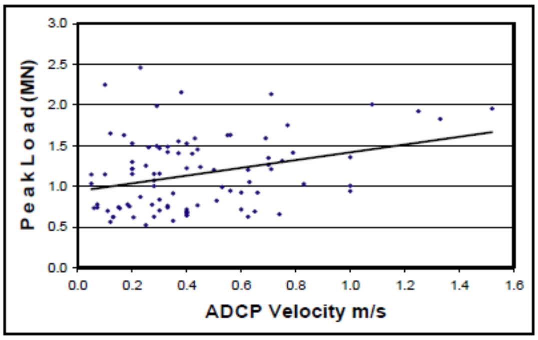
First year ridges are generally formed of three parts: sail, keel and consolidated layer. The most important geometric properties of first year ice ridges are: the keel depth, keel width and the consolidated layer thickness. One of the important parameters that has been neglected by most of the first year ice ridge load models is the ridge velocity. Four parameters were selected to study their direct influence on the ice ridge load value, namely: ice ridge velocity, keel depth, keel consolidated layer thickness, and keel width. This article describes a detailed probabilistic study based on the data given by the Confederation Bridge Monitoring System. The aim of this article is to present the results of the statistical study that has been done based on the results of the Confederation Bridge Monitoring Program. It concentrates on the part related to the influence of the geometric properties of the keel and the consolidated layer on the load resulting from the interaction of first year ice ridges with offshore structures. This article introduces the influence of the ridge velocity on the load magnitude plus its relation with the ridge geometric properties.

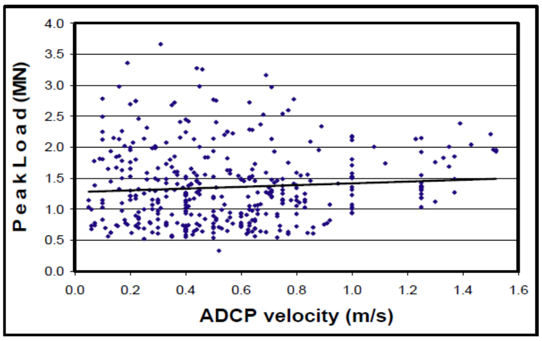
Ridge Velocity vs Load
The ice ridge velocity is one of the parameters that may affect the load resulting from the interaction of first year ice ridges with offshore structures. The four figures below present the concept that when the ridge velocity increases, the load increases as higher velocities will result in higher inertial load. The load has been related to the ridge velocity for different sizes of the ridge keel depth (H_k):





Similarly, the relation between the velocity and the load is studied for varying keel width ranges:

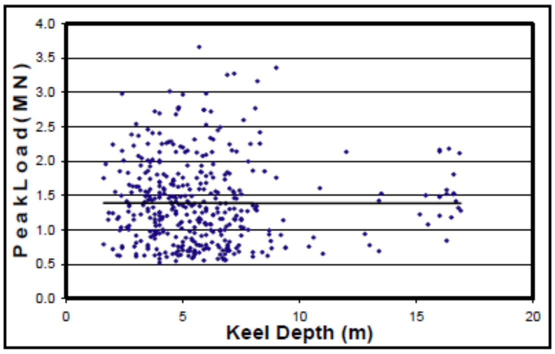




The size of the ridge plays an important role on determining the level of the influence of the ridge velocity on the load. Decreasing the size of the ridge increased the influence of the ridge velocity on the load magnitude. This may be attributed to the fact that in order to have a large load, high kinetic energy must be exerted. In order to exert high amount of kinetic energy, either the mass or the velocity of the ridge has to be high.

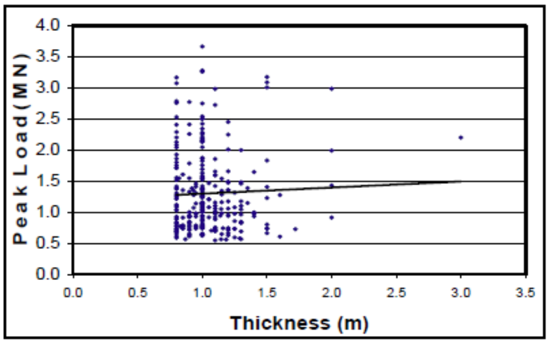
<u>Keel Depth vs Load</u>

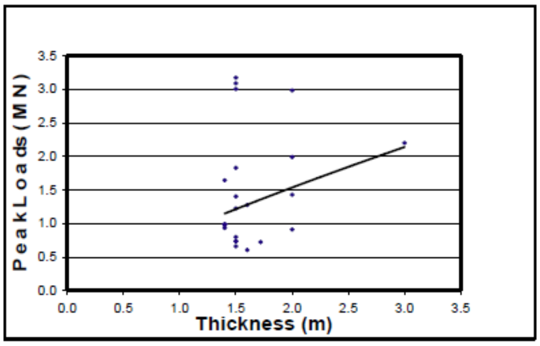
In all failure models the keel depth is the most important geometric parameter aside from the physical strength of the rubble. All models assume a full contact with the structure over the entire depth of the keel with pressure either constant or varying with depth. Global failure models are also dependent on the keel as the failure plane must exit the far side of the keel. The keel has no visible trend on load.



<u>Consolidated Layer Thickness vs Load</u>

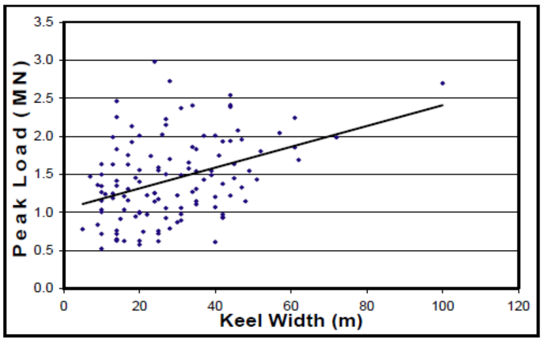
The consolidated layer thickness effects are not yet included in the keel failure models but added separately as a flexural failure or a crushing failure. It is stated that the keel and the consolidated layer must be treated as a system functioning together and failing together. It can be noticed from the following figures that increasing the consolidated layer thickness range increases the influence on the load value. The thicker the consolidated layer means the thicker the level ice that formed the ridge. This way the consolidated layer is much more solid because the longer the level ice lives, the more consolidated is the consolidated layer formed from this level ice. Once the consolidated layer is much more consolidated, this increases the load.

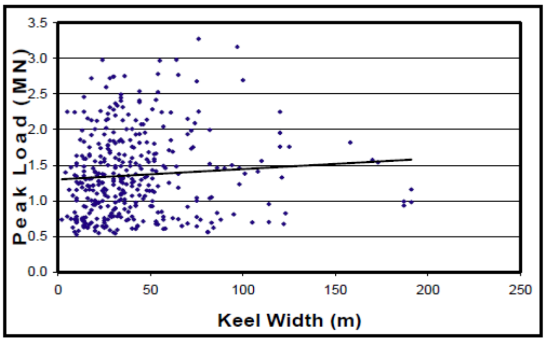




<u>Keel Width vs Load</u>

Keel width has been neglected in most of the proposed load models. The figures below make it clear that when the keel width increases, the load increases as larger keel widths will result in higher inertial load on the cone. This may be attributed to the fact that in order to have a large load, high kinetic energy must be exerted. In order to exert high amount of kinetic energy, either the mass or the velocity of the ridge has to be high. Increasing the keel width increases the mass of the ridge and consequently increases the impact load of the ridge. Decreasing the consolidated layer thickness, the keel width influence on the load magnitude increases.





<u>Conclusion</u>

This article showed that the ridge velocity is a parameter that cannot be neglected while developing a new first year ice ridge load model. The reason for this is that the ridge velocity showed a good correlation with the recorded loads. Similarly, the keel width and the consolidated layer thickness showed good correlation with the recorded loads. On the other hand, the keel depth which was the most important parameter in the proposed models, showed no correlation with the recorded loads. This implies that future research has to put in mind that the ridge velocity, keel width and the consolidated layer thickness are important parameters that must be given priority while proposing new ridge load models. Also they will have to review the influence of the keel depth on the load magnitude while proposing new first year ice ridge load models interacting with conical offshore structures.

Ref:	Title:	Author:	Date:
2.21	Global Ice Loads on Lighthouse in Gulf of Bothnia	M. Bjerkas S. Løset	2003

Summary:

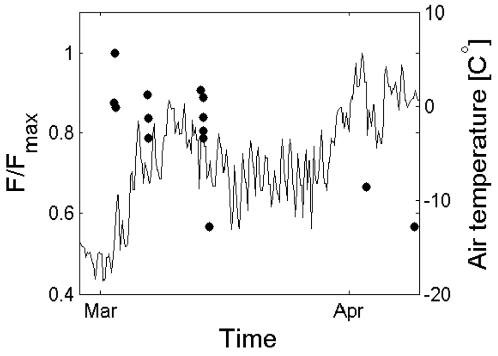
Relevance to thesis
drift ice loads, Gulf of Bothnia, level ice thickness, global ice loads

Introduction
Coastal structures in northern and central European waters as well as offshore structures in the European Arctic have to be designed to withstand the loads caused by moving ice. Ice loads govern the design in most cases where ice is present. The largest ice loads are caused by pressure ridges and by level and rafted ice on vertical structures. Several full-scale measurements have shown that the ice loads on vertical structures are lower than what are recommended practice in several common ice codes. From this scenario this article shows a way to calculate the global ice load on a lighthouse structure in the Gulf of Bothnia from the loads measured by measurement panels.

During measurement 136 ice-structure interaction events were recorded. From these 136 events, the highest global peak values of registered load were selected and corrected to the ice drift direction. The highest registered peak values were caused by failure of pressure ridges. A selection of the events shown in the table with corresponding ice thickness h, air temperature Ta, drift speed v, drift direction μ, ice feature and failure mode. Loads are divided by value of Fmax.

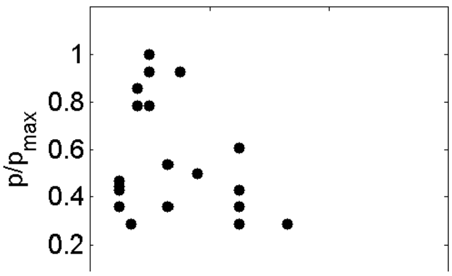
Date	Time	h [m]	v [m/s]	T_{air} [°C]	θ [from N]	F/F_{max}	Ice feature	Failure mode
01.03.01	17:28	0.44	0.25	-16.2	45	0.47	Level ice	Crushing
02.03.01	18:11	4.17	0.25	-11.8	68	1.00	Ridge field	Crushing
02.03.01	11:57	0.39	0.25	-11.8	68	0.60	Level ice	Crushing
06.03.01	20:54	0.60	0.15	-7.0	22	0.90	Ridge field	Crushing
06.03.01	16:30	0.23	0.10	-7.0	22	0.47	Level ice	Crushing
13.03.01	13:24	1.81	0.05	-4.6	0	0.91	Ridge field	Crushing
14.03.01	14:43	1.82	0.20	-7.2	45	0.57	Ridge field	Bending
03.04.01	03:20	1.07	0.10	2.6	0	0.67	Ridge field	Bending
09.04.01	06:31	0.60	0.10	0.8	90	0.50	Ridge field	Mixed

Occurrence of global peak loads
In arctic regions the highest ice loads on structures are assumed to be caused by crushing failure of the consolidated layer in pressure ridges. A pressure ridge is composed of three different parts, sail, keel and consolidated layer. The main part of the ice loads from pressure ridges are from failure of the consolidated layer. The crushing strength of the consolidated layer is assumed lower than the strength of the adjacent level ice. Pressure distribution around the perimeter of the structure are not the same for ridges as for level ice. From visual observations of the failure of pressure ridges at the lighthouse, we know that the ridges are able to ground and touch the foundation. This grounding will cause a rubble pile-up in the front towards the drift direction and level ice in front of that can fail instead of the consolidated layer of the ridge. The measured loads from level ice crushing are lower in magnitude, but the local pressure is as a rule higher for level ice than for ridges. One of the reasons for that is the porosity of the consolidated layer from first year sea ice.

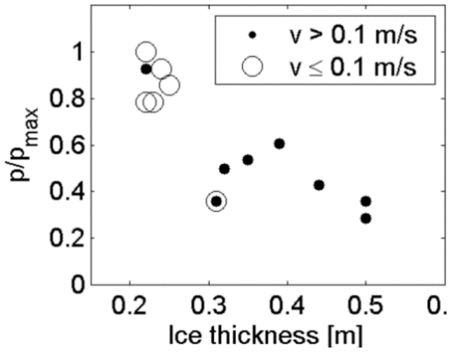


<u>Global load versus air temperature</u>
Peak values of calculated global ice loads versus time, and the air temperature versus time are shown in the figure. All these values are loads from pressure ridges. The drift speed for these events is ranging from 0.10 m/s to 0.25 m/s. Thickness of the ridges (keel to sail) ranged from 0.5 m to 3 m.

<u>Effective pressure versus drift speed</u>
Global effective pressure is calculated as *P=Fglobal = Dh* for the events with level ice. No effective pressure is calculated for the loads from pressure ridges. Thus *Pmax* is the maximal value of the effective pressure from level ice crushing. The figure shows the influence of drift speed on the effective pressure from crushing level ice. The corresponding ice drift speeds from the 17 peak loads with level ice show values from 0.07 m/s to 0.33 m/s. Air temperature when these events were recorded ranged from -8°C to -15°C, and the ice thickness ranged from 0.18 to 0.5 m during these events.



<u>Effective pressure versus ice thickness</u>
The ice thickness for ridges is taken as the total distance from the keel to the sail, and there is no possibilities to distinguish between rubble and consolidated layer. Measurements contain both level ice and ridges, and it is easy to distinguish between level ice and ridges from the ice thickness measurements. As shown on the figure, the highest valuesof effective pressure is caused by low drift speed.



<u>Conclusions</u>
A method to calculate the global ice load on a cylindrical structure with load measuring panels is discussed and used on data from full-scale measurements. The method uses a mirror technique and the symmetrical conditions of the circular structure. All these peak loads are caused by failure of pressure ridges. The following trends are found:

- The global ice load shows a decreasing tendency when the air temperature increases.
- Calculated effective pressure from crushing of level ice shows a decreasing tendency when the drift speed increases in the range of 0:05 m/s to 0:33 m/s.
- With increasing ice thickness, the effective pressure seems to decrease, however high values of effective pressure appear at low drift speeds.

APPENDIX C – SUMMARY OF ARTICLES RELATED TO OFFSHORE ARCTIC ENGINEERING

Ref:	Title:	Author:	Date:
3.01	Cost Effect of Ice Loads on Offshore Wind Generator Foundation	M. Määttänen	06-2001

Summary:

Relevance to thesis
offshore arctic wind support structure, cost effects of ice loading, ice design loads

Introduction
Along the Finnish Baltic coast prevailing Southwestern winds have average annual speed between 6–8 m/s. There is practically no tide in the Baltic but the ice is frequently moving driven by the winds at open seas. All first year ice features are present and will exert both heavy static and dynamic loads on any offshore structures. The additional cost of foundation to resist ice forces has discouraged to develop offshore wind farms. The present trend to increase the wind generator size is increasing both wind and inertia related loads. Same time the hub has to be raised higher due to the increasing propeller diameter. The results are foundations moments increasing a bit faster than wind generator size. This makes the wind-induced loads decisive in foundation design and cost. Due to shallow water depth the wind energy potential is so large that the whole Finnish annual electricity consumption could be easily harvested at offshore parks. In this article a review on ice load scenarios and ice loads on a typical offshore wind generator foundation are presented. The chosen ice conditions present a severe combination of level ice, rafted ice, and first year pressure ridge loads. A cost comparison is made on ice load effects on caisson and single pile foundations. Different water depth and ice load scenarios are compared to find out the cost effect and the potential of different foundation types.

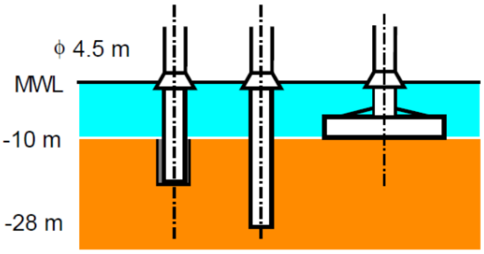
Ice and Environment
The thickness of moving ice depends on the distance from the shoreline. Close to shoreline even thin ice can stabilize. Thicker moving ice has greater probability further offshore. Everywhere in the moving ice zone first year pressure ridges will be encountered. Ridge keels can be over 20 m deep. At shallow locations moving ridge keels are scraping the sea bottom or grounding. Design ice conditions were assessed, and shown below.

Moving level ice 0.70 m Moving rafted ice 1.20 m Ridge keel depth 12.0 m
High water, H.W.L +0.8 m Low water, L.W.L -0.5 m

At location the ice is always moving with winds. Moving pressure ridges are common and they often ground on shallow reefs. The sea depth varies from less than 10 m up to 30 m. There is no tidal water level change. Storm and wind surges will either raise or lower the water level. With thick ice cover the water level changes are less than at open water. Wind driven water circulation causes slow water flow but not enough to enhance ice movement. Wave induced bottom erosion is a concern for caisson type foundations.

Foundation Type

Moving level ice is likely to cause severe vibrations while crushing against a vertical bottom-founded structure. Full-scale measurements have indicated ice crushing failure frequencies from 0.3 to 8 Hz. This is critical range for wind generators. A conical section at the waterline reduces global ice loads and reduces ice-induced vibrations due to ice bending failure. Wind driven ice movement velocity in the Baltic can never be so high that a resonant bending failure excitation could occur. Thus a conical section at the waterline is a desirable structural shape. The sea bottom at Pori offshore is mostly a 5 - 20 thick moraine layer on top of the rock but at some locations there is also bare rock. This suggests that most likely foundation choices are caisson, a single pile in a rock pit, or a pile driven down into moraine. The major design considerations are foundations moment capacity and lateral resistance. With the driven pile the moment capacity is decisive.



The design parameters that have direct effect on foundation cost are for a driven pile: diameter, wall thickness, and driving depth, and for caisson: diameter and mass. All these parameters are determined based on total loads and water depth.

Wind Loads

Wind induced loads are coming from the propeller and generator. Most severe loadings results from wind gusts, rotor unbalance and assumed generator short-circuiting. Wind speed at 60-80 m height is assumed constant. Drag load needed for energy production is then directly proportional to the unit size. The estimated foundation design moment at waterline is 60 MNm for a 3 MW wind generator.

Ice Loads

Ice failure against a cone includes first ice edge contact with local crushing to make even such a large contact area that allows in a later phase high enough loads to cause radial cracking and ice edge failures, either by bending or shearing. Local crushing as well as ice edge failures are not normally occurring simultaneously along the whole contact perimeter but more or less randomly. The last phase includes clearing mechanisms, raising and pushing aside broken floes and rubble. Friction both in ice failure and clearing phase plays an important role. In the case of a first year pressure ridge there is additional rubble to be cleared and a consolidated layer inside the ridge including the parent ice sheet.

An cone ice load model is used to determine the ice loads. A 60° cone with 5.5 m diameter at waterline will cause 1.4 MN horizontal ice load while 0.70 m thick ice is breaking. Respectively a 1.2 m thick consolidated layer or rafted ice will yield 2.7 MN horizontal ice load. With such thick ice, shear failure may occur at same or even lower ice load level. The reduction of ice loads using cone is significant. Without cone the level ice design load would be 7.6 MN and about 10 MN for the rafted ice. These crushing loads would also bring with severe dynamic interactions. Uncertainties in pressure ridge load are much higher than in cone level ice load. It has been shown that the pressure ridge load is about 2.5 times the parent ices sheet crushing load. In the case of a cone this would end up from 3 to 7 times the cone ice horizontal load.

The following method can be used to predict first year pressure ridge load:

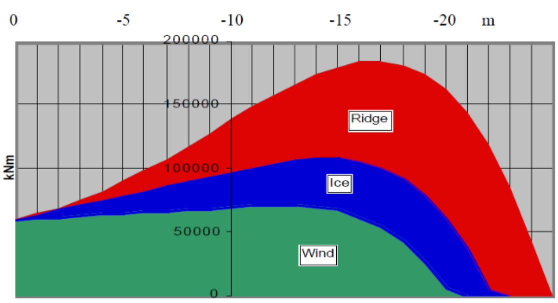
$$\begin{cases} F_p = \mu H_e D(\tfrac{1}{2}\mu H_e \gamma_i + 2c)(1 + \dfrac{2H}{3D}) \\ \mu = \tan(\dfrac{\pi}{4} + \dfrac{\phi}{2}) \\ H < H_e < H + \dfrac{D}{2} \end{cases}$$

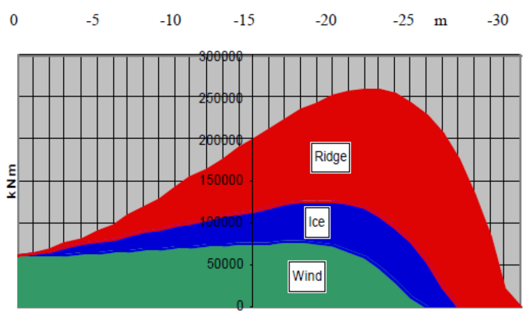
where H is keel depth and He is the design depth, D structure width, c and are ice rubble cohesion and internal friction, and □i is ice buoyancy body force. The following data is now used:
H=He=10 to 12m, D=5 m, □□i =510 N/m3, □= 25, and c = 12 kPa. The resulting ridge load is 6.1 up to 8.1 MN.

Other ice load scenarios are uplift loads, thermal ice expansion loads, ad-freeze loads, and dynamic loads. Compared to rafted ice breaking and pressure ridge loads the first three are no design concern now. No resonant dynamic loads are expected with the conical section at the waterline. Single level ice failures will cause a transient relaxation type vibration. As rubble pile-up is normally present even more damping can be expected to further reduce dynamic response. If pressure ridge is moving one has to add also simultaneous parent ice sheet failure load to get the maximum load. The level ice loads together with the pressure ridge present the maximum design load that determines the foundation cost. Now the total ice load is 10.8 MN for 1.2 m rafted ice in conjunction with 12m pressure ridge.

Foundation Cost

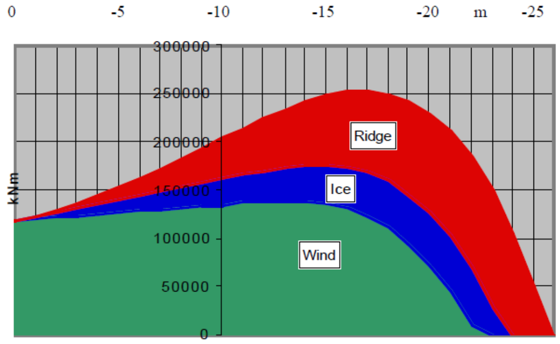
The final foundation cost depends on foundation type, manufacturing and installation techniques, economic conjunctures etc. Manufacturing and installation costs are supposed to be directly proportional to the amount of steel in the pile, or on the weight of the caisson. The underwater cost of the steel pile is directly proportional to pile wall thickness that is determined from the bending moment distribution. In the case of caisson the pile moment reduces fast inside the caisson. The required mass of the caisson and its diameter are determined from the overturning moment and total horizontal load at the sea bottom.
The cost comparison is made for a pile driven into sea bottom. The bending moment distributions are presented in the figures below. The horizontal axis presents depth, vertical axis the moment.





The moment area above the wind only moment is directly proportional to the additional cost. It can clearly be seen that the presence of moving pressure ridges is a significant extra cost factor for the foundation pile. With only moving level ice the extra cost is minor. Increasing pile diameter can further reduce foundation pile cost.

For projected 5 MW wind generators the effect of ice loads is further diminishing, as can be seen in the figure. It is assumed a 119 MNm moment at waterline and 5.0 m pile diameter. The 1.2m thick rafted ice load increases moment curve area only 27 %, and with simultaneous pressure ridge load the increase is only 82 %. Thus even driven pile foundation is becoming cost effective with increasing wind generator size.



In the case of caisson foundation the foundation pile cost increase is a minor factor due to shorter exposed underwater steel pile. The increase in the exposed foundation pile moment area is minor; the moment area due to wind is decisive. If the caisson shape is kept constant, the caisson mass related to that of wind only loads has to be increased to power 0.75. If only caisson diameter is increased the mass and cost increase are to power 2/3 that would further decrease the overall cost.

The foundation cost increase has to be based on the overall cost of the wind generator, and on better productivity at offshore location than in inland. Measurements have indicated that an offshore wind generator will produce about 15 % more wind energy per annum than an onshore generator. For 2 MW wind generator wind energy park the offshore foundation cost was 16.8 % of the total. Hence about 90 % foundation cost increase at ice infested offshore site is already compensated directly by the better productivity. In long run the better productivity is a continuous bonus. Thus at 10 m water depth driven pile is still cost effective and a caisson foundation even in deeper water. This result justifies developing wind energy farms also at offshore locations where ice conditions can be severe.

Conclusions

The trend of increasing wind generator unit size is bringing with the wind-induced loads to foundation to the same level as ice loads in the Northern Baltic. In the future the wind effect will be the dominating foundation design factor. Vast areas of shallow offshore sites are available for wind energy harvesting in ice-infested waters. Outside land fast ice zone wind is making all the first year ice features to move, including level ice, rafted ice and pressure ridges. A conical section at waterline is effective in reducing both ice loads and dynamic effects. Additional cost for a driven pile and caisson foundation is estimated. The cost increase is a related to additional moment due to ice loads in foundation on top of the wind-induced moment distribution. The comparisons at different water depths indicate that level ice has a minor effect, rafted ice significant factor, and simultaneous pressure ridge more than doubles the driven pile foundation cost. The increase is significantly less with a caisson foundation. As the foundation cost is well below 20 % of the wind generator total cost, and while the offshore wind energy production is about 15 % better than inland, the offshore wind energy farms with 3 to 5 MW generators are becoming economically feasible also at areas where pressure ridges are moving.

Ref:	Title:	Author:	Date:
3.02	When Will Ice Ride-Up or Pile-Up Occur	G. Li K.W. Brown	06-2009

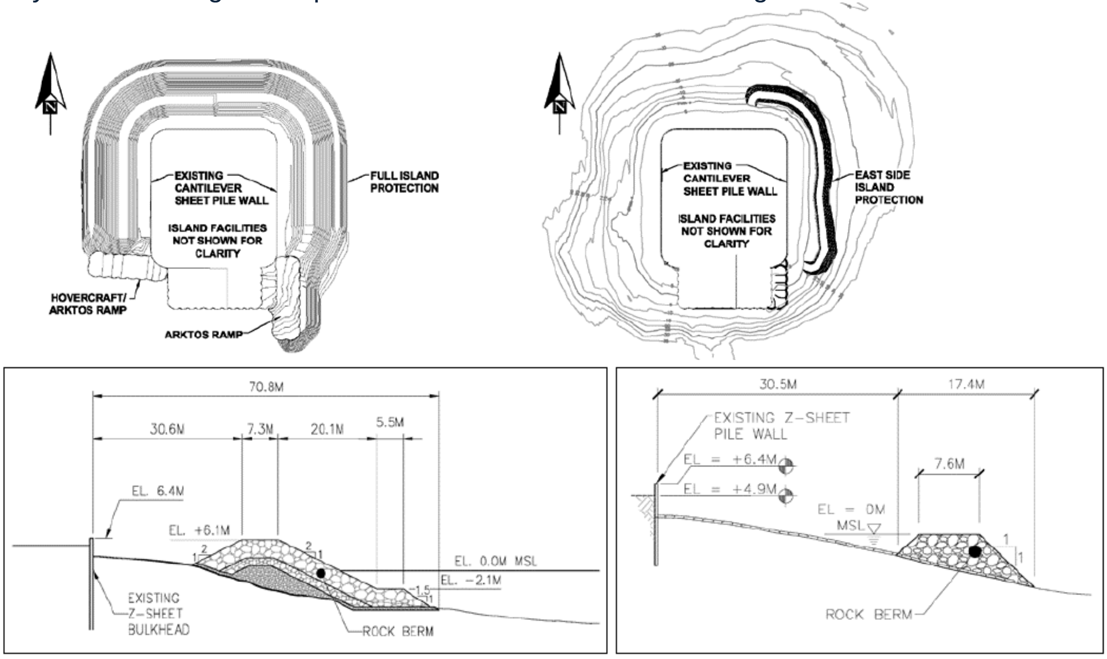
Summary:

<u>*Relevance to thesis*</u>
ice pile up, inclined surfaces, ice rubble

<u>Introduction</u>
Ice sheet movement onto a beach can result in either ice ride-up or pile-up. Ice ride-up occurs when the ice sheet continues to advance upon land while remaining a relatively level sheet of ice. Ice pile-up occurs when the ice sheet breaks into pieces and builds upward into a pile of rubble. Ride-up can encroach upon land a far greater distance than pile-up and, therefore, may pose much more severe threats to man-made structures.

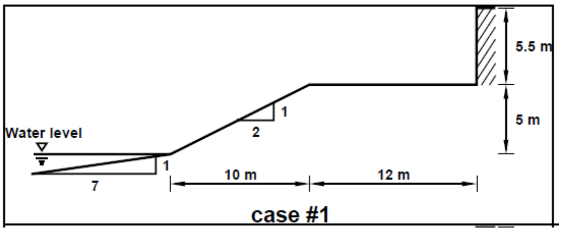
Prediction of ride-up or pile-up under various scenarios is not always possible. Thickness of the ice sheet, elastic modulus and structure geometry at or near waterline has a large influence on the behavior. Physical model test results demonstrated thicker ice tends to produce ice ride-up, while thinner ice rubbles and favors pile-up. In addition, the elasticity of ice appears to have an influence whereby lower elastic moduli tend to promote ice ride-up. Numerical analyses also reveal the influence of variables on ice behavior.

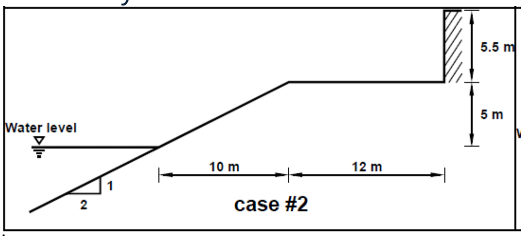
<u>Physical modeling</u>
Physical modeling of two protective barriers is shown in the figure below:



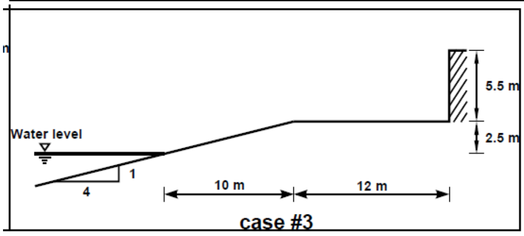
The physical modeling provided some insight into how ice thickness and shoreline configuration affect ice encroachment. Each barrier was impacted with multiple thicknesses of model ice from various directions. In all these cases the ice tended to ride approximately half way up the front face of the rock berm with ice sheet fracture, taking place through both buckling and bending behavior, occurring seaward of the berm. Subsequent ice then built rubble through a combination of buckling and bending failures in front of and on top of the original ice sheet. Rubble generation typically progressed seaward. For the case of western ice approach, ice initially rubbled in front of the berm but was eventually able to form a ramp that allowed ice to ride over the berm. Thicker ice rode over the berm and impacted the landside slope of the berm before exhibiting rubbling behavior. Ice overrode the berms immediately on all of the thickest level ice runs. The ice broke near the landside berm slope and began riding over itself, advancing towards and onto the island.

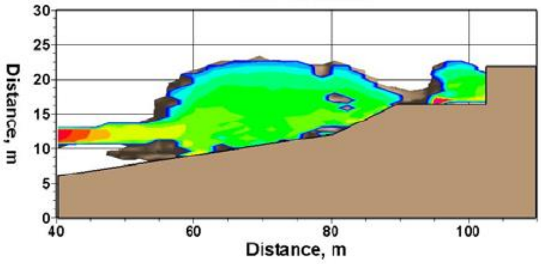
<u>Numerical modeling</u>
ice ride-up and pile-up was examined considering differing ice thicknesses, ice\shore friction properties, ice bending strengths and shore slopes. In all, three shore slopes were evaluated as shown below. Although ice velocity does affect the rubble outcome all cases were evaluated using 0.25 m/s as the incoming ice velocity.

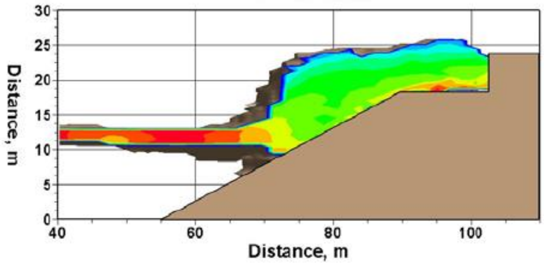




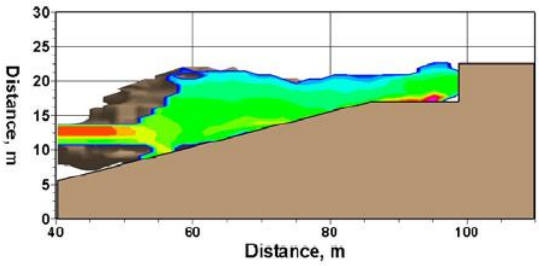
Though none of the shore slopes evaluated were able to keep the ice from encroaching all the way to the 5.5 m high wall, cases #1 and #3 were able to keep a larger portion of the pile-up away from the wall as opposed to case #2. Case #2 showed large areas of pile up extending from the wall all the way back to the waterline.







The bending strength was varied, and for low bending strength the ice was still able to encroach all the way to the wall and produce a very similar pile-up to the stronger ice. However, encroachment was slowed with the weaker ice indicating that a more extreme event would be required to produce the similar pile-up. Ice/shore friction angles were varied from the 1.5 in case #1 to 0.8 and to a nearly infinite value (no-slip). At 0.8, the ice reached the wall quicker than in the higher friction run, but ultimately produced a very similar pile-up. As a sensitivity run the friction was also increased to a no-slip condition. This run showed a pile-up that stabilized well in front of the wall and increased seaward.



Ref:	Title:	Author:	Date:
3.03	The effect of Structure Shape on the Broken Ice Zone Surrounding Offshore Structures	A. Barker G. Timco	06-2003

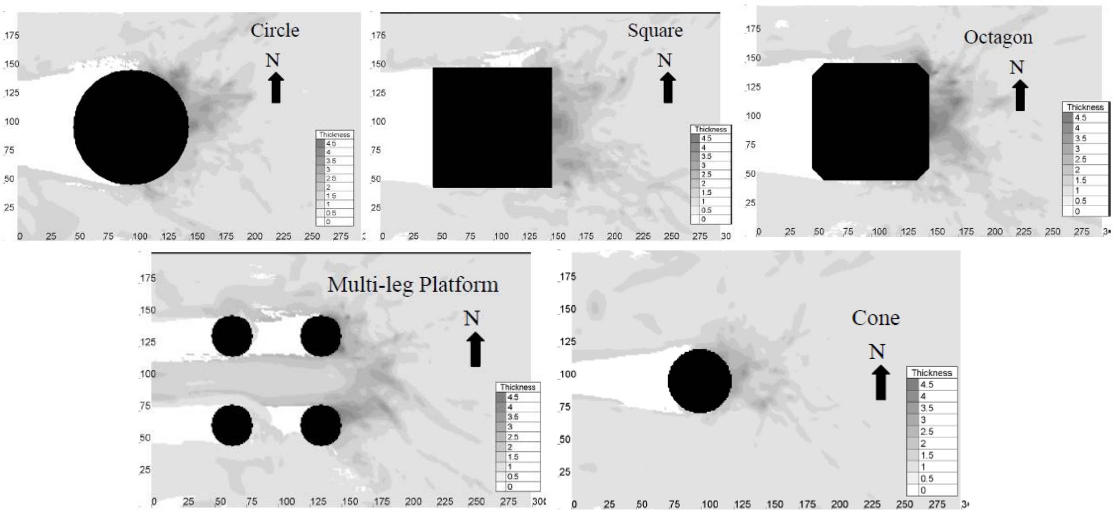
Summary:

<u>Relevance to thesis</u>
structure shapes, ice load modeling, shape factor on ice load

<u>Introduction</u>
Safe evacuation of personnel from offshore structures is of paramount importance in the event of a problem on the structure. For a number of offshore regions, the waters surrounding the structure may be ice covered for part of the year. This can create unique problems with respect to emergency evacuation from a structure. One of the key areas of concern relates to lowering a survival craft into the region of broken and dynamic ice surrounding the structure. The size of this zone was a function of the ice thickness and the morphology of the ice. In this article, the influence on the shape of the offshore structure is investigated to determine its influence on the size and shape of the damage zone. A numerical model has been applied to a realistic situation of different types of offshore structures in a moving ice cover.

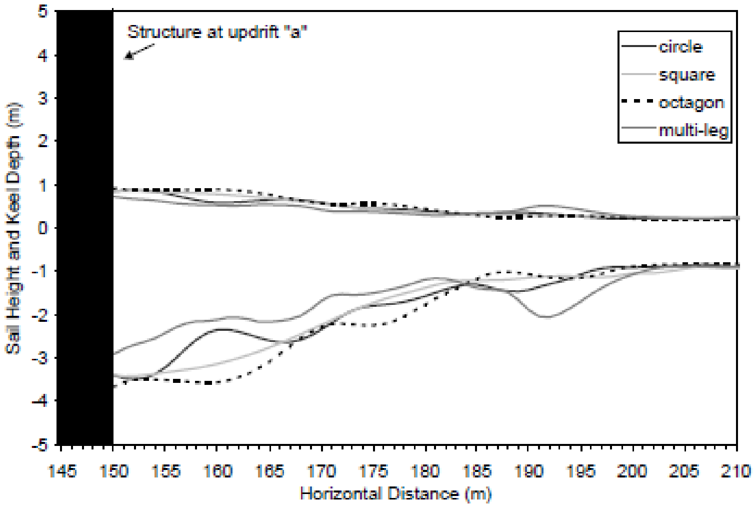
<u>Modeling results</u>
Five different structure shapes were used in the test simulations: circular, square, octagonal, multi-leg platform and conical structures. The test runs were chosen such that ice properties and other parameters would represent conditions that are commonly encountered in the Beaufort Sea. The ice was initially “placed” upstream of the structure with the initial ice concentration at 8/10ths. The waterline diameter of the circular, square and octagonal structures was 100 m. The equivalent width of the entire 4-legged platform was also 100m, however each leg had a diameter of 30 m, with a spacing of 40 m between them. The waterline diameter for the conical structure was 50 m. The ice moved from east to west with a velocity of 0.25 m/s. The ice cover was given an angle of internal friction of 45°. Its cohesion intercept value was 15 kPa, which corresponds with a global tensile strength of 10 kPa.

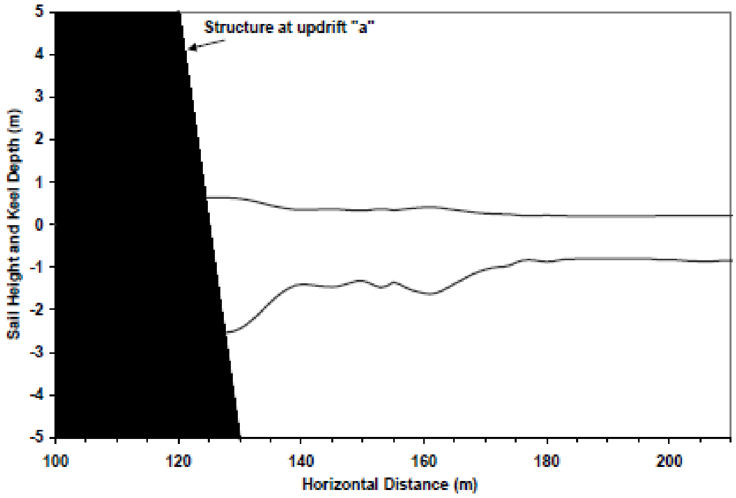
Plan views of the thickness contours after 1500 s for the various structures are shown in the figures below.



The contour levels are shown, with minimum and maximum values of zero (white, representing the open water wake downstream of the structure), and 5m (dark grey) respectively. A narrow wake forms downstream of the structures and the ice rubble surrounds the remaining three sides of the structures. It should be noted that the contours include both the sail region and the keel. The open-water wake formations for the structures showed some variation in shape. For all but the conical and multi-leg configurations, the wake down-drift of the structure remained open for at least 50 m, where the test grid ended. For the platform structure, the wake immediately downstream of the upstream legs closed, while the wake further downstream remained open for approximately 30 m. For the conical structure, the wake closed quickly, approximately 25 m down-drift of the structure.

The maximum rubble extent along up-drift was 43 m, observed up-drift of the multi-leg structure. Along up-drift for the multi-leg structure, that is, the center line of one of the platform legs, the rubble extent was much less at 21 m. From these results, it would seem that although the extent of the rubble pile-up is small for these relatively narrow legs, the closeness of the platform legs causes the ice to jam to a certain extent between the up-drift legs. The rubble extent was smallest for the conical structure, while the extent was similar for the circular, square and octagonal structures. The pattern of ice thickness and associated sail heights build-up showed that regardless of structure type, the pile-up up-drift of the structures was similar.





Implications for evacuation

If an evacuation procedure involves launching a lifeboat-type vessel from a structure, the emergency evacuation procedure should have the flexibility to be quickly launched from any side, as well as the capability to be deposited a safe distance away from the ice rubble zone surrounding the structure. In reality, launching flexibility is often not a practical option for offshore operations, given the location of drilling and processes operations on the structure. With respect to launch direction, launching in the up-drift direction could be catastrophic since the ice would move the lifeboat back into the structure. If launching is done in the alongside direction, the launch distance must be larger than the width of the moving broken ice zone (the failure zone). Launching in the down-drift direction would put the lifeboat in relatively ice-free water and might be the best approach; however this is often the downwind direction, which could be problematic if there are toxic fumes from the structure.

<u>Conclusions</u>

The shape of the structure can significantly influence the size and shape of the damage zone and broken ice accumulation around the structure. A circular-shaped structure appears to allow the broken ice to move relatively easily around the structure. This gives a narrower ice pile-up in the up-drift direction. A square or octagonal structure allows less ice movement around the structure and wide zones of ice accumulate in the front of it. The largest up-drift zone occurred with the multi-leg platform where the ice jammed between the two front legs. This shape also did not produce a well-defined wake so placing a survival craft in the down-drift direction could be hazardous. The conical structure had similar response to that of a vertical circular structure.

For a conical structure, the waterline diameter would be smaller than that for a vertical-faced structure. However, the deck size would be the same. Thus, for a conical structure the ice interaction takes place “underneath” part of the deck. The present analysis shows that the damage zone is not particularly large for the cone shape, so lowering a survival craft from the deck of a structure based on a conical shape may not require as much distance to the non-damaged zone.

It would initially appear that the extent of the accumulation of broken ice under the ice sheet would provide more buoyant support for loads put on top of the ice sheet and could add to the “effective” thickness of the ice for bearing capacity purposes. However the majority of the ice accumulates in the up-drift direction, with very little extent in the alongside direction and therefore, this added buoyancy should not be considered in determining the bearing capacity of the ice.

Ref:	Title:	Author:	Date:
3.04	Ice Force Design Considerations for Conical Offshore Structures	T.D. Ralston	1977

Summary:

Relevance to thesis
design considerations, conical structures, ice forces

Introduction
Arctic offshore structures are exposed to a variety of ice features including sheet ice, unconsolidated ridges, ice rubble fields, and consolidated multiyear ridges. Cone-shaped structures in ice covered waters are designed to resist ice forces by failing ice in flexure. The selection of an appropriate constitutive description and failure criterion for ice is a non-trivial exercise. The adjectives elastic, viscous, and plastic are often used loosely to describe ice deformation; however, the applicability of any particular material description must be examined within the context of the intended application. The ice property measurements, model tests, and full scale situation must all be viewed within the context of the same material description. In this article, a plasticity description of sheet ice failure against conical structures is presented in the following section. This analysis idealizes the floating ice sheet as an elastic-perfectly plastic plate supported by an elastic perfectly plastic foundation.

Sheet Ice Bending Failure
A conical structure with inclination *a* from the horizontal, waterline diameter D, and top diameter DT is subject to the forces imposed by an advancing ice sheet of thickness t. The leading side of the exposed surface of the cone is assumed to be covered by a single thickness layer of broken ice pieces. The effective friction coefficient between the ice and the structure is denoted by μ The strength of the ice sheet is characterized by its flexural strength, *σf*.

A pure bending failure criterion is used for the ice sheet in this analysis. The analysis follows the ideas of plastic limit analysis. In the absence of frictional forces, the procedure would lead to a rigorous upper bound for the exact plasticity problem. In the presence of friction, the "non-associated" flow rule for frictional sliding violates the upper bound assumptions and we proceed without the claim of a rigorous upper bound. The result of the plastic analysis can be expressed:

$$R_H = [A_1 \sigma_f t^2 + A_2 \rho_w g\, t\, D^2 + A_3 \rho_w g\, t\, (D^2 - D_T{}^2)]\, A_4 \quad , \qquad (1)$$

$$R_V = B_1 R_H + B_2 \rho_w g\, t\, (D^2 - D_T{}^2) \quad , \qquad (2)$$

The first two terms in (1) arise from the breaking of the advancing ice sheet. The coefficients Al and A2 depend only on the value of the parameter Pwg D2/uf t. The third term in (1) results from the broken ice pieces sliding over the surface of the cone. The coefficients A3 and A4 are functions of the cone angle and ice/cone friction coefficient. The vertical force can be computed from the horizontal force using (2) and coefficients Bl and B2. These coefficients also depend on the cone angle and friction coefficient.

Since both the ice property measurement and the failure process are interpreted in the sense of plasticity, one should not assume a priori that this analysis would necessarily predict forces in excess of those of the elastic analysis. Part of the observed difference may be due to the effect of ice riding over the exposed surface of the cone, which may not have been included in the elastic analysis.
Multiyear pressure ridges

Multiyear ridges are an important design consideration for offshore structures in the deeper waters of the Beaufort Sea. The failure of such ridges moving against conical structures has been discussed within the context of the theory of elastic beams on an elastic foundation. Two significant events - initial crack formation and hinge crack formation - have been identified. The forces that correspond to these events have been estimated by assuming that the initial failure is analogous to an infinite floating ice beam subjected to a vertical load, and that the hinge crack formation is analogous to the simultaneous failure of two semi-infinite floating ice beams subjected to vertical loading. Under these assumptions, the vertical force on the cone for these two events would be predicted by:

$$R_V^{\infty} = 4\ I\ \sigma_f\ /\ y_t \ell \quad , \qquad \text{(Initial Crack)}$$

$$R_V^{\infty} = 6.20\ I\ \sigma_f\ /\ y_b \ell \quad , \qquad \text{(Hinge Crack)}$$

The corresponding horizontal forces would depend on the cone angle and ice/structure friction coefficient. If the same elastic model were applied to ridges of finite length, the vertical force predicted to cause flexural failure of the ridge will increase with decreasing ridge length. In other words, given two ridges of the same cross section but different length, the elastic beam analogy would predict that the shorter ridge may impose the greatest force. If the ridges are sufficiently short, they may form the initial crack and then slide over the surface of the cone without forming the hinge crack. Even shorter ridges may not break at all, but simply move past the cone or perhaps lodge in front of the cone, with the advancing ice sheet failing against them. The striking effect of ridge length predicted by this mathematical model suggests the need for physical model tests to establish the basis for a more appropriate description. Many mathematical models, including our plasticity analysis of sheet ice failure, are heavily motivated by physical tests that provide insight into the appropriate failure mechanisms of the ice. Further investigations of the failure of pressure ridges against conical structures are presently underway.

Conclusions

- The plasticity approach provides a comprehensive analysis of sheet ice moving against conical structures. This description includes the effects of cone angle, waterline diameter, ice ride-up over the exposed conical surface, ice/structure frictional forces, ice flexural strength, and ice sheet thickness.
- The plasticity analysis is in good agreement with published model test data that include variations of all of the significant parameters in the analysis. A previously published elastic analysis significantly underestimated these data.
- Only the relevant engineering parameters need to be specified, and no specialized knowledge of plasticity is required.
- The elastic analysis of multiyear ridge failure, with the ridge modeled as a beam on an elastic foundation, leads to the conclusion that short, rather than long, ridges may impose the greatest ice forces on structures that are designed to fail ice in flexure. Such an analysis is obviously a crude description of the failure process.

Ref:	Title:	Author:	Date:
3.05	Ice Loads for Offshore Wind Turbines in the Southern Baltic Sea	H. Gravesen T. Kärnä	06-2009
Summary:			

Relevance to thesis
ice loads on turbine foundations, Baltic Sea design conditions, ISO19906 design code

Introduction
Wind turbine structures shall resist ice loads in the southern areas of the Baltic Sea. This article describes a method of determining site-specific load values for structures to be built in this area. This method is based on the forthcoming standard ISO 19906, which emphasizes the use of field data and site-specific considerations. The objective of the article is to develop rational design criteria for ice loads for a cylindrical monopile in the Southern Baltic Sea. The new arctic standard ISO 19906 shows substantial progress in considering full-scale data on ice loads.

Global Load Determination
According to the ISO/DIS 19906 the global load is calculated as

$$F_G = p_G\, h\, w \qquad (1)$$

where h is the ice thickness and w is the contact width against the structure. The global pressure p_G is determined as

$$p_G = C_R\, h^n \left(\frac{w}{h}\right)^m \qquad (2)$$

where

p_G	is a value of the external global pressure (MPa),
w	width of the structure (m),
h	thickness of the ice sheet (m),
m, n	empirical exponents to take account of the size effect. $m = -0.16$; $n = -0.50 + h/5$ for $h < 1.0$ m and $n = -0.30$ for $h \geq 1.0$ m,
C_R	coefficient to consider the ice strength in different ice regimes, as well as effect due to ice speed and waterline displacements of the structure.

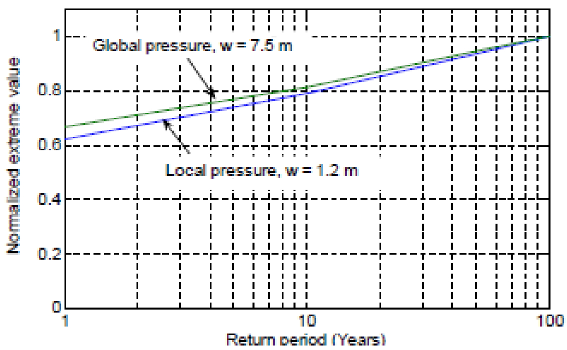
The aim of the expressions (1) and (2) is to provide a global load that will occur in average once during the life time T of the structure. ISO 19906 assumes that T = 100 years for an "Extreme Level Ice Event – ELIE". For offshore wind turbine structures T = 50 years. ISO 19906 recognizes that the global load will become overly conservative if both the ice thickness and the ice strength parameter CR are put into Eq. (2) using their extreme (50 year) value. To avoid this, ISO 19906 recommends that the ice thickness is taken at its extreme value whereas an upper bound value, such as the maximum global ice pressure expected in a year can be used for the ice strength parameter CR.

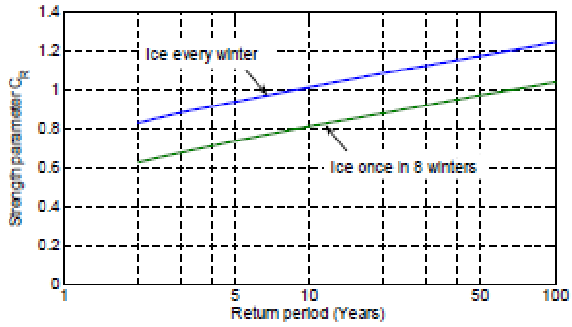
Design Ice Thickness
Observations of fast ice confirm that the fast ice thickness is substantially lower than the reference ice thickness. It is seen that the observations of maximum ice thickness are indicating larger ice thicknesses than the calculated reference ice thickness, but this is most probably is associated to observation of rafted ice. The 1/50 y reference ice thickness is h = 0.57 m. It can be concluded that the most probable 1/50 year ice thickness is 0.40 m for the Southern Baltic Sea. A safe 1/50 year ice design thickness is 0.48 m.
Ice Strength in the Southern Baltic
According to the ISO, the ice strength parameter can be taken as CR = 1.80 for stiff structures in the Baltic Sea area. This value was determined by using data that was

obtained in 1999-2003 on the lighthouse Norströmsgrund. The value of CR = 1.80 is valid for very rigid structures. It was derived for ISO 19906 by using the following further assumptions:

- Ice actions on the structure take place every year.
- The accumulated number of freezing degree days was about FDD = 1000 in the area and in the time period of the measurements.
- Data on local force panels were processed by using a spectral model /4/ for the global pressures. This model is conservative for thin ice because it does not consider mixed modes of ice failure.

This list of assumptions made in ISO 19906 indicates that the ice loads that a wind turbine structure will experience in the Southern Baltic Sea area will be lower than what a direct application of ISO/DIS 19906 will give.





The return period influences the representative value of local- and global pressures, as can be seen on the figures. The first figure is based on an extreme value analysis where a larger amount of data was reduced to a smaller set of data that satisfies the theoretical requirements of an extreme value analysis. The results are shown in the second figure for the Northern Baltic Sea as the curve “Ice every winter”. The curve “Ice once in 8 winters” shows the corresponding results for the Southern Baltic Sea.

<u>Velocity Effects</u>

ISO/DIS 19906 indicates that the ice strength parameter depends on ice speed and the waterline displacements of the structure. However, speed effects are not evident in the directly measured global pressures. It is deemed that this is due to the variations in the ice failure modes. Due to the speed effect that has been confirmed on local pressures, it is considered that the strength parameter should be increased by 20% to consider the velocity effect alone. As discussed above, ISO recommends that the strength parameter can be taken as CR= 1.80. This value is based on a spectral model where the global load is calculated from local loads assuming that additional effects such as flexural failure do not influence the global load. It was also assumed that there is a small velocity effect (20 % to 25%) even for very rigid structures. It can be seen that this value is significantly higher than what was obtained from direct measurements of the global load.

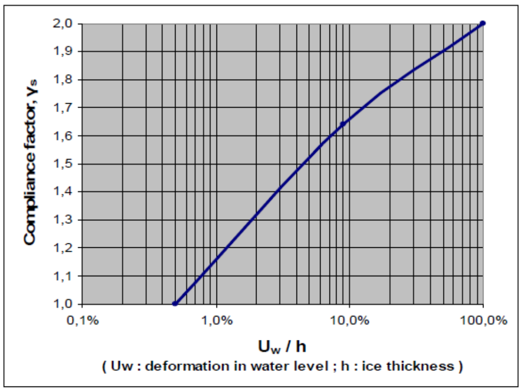
Methods based on full scale action and response data from measurements on instrumented structures shall be used for the determination of design ice actions on offshore structures, with due account of their applicability. This approach is used in the present document. However, the results obtained in the expressions show a significant difference.
This difference can be explained as follows:

- The expression is non-conservative due to the test arrangements.
- The estimate for the strength parameter is conservative because of the data analysis procedures.

- The main reason for the difference is that thin ice tends to fail in bending instead of crushing. For thicker level ice a mixed failure mode (bending + crushing) was often seen. Mixed failure mode does not necessarily influence the highest local pressures that act on the structure. However, it has a significant reducing effect on the global load.

<u>Compliance Effect</u>

Both laboratory data and field data show that ice loads acting on a vertical structure will increase if the compliance of the structure "as seen by the ice" increases. It can be concluded that the apparent ice strength will increase if the waterline displacement is higher than 0.5 % of the ice thickness. A generalized empirical curve is proposed for narrow monopile foundations that are a common option for offshore wind turbines. The compliance parameter γ shown in this figure is used as a multiplication factor on the basic ice strength.



<u>Calculated Design load on a monopile</u>

Consider a narrow monopile foundation with *w*= 4.0m, *h*= 0.48m and *uw/h*= 9%. Then it follows that *γs* = 1.65. The exponent *n* needed in Eq. (2) is *n = -0.5 + 0.48/5 = -0.404.* The global pressure is then obtained from the expression below:

$$p_G = 1.65 \cdot 1.0 \cdot 0.48^{-0.404} \left(\frac{4}{0.48}\right)^{-0.16} = 1.58\ MPa$$

The characteristic value of the quasi-static global load is then provided by Eq. (1) as FG = 3.03 MN. Using the partial coefficient of 1.35 the design load is given as F = 4.1 MN.

<u>Dynamic Sensitivity</u>

The results discussed indicate that the foundations of the structures being considered are not very stiff. It is almost sure that actions of ice sheets will sometimes create ice-structure interactions that are known as intermittent crushing. This phenomenon is associated with transient vibrations. These vibrations are not necessarily a problem for the ultimate strength of the structure. But they may create fatigue problems. ISO can help estimate whether a vertical faced structure will be sensitive to another kind of vibration, known as self-excitation (or lock-in). A preliminary check of the dynamic characteristics of a typical foundation for an offshore wind turbine shows that there is an urgent need to make a proper dynamic analysis on this issue. The ice-induced vibration is not necessarily a real issue for a foundation in the southern Baltic Sea because the magnitude of the ice load is not very big. It should also be noticed that ice-induced vibrations can be effectively mitigated.

Ref:	Title:	Author:	Date:
3.06	Life-Cycle Cost-Effective Optimum Design of Ice-Resistant Offshore Platforms.pdf	G. Li D. Zhang	08-2009
Summary:			

Relevance to thesis
life-cycle cost, cost-effective design, structural reliability, offshore platform, ice loads

Introduction
To design the offshore platforms with both an ice-resistant capacity and a lower cost is the main task of the designers. Present design codes do not account for the effects of the dynamic properties of the ice load, and these platforms underwent severe ice-induced vibrations. This resulted in human discomfort, flange loosing, pipeline fracture, and fatigue of tubular joints. There are many uncertainties in design of offshore platforms, such as the randomness of ice thickness, ice velocity, ice strength. Also, the global resistance of the offshore platform deteriorates over time. The risk is involved in the design, construction, utilization, and maintenance of marine platforms as uncertain events may occur during the life-cycle of a platform. It is necessary to pursue both economical and ice-resistant aims for the ice resistant platforms by life-cycle cost-effective optimum design, which is the motivation of this article.

The concept of performance-based design is to seek a balance between the initial cost and potential large losses over the structural lifetime by minimization the expected lifecycle cost. Most of structural optimization of offshore structures up to now focused on the minimum initial cost design with the constraints of the performance requirements specified in the design code. In this article, the optimum design model to minimize the expected life-cycle cost for the ice-resistant platforms based on the cost-effectiveness criterion is proposed.

Performance Requirements of Ice-Resistant Offshore Platforms
The performance requirements of the ice-resistant offshore platforms can be classified into three groups: performance requirements of structure, facilities, and crew members. From the viewpoint of mechanical characteristics, the performance requirements can be classified into the extreme static and dynamic requirements due to the inherent property of the ice load. In the current code-based design of offshore platforms, the seismic load, waves, sea current, wind, and ice load are usually converted into static actions. The strength, stiffness, and stability demands of the structures or components are evaluated under the possible load combinations to guarantee that the stress, deformation, and buckling loads are less than their threshold values. Due to the internal dynamic characteristics of the ice load and the ice-structure interaction, the ice-breaking period may coincide with the natural period of the structure and cause resonance vibration. The corresponding failure modes are as follows:

1. Structural safety failure mode.
2. Human factor failure mode..
3. Facility failure mode.

Formulation of Life-Cycle Cost-Effective Optimum Design
Life-cycle effective optimum design of the ice-resistant offshore platforms involves not only the initial cost but also the expected life-cycle cost, which requires the assessment of the failure probabilities for all failure modes considered in the cost model. The initial costs include those of construction and the consequences of structural failure modes are formulated in consideration of the damage loss, repair cost, death, and injury loss, as well as discounting factor over time.
Over a time period, t, the expected life-cycle cost is calculated by:

$$E[C(t,X)] = C_0(X) + E\left[\sum_{i=1}^{N(t)}\sum_{j=1}^{k} C_{ij}e^{-\lambda t_j}P_{ij}(X,t_j)\right]$$

in which E is the expected value; C0 is the initial cost for new structure; is X the design variable vector, Cij is the cost value of the jth failure mode being reached; Pij is the probability of the jth failure mode being exceeded given the ith loading occurrence.

Application to the Design of a Typical Offshore Platform

For an offshore platform, the structural responses under the dynamic ice load and extreme static ice load are mainly determined by the structural global resistance, which is closely related to the initial cost. In the optimal design, the structural global resistance is taken as the design variable. Within the given structural stiffness, the plots of the resulting life-cycle cost function, including the initial cost, expected damage cost, and total cost are shown in the figure below. The life-cycle optimum results are compared with the conventional static design and the dynamic deterministic optimum design, shown in the table.

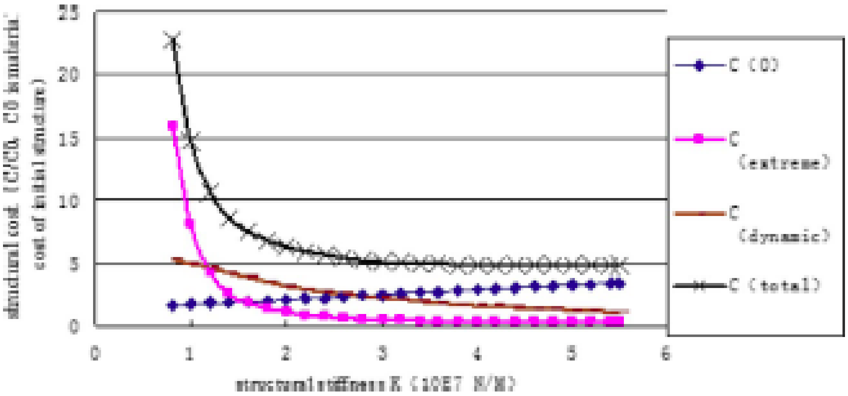


Table 5 Comparison of life-cycle optimum design, conventional static design, and dynamic optimum design

	Conventional static design	Dynamic optimum design (DUT [30])	Life-cycle optimum design
Global stiffness (N/m)	5.36×10^7	3.64×10^7	4.4×10^7
C_{initial} (C_0)	3.40	2.69	3.08
C_{extreme} (C_0)	0.32	0.40	0.36
C_{dynamic} (C_0)	1.13	1.80	1.37
C_{total} (C_0)	4.85	4.89	4.81

Based on these comparisons above, some observations can be made:

- The trade-off between the initial cost and the expected cost of damage is the pursued aim in the optimal design. Structural responses, such as the global deformation under the extreme static ice and the RMS of the deck acceleration under the dynamic ice load, and the corresponding damage costs go down as the structural global stiffness increases, while the initial cost increases significantly. When the structural stiffness is larger than $1.2*10^7$ N/mm^2, the expected damage cost under the extreme static ice load is much less than that under the dynamic ice load, which makes it necessary to consider the dynamic performance requirements in the life-cycle cost-effective design.

- The initial costs of dynamic optimum design and life-cycle optimum design are decreased by 21% and 9% compared to that of the conventional static design. The expected cost of life-cycle optimum design is improved compared to that of the other two design methods. The conventional static design is conservative in that the initial cost is very high, and the dynamic optimum design does not account for the structural performance under the extreme static ice load.

- In the life-cycle optimum design, the global displacement of the optimal structure under the static extreme ice load satisfies the engineering demand. The RMS of the acceleration under the dynamic ice load ensures work efficiency level of the crew members and normal serviceability of facilities on the platform.

Conclusions

Both the ice resistant capacity and the economical investment are two design aims of great concern for offshore platforms. The life-cycle cost-effective design is a promising design approach, which has undergone a lot of developments in many engineering areas. The optimum design is addressed to minimize the expected life-cycle cost for the ice-resistant platforms based on the cost-effectiveness criterion. A practical life-cycle cost formulation for the ice-resistant platforms comprising of the initial cost and the damage cost, repair cost, death and injury loss, and indirect socio-economic loss, as well as discounting cost over time. Multiple performance demands of the structure, facilities, and crew members under the static and dynamic ice loads are treated, The algorithms for failure probability analysis of different types of failure modes are proposed, including the static global reliability analysis under the extreme ice load, the dynamic reliability analysis, and fatigue life analysis under the dynamic ice load. Finally, the life-cycle cost-effective optimum design formula is applied to a real jacket offshore platform, and the results show that the life-cycle cost-effective design may lead to more a rational, economical, and safer design compared with a dynamic optimum design, as well as a conventional static design.

Possibly useful references:

Pinna, R., Ronalds, B. F., and Andrich, M. A., 2003, "Cost-Effective Design Criteria for Australian Monopod Platforms," ASME J. Offshore Mech. Arct. Eng., 125, pp. 132–138.

Ref:	Title:	Author:	Date:
3.07	Meeting the Challenge of Founding Wind Turbines in the Baltic	E. Eranti E. Holttinen	2003

Summary:

<u>*Relevance to thesis*</u>

offshore wind foundation, ice loads, Baltic Sea, concept development, construction economics

<u>Introduction</u>

Offshore areas have great potential for wind power generation in Northern Europe. However, construction of foundations for offshore wind turbines facing heavy ice conditions has been considered to be a challenge. Offshore construction of wind turbines is desirable, because wind conditions are favorable, visual impacts can be accepted more easily and environmental concerns are minor. Potential offshore areas featuring average wind speeds in excess of 7 m/s, easy access to sufficiently strong power infrastructure and water depths up to 15 meters. There are six offshore areas that show greatest potential in Finland, as can be seen on the figure. The estimated electricity production cost is around 5 cents/kWh without subsidies. The moderate cost estimate for offshore wind power generation is partially based on a new ice resistant foundation concept for the wind turbine. This concept is described in this article.

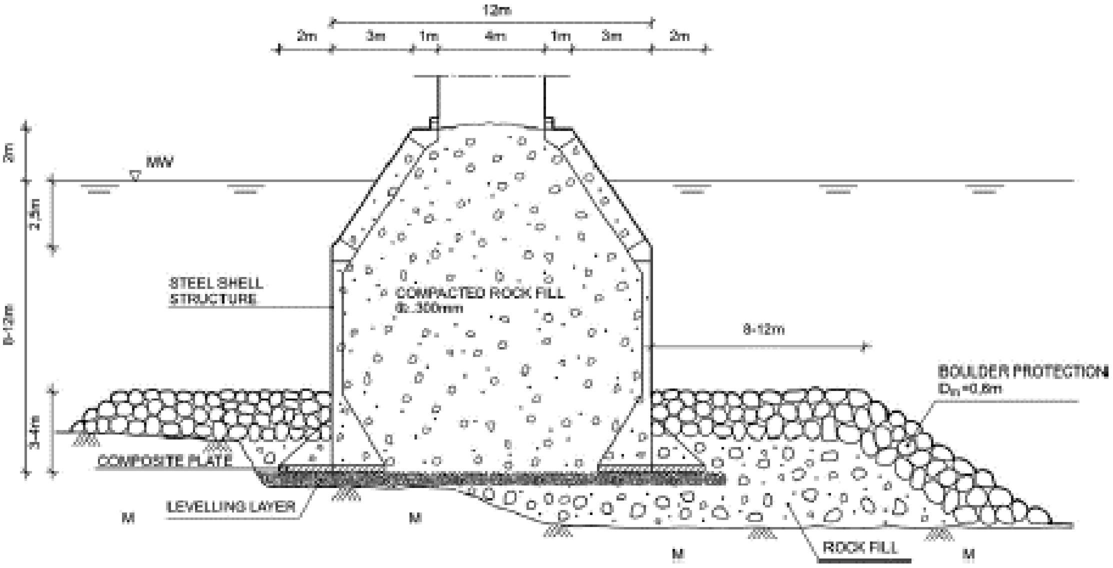
<u>Foundation Concept</u>

The new structural concept features a thin walled cylindrical shell with ring footing, conical upper part and granular fill. The concept is based on composite action between the shell and the fill. Soil, water and other pressures are easily handled by membrane forces because the shell is cylindrical. The solution is best applied to bottom conditions ranging from firm to hard. There is just one compartment, no bottom plate, no partition walls, wall and plate thicknesses are very thin and composite action between fill and steel shell is utilized. The whole mass of the rock fill stabilizes the structure against sliding and stabilizes the structure against overturning, because of the arching effect. Uneven base pressures are transferred from the ring footing to the shell structure by the help of stiffeners. The stiffness properties of the structure with a ring footing are practically the same as those of a structure with a uniform base plate. The structure performs well without the ring footing against static loads, because the fill arches at the compression side and resists movement by friction at the tension side. However the primary external loads on the foundation (wind load, ice load and wave load) are dynamic in nature. The frictional grip slides under dynamic loading in this case. That is why the ring footing is not only a structural element increasing the overturning capacity of the foundation but also a vital anchor at the tensile side.

- The rock fill supports the thin shell against local loads first linearly according to the theory of shells on elastic foundation and then nonlinearly. The composite structure

has still a huge reserve capacity against failure after yielding of steel plate has started under the local load.
- The rock fill prevents the stability loss of the thin steel shell under bending or compression forces. This effect becomes even more important in the cone-cylinder junction or if the structure is imperfect for example due to fabrication errors or plastic deformation caused by local loads.
- The rock fill supports the shell structure so that it can much better resist moments created by uneven base stresses. This effect becomes even more important when the bottom pressures start to increase and become more one sided near limit state, or when there are bumps on the foundation layer.

The cylindrical shell structure takes the fill pressure effectively by loop forces like in a water reservoir. The rock fill inside the steel shell increases damping considerably. The damping of the foundation portion of the structure is close to critical. Thus the foundation does not swing back at load release with the same intensity and amplitude as an equivalent traditional caisson. Furthermore it is much more rigid than a pile structure. The concept is shown below.



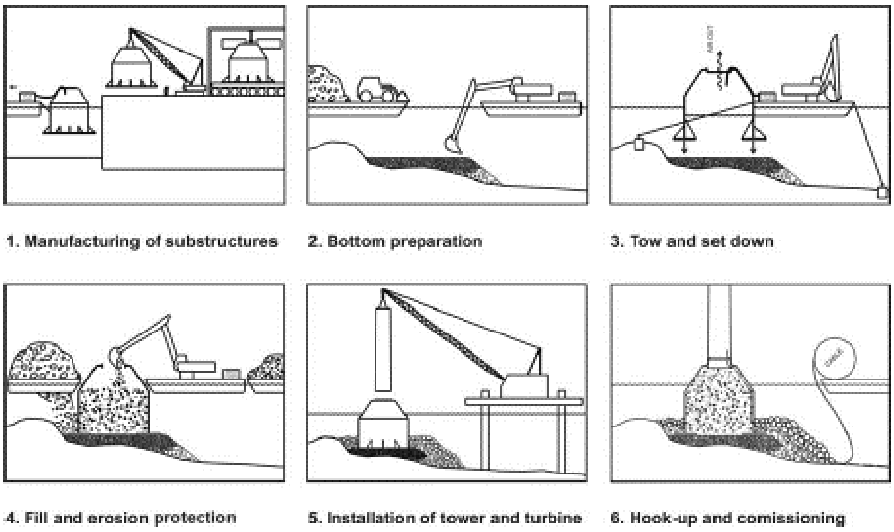
<u>Model Tests</u>

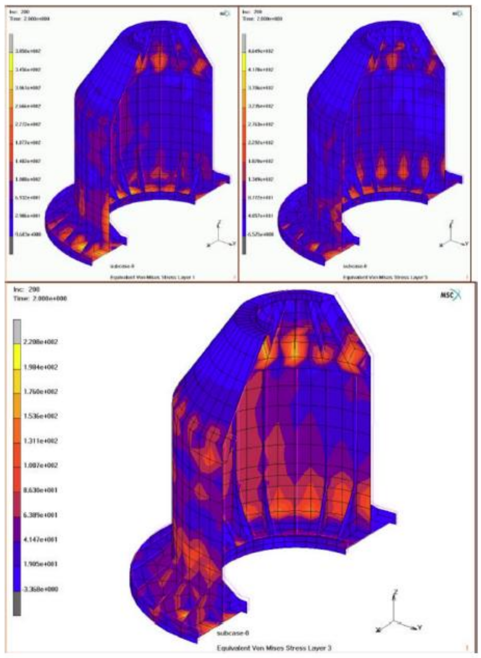
Small scale model tests have been performed for the feasibility study to verify the concept.

- Static and dynamic overturning tests in dry condition and in water.
- Local loading tests.
- Tests to study the dynamic properties of the soil-foundation-wind turbine system.
- Floating stability and set down tests.

<u>Construction sequence</u>

The construction sequence of the system is illustrated in the figure below. The shells are fabricated at a workshop. They are lifted to water, where they float by the help of entrapped air. At the same time foundation sites are dredged and leveled. The shells are towed to site and set down by help of a barge in an easily controlled operation. The shells are then filled with granular material, preferably with a good angle of friction and surrounded by erosion protection. This is followed by erection of wind turbines using an offshore crane. In the final phase, cables are laid and the system is hooked up and commissioned. As an alternative, the shells can be transported by a barge. Since they weigh 200 – 400 tons, they can be handled and lifted on place with quite conventional equipment. By overlapping the construction phases one set of working groups can install 100 MW of wind power during a single construction season.





The design ice forces have been evaluated based on well-established theories and full scale measurements. The behavior of the soil structure system has been simulated numerically as it approaches limit state. Non-linear models have been used both for soil and steel. The dynamic ice structure interaction simulation has been performed using the FEM model shown in the figure. The response remains well within acceptable limits in this case as well as in the case where ad freeze bond between the foundation and the ice field abruptly breaks due to pressure in the ice field.

In the case of the Pori offshore wind farm project the cost of the foundations in place is estimated to be under 20 % of the total investment cost. The design life of the foundation is 50 years and that of the wind turbine 25 years.

Conclusions

A new type of foundation has been developed for offshore wind turbines. As a result of composite action between the fill and the steel shell the structure is light and inexpensive. Installation is easy and rapid, which is an advantage considering the short weather windows in offshore construction. The foundation system takes advantage of serial production and overlapping work phases. The foundation is best suited to firm to hard bottom conditions. The cost of the foundation is not anymore an obstacle for the feasibility of offshore wind power projects in the Baltic Sea.

Ref:	Title:	Author:	Date:
3.08	A novel Offshore Windmill Foundation for Heavy Ice Conditions	E. Eranti H. Pukkila	06-2011

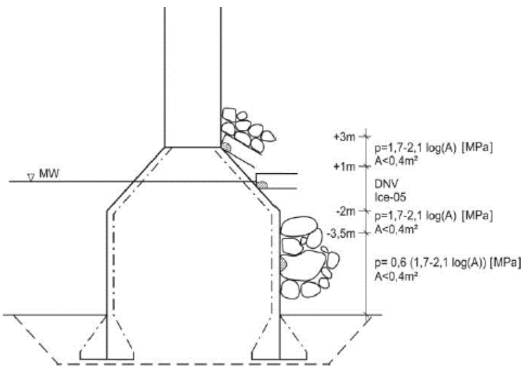
Summary:

Relevance to thesis
offshore wind foundation, ice loads, Baltic Sea, concept development, construction economics

Introduction
Finland has set itself a target of installing 2,000 MW of wind power capacity by 2020. The northern Baltic Sea is particularly attractive among sub-arctic sea areas as it offers large shallow areas suitable for industrial-scale wind power development. Although windmills have been installed in areas with seasonal ice, no windmill has been erected in an area with heavy dynamic ice conditions. The main technical challenge described in this article was to develop a concept that could deal with ice and wave loads in a variety of water depths and bottom conditions, and allows for erecting dozens of turbines within a short seasonal window. Pile foundations are problematic in hard and rocky bottom conditions, and traditional caisson foundations tend to be expensive.

Pilot foundation
A GBS concept was developed in [3.07] by E. Eranti. This concept was adopted and a pilot project initiated. Unlike traditional, gravity-based offshore structures, the foundation is light and has an open bottom, making it easy to lift into place. The ring footing increases the stabilizing moment arm, and the tension side acts as an anchorage against slip under dynamic loads. Granular fill provides the major portion of the gravity and stability for the foundation. The entire weight of the fill acts against sliding and roughly 90 % against overturning due to the arching effect (as verified by model tests and FEM analysis). The fill also supports the shell against local ice loads, as well as stability loss under compressive and bending loads. The conical shape helps reduce ice and wave loads, and effectively eliminates ice-induced vibration. The foundation does not respond much to the ice force and the tower with the turbine is too slow to react to the ice force fluctuations. The foundation dimensions are a result of iteration-balancing of ice and wave forces.

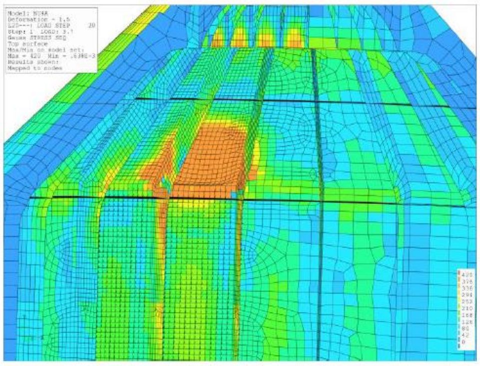
Site conditions and loads
Winter ice conditions in the area, although generally light with mainly thin, broken ice floes, can be severe. The characteristic ice-loading condition is an ice ridge impact. The ridge has a consolidated ice thickness of 1.2 meters and a keel thickness of 8 meters. The ice-ridge load was calculated by combining the solid ice failure component with the keel failure component. The 50-year significant wave height for the Bothnia Sea is around 7 meters with a period of 11 seconds. However, the effects of shoals and shallow water are felt at the pilot wind turbine site. The governing wave loading condition corresponds to an impact of 8 meter-high spilling breaker with a period of 10 seconds.
The Siemens 2.3 MW wind turbine had a hub height of 80 meters. The following characteristic loads and moments at base level were used in the foundation design: *Wind 0.85 MN 70 MNm, Ice 6.1 MN 40 MNm and Wave 3.9 MN 32 MNm*



Structural analysis and design

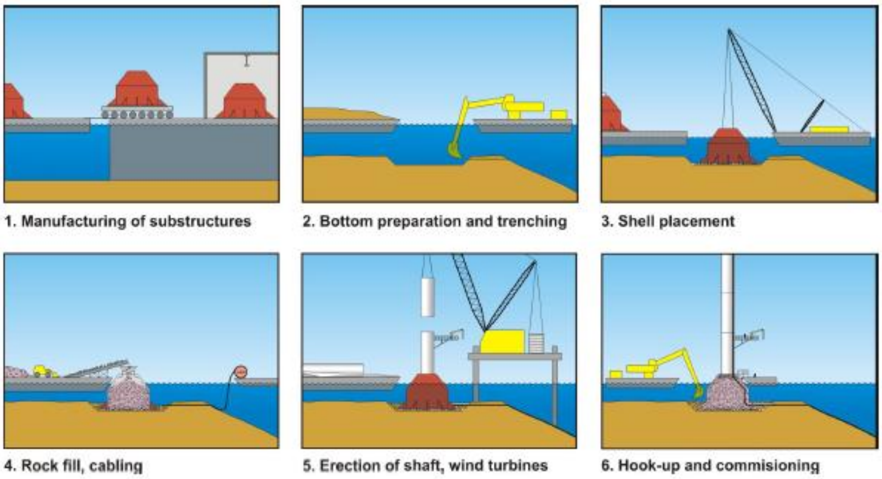
The methodology is based on recognized offshore structural engineering standards and rules. The main engineering rule followed is DNV-OS-J101: Design of Offshore Wind Turbine Structures. Some adjustments were done based on local site conditions and experience with ice loading. Based on wind speed records from severe-ice winters, it was concluded that F = Fice + 0.6 Fwind would be a conservative estimate for the characteristic load combination. Conservative estimates for characteristic wave and wind load combinations, F = Fwave + 0.9 Fwind and F = 0.9 Fwave + Fwind were used. The structural analysis was performed with FEM software. Soil support was included in the cylindrical section. Granular fill support and membrane forces were shown to reduce the shell moments caused by uneven pressures on the ring footing, especially under extreme global loads.

The wind turbine manufacturer set strict limits on the natural frequency of the structural entity. Our dynamic analysis of the structure thus considered the stiffness and mass of the seabed soil, foundation steel structure, internal fill, windmill tower, and outside water. The analysis showed that the foundation was dynamically massive and rigid like an onshore foundation. A fatigue issue was identified at the intersection of the cone and the shaft. Eventually, the issue was resolved with a special structural arrangement.



Foundation construction

The foundation installation, inside fill, and wind turbine erection took one week. The windmill component lifts were done during a single working day.



While the foundations are rolled out from the manufacturing yard, one working group prepares bases for wind turbines, another group installs foundations, a third group fills foundations, a fourth group does trenching and cabling, a fifth group erects wind turbines, and a sixth group does the hook-up and commissioning works while the first group returns to complete erosion protection works. A serial approach to manufacturing and erection alone was roughly estimated to cut the foundation cost by a third. As mentioned, further cost savings are available by design development.

Future developments

Offshore wind power, which has high up-front costs, has to compete not only with onshore wind power but also other forms of electricity production. Wind availability is greater offshore, but cost-competitiveness dictates that prices still need to fall for the wind turbine and its foundation.

The Pori pilot wind turbine project has provided valuable hands-on experience on offshore wind power development in northern Baltic Sea conditions. Four areas (design, manufacturing, installation and cost structure of the pilot wind turbine) were examined after the project. Design solutions for a variety of ice conditions, water depths and bottom conditions were developed further, and methods and costs of serial manufacturing and installation were studied. The rigid joint between the cone and shaft proved to be problematic. One option would be a simple offshore bolt connection. This would reduce manufacturing costs and enable filling the foundation directly from a deck barge.

For economic reasons large blocks of new development, say, 50–200 MW, should be brought on stream in a single construction season. Leaving the construction unfinished over winter can have severe economic consequences (e.g. re-mobilization of equipment that may already be reserved elsewhere, loss of energy production, and heavy capital costs). Delays also add to greenhouse gas emissions (1,000 to 2,000 metric tons of CO2/MW per year). This calls for an industrial approach to wind farm construction. Construction should proceed like clockwork even as depths and bottom conditions vary.

Conclusions

The Pori pilot offshore wind turbine project is an important step towards large-scale wind power development in the northern Baltic Sea. The concept is also applicable to other shallow sea areas with firm-to-hard bottom conditions with or without ice. The gravity-type foundation consists of a light ice-strengthened steel shell with a ring footing, ice-breaking cone, and crushed rock fill. The fill provides mass for the foundation and supports the shell against local ice impacts and moments caused by uneven base pressures, as well as stability for the thin shell structure. The ring footing extends the stabilizing moment arm and provides anchorage against overturning. Industrial-scale manufacturing and installation will reduce costs of foundations and offshore wind power. Improvements in design and construction will also cut costs, making offshore wind a viable energy production option in sub-arctic conditions.

Ref:	Title:	Author:	Date:
3.09	Sea ice and icing risk for offshore wind turbines	L. Battisti A. Brighenti	04-2006

Summary:

Relevance to thesis
offshore wind turbine, cold climate, icing, risk analysis, anti-icing.

Introduction
There are two important issues related to wind turbines performances in offshore sites that locate in cold climates, namely sea ice and the presence of atmospheric icing which may potentially lead to ice formation on turbines' structures. In offshore conditions ice pack or floating blocks on the sea surface cause additional static and dynamic forces on the turbine structure. The presence of sea spray, associated with atmospheric icing, determines complex icing phenomena that are highly dependent on the elevation of the turbine rotor over the sea level and on the size and type of wind turbine. High water vapor content and sea spray could cause important water condensation and ice growth. These factors impose important constraints for a cost effective and reliable development of the wind energy production.

Icing of wind turbine affects three different aspects: the design, the safety and the cost-effectiveness. Icing also affects wind sensors, both in resource estimation and controlling the turbine. The experience on inshore sites teaches that heavy icing can result in a total stop of the turbine and that the ice can last considerably longer on the blades than the time at which icing conditions occur. In detail, ice can cause:

• inefficient or inoperative wind measuring equipments
• rapid performance degradation;
• increased noise level;
• increased fatigue on wind turbine and foundations;
• down time due to excessive vibrations;
• risk of ice throw
• additional troubles (site accessibility, site data communication);
• limited length of "weather window" during project installation;
• possibly more complicated building permission granting process.

De-icing and anti-icing systems are still under development. Thermal anti-icing systems are at the moment the most used systems to face moderate icing. The selection and design of those systems shall be based on the consistent evaluation of the heat fluxes that the blades exchange with the environment during icing events. The computation presents a high degree of complexity due to the dependency of the heat fluxes on a great number of variables, both climatic and machine dependent. These systems require an anti-icing power for the rotor ranging from 10 to 15 % of the machine's rated output, depending on environmental conditions, turbine size and type. Ice throw risk in a form of ice shedding may pose a major safety hazard in certain environments. This affects the safe operations of the turbines in wind parks because of the possibility of being hit and damaged by ice pieces. Offshore wind turbines suffer from sea ice actions much less at the areas where sea ice is mostly land fast ice compared with that of the drifting ice. The ice sheet interacting with the turbine structure produces a wide range of deformation states, each generating different reactions on the structure. Static loads are induced by a stationary contact of the ice with the turbine tower, and the surface forces arise from loads applied by a combination of winds, currents drags and thermal expansion, which push slowly the ice cover against the structure. The tower behaves as a single isolated pinning point resisting the applied driving force, which can be more or less distributed over the tower surface. Weather

conditions, applied force level and icing-deicing cycles of the interface determine the uniformity of the mutual ice-structure contact. Thick ice in cold seawaters may sometimes induce the pile-up phenomenon. The ice contact areas is an important parameter to determine the foundation sliding resistance, foundation shear bearing capacity and overturning moment at the seabed of a wind turbine structure. Static and dynamic loads cause different response of the structure. Therefore the prevailing sea ice conditions and icing mechanism should be known in advance to properly design the type of foundation. Floating and pack ice on the water surface and atmospheric icing induce the wind turbine to excessive vibrations. Ice drift and hitting against the foundation might trigger structural vibrations or even damage it by exciting the tower, while structures' icing will excite flap wise the blades but the main effect is felt on the tower. The turbine components need to be resistant to vibration under time-varying environmental or operational loads. Structural damping is almost always an effective solution against excessive vibrations. The foundations of the wind turbines have also an effect on preventing ice induced movements. Sea ice accumulation on the tower could possibly modify the tower weight and aerodynamic, thus modifying loads on foundations.

Icing severity at offshore sites

Ice formation in open sea is often a combination of spray and atmospheric icing and their relative importance can vary according to the ocean conditions and the wind turbine components elevation above the sea surface. Usually sprays are reaching just the lower levels structures, like the bottom of the tower and the blade tip during its azimuthally downward pointing. Data from shores can modestly contribute to assess the actual conditions and determine still a huge area of inaccuracy in assessing the probability and severity of icing events for potential sites. When site developers attempt to assess icing severity, they are faced with the following problems:

- establishing consistent simultaneous combinations of LWC, MVD, wind speed and temperature, which can occur at a given offshore site;
- determining how these combinations will affect the rotor, leading to ice accretion (icing severity);
- assessing the penalties (in terms of both energy losses and components reduced life) associated with icing severity;
- assessing the energy and power requirement depending on the ice mitigation system adopted (thermal anti/deicing,
- mechanical de-icing, etc.).

Ice shedding hazard

The diameter of the ice risk zone is dictated by the mass and size of the ice fragments and turbine functional parameters. The output fragments distribution on the surface are presented in terms of strikes probability and recurrence period, as a function of the input parameters. For this purpose, a parametric analysis was performed varying ice pieces mass and shape. Numerical simulations were performed to predict the ice fragments' distribution on the sea surface around a typical MW-size three bladed offshore wind turbine. The simulations, show similar ice pieces distributions in the two cases, with a major strike probability in the area within 200 m around the turbine. The maximum distance covered by an ice piece is about 250 m. In a wind farm, the turbines are about 200 m far from each other when they are arranged in a single row, while they
locate 500 to 800 m from each other when they are set up in more than one row. As a consequence, a moderate probability exists for a turbine to be struck from an ice piece which is ejected by the nearest turbine, only for turbines located on a single row. O&M personnel will likely to face higher risk while maintaining the power plant. Different risk areas can be identified
in terms of recurrence period in the two figures: the yellow contour indicates a 10-years recurrence period.

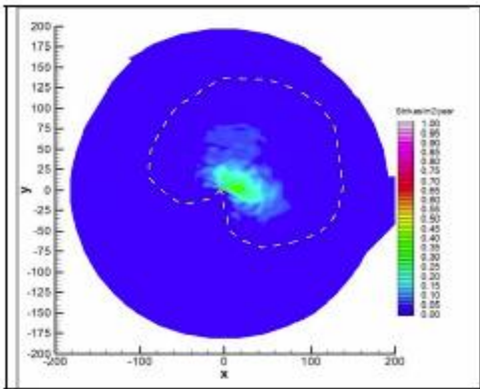


Figure 4: Strike probability for moderate icing site.

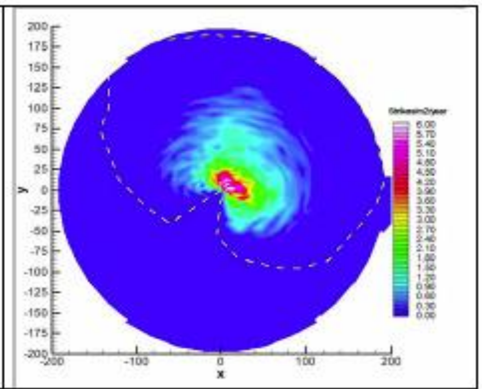


Figure 5: Strike probability for severe icing site.

Assessment of ice prevention systems

Ice prevention systems (IPS) on wind turbines cause additional investment and operational costs. On the basis of environmental data and technical guidance issues, manufacturer design requirements and objective, the procedure first assigns the boundary conditions for a series of numerical simulations and experimental campaigns. Ice accretion analysis is necessary to provide the new contaminated blade profile shape and the induced performance and load. A performance deterioration analysis allows the energy output to be evaluated. Shed-ice trajectory and structural damage tolerance analysis is also an output of the integrated procedure. A technical level decision is now made on the need of ice prevention systems. For light icing, where negligible structural and performance penalties and an acceptable risk for people and goods is evident, no ice prevention system is required and only limitations can be prescribed for in icing operations. According to the choice, simplified methods are used to evaluate the anti-icing installed power and the energy consumption, and a break-even analysis is carried out to assess the economic viability of the system. In the case the system ends as non-economically worth, only limitations are prescribed for operation in icing conditions. Numerical and in-field tests on models are necessary to assess the technical availability and reliability of the ice prevention systems.

Conclusions

The knowledge on how to mitigate the effects of the ice action is of great importance for the future development and reliability of offshore wind installations at such areas in Northern latitudes where sea ice occurs annually. Cost-effective methods need to be developed to measure and to respond to the different ice actions in order to reduce the additional loads that occur in the presence of ice. Therefore a risk analysis needs to be performed to assess the life reduction and the hazard of ice shedding which is relevant to neighbor turbines and O&M personnel. Ice mitigation systems should comprise cold weather packages, anti-icing/de-icing devices and systems reducing the actions of sea ice. The design of such systems should be integrated in the design of the turbine to assess the economic benefit of their operation in cold climates and to set limits for continuous operation during icing periods.

Ref:	Title:	Author:	Date:
3.10	Extreme Ice and Wind Loads to Foundations	H. Gravesen C. Brojas	06-2002

Summary:

Relevance to thesis

offshore wind turbine, foundation, ice loads, cone, combined loads, safety, partial safety factors

Introduction

For the first large offshore wind farms in Denmark it has been required to develop procedures to combine loads from wind with loads from ice. The procedure includes a method for defining a consistent set of partial safety factors for the various extreme load cases. The partial safety factor for wind loads is defined in the Danish standards to 1.4 to 1.5. The safety factors are different for the other environmental loads. The partial safety factor for ice load will be typically 2.0-2.5, due to a larger statistical uncertainty. The combined load cases need to include a consistent weighted average of the different partial safety factors. The combined load time series at the foundation level may be calculated on the basis of wind and ice load time series. This article the result for a relatively stiff foundation with limited dynamic interaction between the wind and the ice loads. It contains a presentation of approximated easy-to-use methods to combine wind loads with wave/ice loads as well as approximated methods to include the effect of the number of repeated design events when the operational wind loads dominate the load cases. The improved design principles can be used to reduce considerably the cost of offshore wind turbine foundations.

Ice characteristics

The extreme ice properties have been estimated, see the figure presented here. The maximum ice forces are evaluated by:

- Maximum size of ice floe 2x2 km
- Maximum current velocities and distributions of current velocities determined for the area.
- The two sites are assumed exposed to major drifting ice floes during once per year water level and current conditions.
- The ice floes are assumed to have a shape so that the force initially is transferred to one wind turbine.

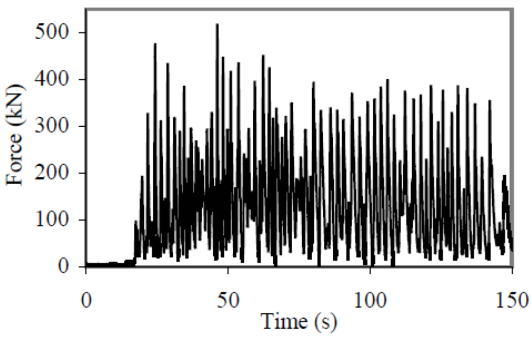
Table I Extreme ice properties in Danish Straits

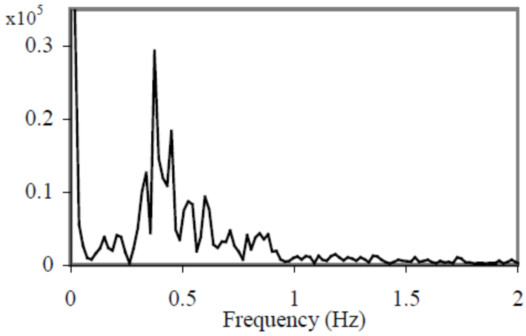
Return period	5 years	10 years	50 years	100 years	1320 years
K_{max} (-°C 24 hours)	170	245	410	480	744
r_u (Mpa)	1.0	1.5	1.9	2.0	2.4
r_f (Mpa)	0.25	0.39	0.50	0.53	0.64
t (m)	0.33	0.42	0.57	0.63	0.80

where
r_u = the crushing strength of the ice
r_f = the bending strength of the ice
t = thickness of the ice = $0.032\,(0.9\,K_{max} - 50)^{0.5}$
K_{max} = frost index = the sum of the 24 hours average temperature (in °C) during the frost period (<0°C)

Ice Load model tests

Results were obtained for a stiff structure and a compliant structure with a stiffness of 50 MN/m. Two models with a cone angle of respectively 55o and 65o were tested. A few tests on a cone-free 5 m vertical cylinder were also carried out. The figures on the following page show the test setup and ice load measurements.

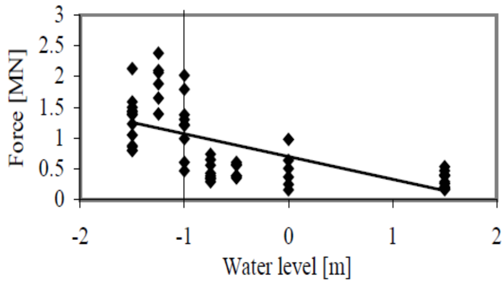


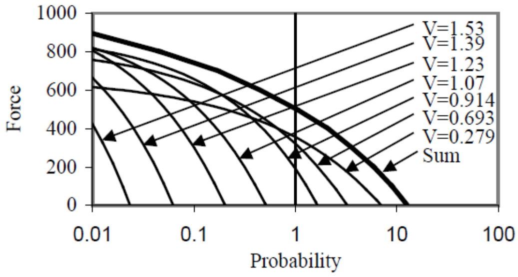


The cone induces typical breaking length around 2.5 m which results in some interaction and a certain increase in the oscillations in the first mode of the tower for the larger ice velocities

Forces depending on water level

The ice model tests show quite a large scatter of the same magnitude as for field measurements. During some tests changes in the breaking mode and pattern appeared and hereby the statistical properties changed. Due to the relatively large scatter it has not been possible to determine the relation between ice load and the actual cone diameter at the waterline. For this reason results with varying diameter have been combined. A major concern in the cone design is the required cone height. The requirement of a large cone height could rapidly become a killing assumption to wind turbine foundations as this would result in a large cone with associated increased wave loads. Basically the cone geometry should make sure, that no crushing of ice takes place on the vertical cylinder.





Combining Ice and Wind Load

Table III Example of maximum of combined extreme ice force with operational wind force for n = 100 events each of 10 min.

Frequency	Wind load (max.)			Ice load (max.)			Wind + ice load **					
-	F_{xv} (mean-max)	M_{yv} (mean -max)	V_v	F_{xi} (mean-max)	M_{yi} (mean -max)	V_i	F_x (mean -max)	M_y (mean -max)	1+ kV_{Fx}	1+k V_{My}	F_x (max)	M_y (max)
Per year	MN	MNm	-	MN	MNm	-	MN	MNm	-	-	MN	MNm
$2 \cdot 10^{-2}$ per year	0.63	43.6	0.23	0.50	9.2	0.30	0.99	50.2	1.62	1.38	1.29	58.3
$7.6 \cdot 10^{-4}$ per year	0.63	43.6	0.23	1.20	21.9	0.30	1.62	60.1	1.65	1.41	2.23	71.2

The table is only applicable to ice load on down bending cone with angle 55°, where the simple composition assume that the mean ice force is 29 % of maximum ice force, the “equivalent mean ice force” (used to perform a simple quadratic composition) = 70 % of maximum ice force, and

the mean wind load = 60 % of maximum wind load. A safe estimate for composition of the maximum force / moment and a variation coefficient is determined from the simulation. The number of events during the design scenario are safely estimated. The example includes realistic estimates of the characteristic loads for a modern 2 MW wind turbine installed offshore in Baltic.

Ref:	Title:	Author:	Date:
3.11	Monocone - Mobile Gravity Platform for Arctic Offshore	W. Jazrawi J. Khanna	-
Summary:			

Relevance to thesis
conical surface, ice load, concept development, monocone

Introduction
In an harsh and arctic environment, it has been shown that a monopod with its single column acting as a vertical indenter could be designed to remain on location year-round in the near-shore areas by failing the ice by the brute force method of crushing. However, in the exceptionally severe ice conditions further offshore, ice crushing loads become prohibitive to the economic design of marine structures. The monocone was developed to keep ice loads within manageable levels by failing the encroaching ice in flexure. The concept also affords a method of controlled set down in deeper water and renders structural costs much less sensitive to water depth.

The monocone employs a steel conical collar to deflect and fail encroaching ice, upwards or downwards, depending on how the collar is deployed. To maintain a constant waterline diameter in various water depths, the elevation of the conical collar can be varied by controlled floatation, and then frictionally clamped onto the shaft at the desired level. The collar, furthermore, is in two mechanically fastened segments which can be unlatched to enable removal from the shaft for repair or inversion. The hull is protected against deep keels of ice ridges by a heavy, sloping perimeter wall and by a system of topside radial ribs with sand infill. On location the steel collar would normally be deployed with a minimum of 4.5 m protruding above water, to ensure proper ice uplift and failure. The monocone was designed to operate year-round as a bottom-founded drilling platform in water depths ranging from its light ship draft to a specified design maximum. The structure is designed with adequate storage capacity for fuel and other drilling consumables to drill a deep 6,100 m hole without resupply.

Ice Design Criteria
Ice-cone interactions were investigated both theoretically and experimentally the latter in ice model basins. The failure mechanism of a fairly uniform and homogeneous ice sheet on a cone is fairly well known. For ridges, finite element analysis was conducted. The latter could model the three-dimensional behavior of the interaction, and incorporate distributions of ice properties above and below the waterline caused by variations in ice temperature and consolidation within the ridge. Ad-freeze is ice adhesion to other materials by freezing. Unlike failure loads of sheets and ridges, ride-up forces increase with waterline cone diameter because of their dependence on cone surface area above water. Ad-freeze forces can become very large in shallow water, again because of the large cone diameter exposed.

Conclusions
This article demonstrates the viability of the monocone as a re-locatable drilling structure

- Comprehensive ice and wave design criteria are available to enable the design of conical bottom-founded structures in ice-infested arctic waters.
- The monocone is a versatile and efficient offshore structure capable of being set down in deep water under complete control. It is a year-round and self-contained concept capable of operating without being resupplied for long periods.

Ref:	Title:	Author:	Date:
3.12	Corrosion Protection for Steel Surfaces against moving Sea Ice	D.H. Teesen	1971

Summary:

Relevance to thesis
corrosion protection, offshore steel corrosion, ice abrasion

Introduction
Where this steel is exposed to sea water and moving ice, special corrosion problems will be encountered. Uncertainties in predicting ice forces will give rise to extra-conservative safety factors for computing the amount of steel to use. The designer must select a steel resistant to brittle fracture at low temperatures, estimate corrosion allowances, and choose a suitable corrosion protection method on the basis of a relatively small amount of accumulated corrosion experience in ice-infested waters.

Corrosion of Offshore Structures
Corrosion rates on arctic offshore structures have far exceeded predictions based on previous offshore experience. The importance of corrosion under these circumstances cannot be overlooked. The supporting columns for the structures are subjected at low temperatures to severe cyclic bending loads from all horizontal directions. Continuing high rates of uniform attack and/or the propagation of stress-raising corrosion pits could set the stage for catastrophic failure. Ice abrasion and the resulting marine corrosion can reduce the efficiency of arctic structures, even those outfitted with bending cones. Increasing the friction coefficient on the ice breaking cone due to corrosion will increase the amount of horizontal force required to achieve enough vertical displacement to fail the ice in bending. Most of the structures were built with an extra allowance of steel in the tidal zone, where the greatest corrosion attack was expected. Corrosion control below the low tide level was expected from cathodic protection using installed, active anodes. From field observations it showed that these systems did not prove to be very effective, even after several years of improvements.

Corrosion Mechanisms
In winter the scouring action of ice prevents the buildup of corrosion products and corrosion rates are controlled only by the oxygen content of the water. In summer, although the accumulation of corrosion products will be slowed by the high water velocities, the corrosion rate will be controlled by the degree to which oxygen can penetrate the iron oxide layers. Areas exposed to high dissolved oxygen content will be cathodic to areas exposed to lower concentrations of dissolved oxygen. On a steel piling the areas closest to the surface, where oxygen is in the greatest supply, will be cathodic to the deeper areas. This may explain the reported increase in corrosion with depth in the tidal zone. Ice plays an important role in the corrosion mechanism because it acts to prevent the accumulation of corrosion products which would otherwise slow the reaction rate.

The cause of the pitting attack on these structures is more difficult to determine. Pitting is a localized, self-propagating form of attack which is usually associated with stagnant conditions because the accumulation of reaction products tends to keep the attack confined to the small anode areas. Local variations in the environment give rise to pits; some of the more common causes are pinholes or "holidays" in paint coating, holes in mill scale, (or patches of mill scale) and local dissimilarities in metal structure or composition.
Corrosion Protection for Offshore Structures
Inorganic zinc - A coating of this type has been applied to the tidal zone of a structure, and apparently has arrested pitting during the summer. This is considered to be a worthwhile

technique because the more cathodic areas of the structure are coated and pitting in the submerged zone should therefore be reduced.

Neoprene - This material requires careful factory application to be succesful. While neoprene may be useful at low temperatures and under heavy abrasive and impact loading, the requirement for factory application will reduce its use in the Arctic.

Plastics - Epoxy and polyester resins appear to be feasible for Arctic structures provided a suitable method of field repairs can be developed.

Concrete - A properly proportioned air-entrained mix will insure good freeze-thaw durability, but abrasion resistance will probably be unsatisfactory unless the concrete is shielded with steel.

Nickel / Copper Alloys – Successful protection with Ni-CU cladding for splash zone protection has been performed. Cladding with this method is probably not feasible for arctic structures because the large surfaces and extreme tidal range would require large areas of cladding, and because the severe mechanical environment would require greater thicknesses of the metal. It may be feasible for protecting smaller piles exposed to lesser tidal ranges.

Copper / Nickel Alloys - These metals are expected to be less resistant to attack than nickel copper since their resistance to attack is roughly proportional to nickel content.

Zinc - A zinc coating used on arctic structures was quickly removed by ice and corrosion, and the corrosion rate of zinc rises rapidly with increased water velocity.

Steel - Protective wraps of steel installed on-site are not considered to be economical owing to the high corrosion rates already experienced and to the difficulty of replacement. When they are installed, precautions must be exercised against crevice corrosion between the wrap and the leg, which could result in ever faster corrosion rates and deterioration.

Stainless steels - Stainless steels perform well in contact with sea water at high velocities. Their resistance to corrosion depends on a thin oxide film which would probably be lost to ice abrasion, which should rebuild after the ice season. If pitting got started during the absence of the passive films, it could continue after the ice season. Low alloy steels coupled with stainless steel in sea water will corrode galvanically; therefore stainless steel cladding should not be applied below the mean low tide level.

Cathodic Protection – The cathodic protection system comprises a number of anodes placed on the sea bottom approximately 15 m from the structure. Adequate current distribution and protecting the remote anodes from ice damage and underscour have been the major problems in implementing these systems.

Steel vs. Concrete - At this point, why use steel at all for Arctic offshore structures, why not use concrete? In all probability, carefully controlled concrete construction will be extensively used in the Arctic. However, steel may still be required as protection against abrasion, and corrosion will remain as an economic factor to be considered in the design of the structure.

Ref:	Title:	Author:	Date:
3.13	Design considerations of ice-resistant structures for shallow water oil and gas areas	Q. Yue D. Zhang	06-2009

Summary:

Relevance to thesis

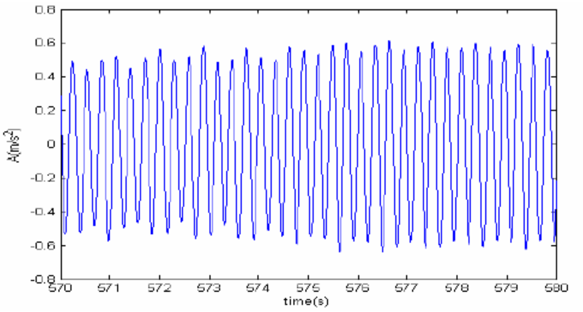
vertical structures, conical structures, pushover analysis, ice load dynamics

Introduction

Offshore platforms designed in the ice infested areas need to withstand not only the extreme ice forces, but also the dynamic ice forces. There are two types of steel offshore structures designed to resist ice forces. One is the caisson structure, which is rigid and has strong ability to withstand extreme ice force and dynamic ice force. The other is jacket structure, which is more economic as it uses less steel in the same depth of water. The jacket structure is more slender and easily to be induced vibrations by ice sheet. Ice-induced vibration for safe development of ice-resistant structures in arctic areas is a key concern. It is well known that ice could induce vibrations on slender structures and the periodic loads are formed because of the ice failure at the structure. The current design codes for offshore structures in moderate ice conditions mainly deal with the extreme force. This is because the interaction between ice and the structure is very complicated, and dynamic ice force is formed when the ice sheet fails. The ice loads and the failure modes of the slender ice-resistant structures are the key concerns in the design. To be able to develop and select appropriate technology, it is of importance to be able to calculate the design actions for safe design of the slender offshore structures. This article discusses the design aspects with attention to ice loads on the slender ice-resistant structures and failure modes induced by ice vibrations.

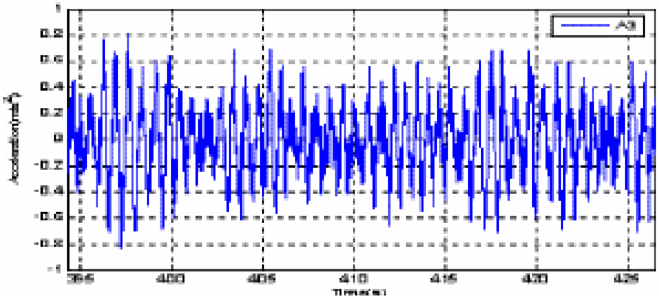
Ice Loads and Ice Induced Vibration on Slender Vertical Structures

There are different failure modes of ice against the slender vertical structures, such as bending, shear, buckling and crushing. Dynamic ice forces are found to be either one of three kinds of ice force features when the ice speed changed from low to high; these could be quasi-static, steady-state and random vibrations. They can appear in crushing failure distinguished by relative speed or ice failure behaviour. The maximum vibrations appear in the steady-state vibration. It was shown that steady-state vibrations take place when ice speed makes ice fail in the transition zone of ductile-brittle and the frequency of ice force is locked in the natural frequency of the structure during steady-state vibrations.



Ice Loads and Ice Induced Vibration on Slender Conical Structures

The idea of adding an ice breaking cone on a cylindrical structure, changing the ice failure from crushing to bending, is an effective way to reduce the static ice load and avoid the steady vibration. Ice-breaking cones produced ice-sheet failure in bending and distinct cyclic failure was observed. In each cycle, three stages could be contained: bending failure, climbing along the cone, and clearing of the ice around the cone. The bending failure of ice starts by radial cracks, propagating to form wedges. The peak load is associated with the formation of a circumferential crack, where wedge beams break simultaneously. The period of ice force is relative to the breaking length and ice speed. At high speeds, the significant ice-induced vibration will be evoked.



<u>Failure modes induced by ice-vibrations</u>

Both vertical structures and conical structures encounter significant ice-induced vibrations. The failure modes of ice-resistant platforms are complicated. Due to the internal dynamic characteristics of ice load and ice-structure interaction, the ice breaking period may coincide with the natural period of the structure. It may cause the resonance vibration, which is quite harmful to the structure. The dynamic performance requirements of ice-resistant platforms include the structural dynamic characteristics and ice-induced vibrations. The intensive ice-induced vibration could result in significant cyclical stress at the tubular joints of jacket structures that may cause fatigue failure, the damage of facilities

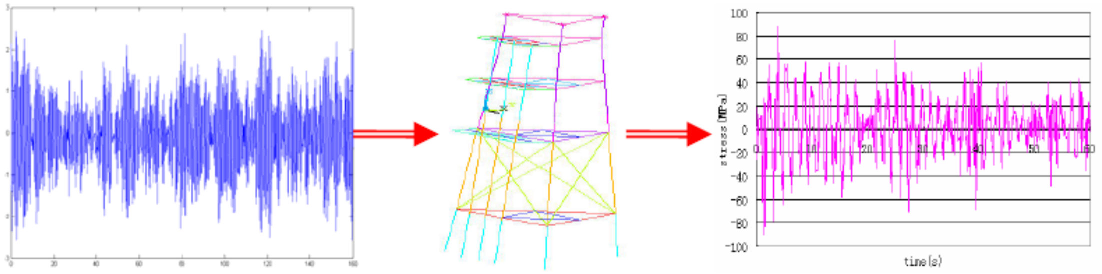
Pushover Failure Modes:

The table below shows results of the maximal deformation, the maximal stress, and RSR of typical ice resistant structures in Bohai Sea under extreme ice loads. The design ice thickness is about 42cm there. The maximal ratios of the calculation to the threshold for the deformation and stress are 27.3% and 27.1%, respectively. The safety reserves are greater, so the structures could withstand the push-over ice force. Even so, structural safety damage under extreme static ice load should be considered in the design or assessment of jacket platforms.

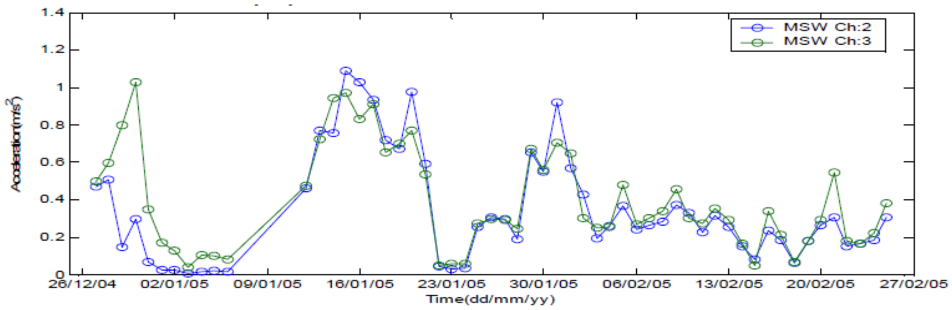
platform	Maximal deformation(mm)		Maximal stress(MPa)		RSR
	Calculation value	threshold value	Calculation value	threshold value	
JZ20-2MUQ	15	168	23	225	11.2
JZ20-2MSW	24	130	61	225	5.42
JZ20-2NW	12	118	32	225	9.83
JZ9-3GCP	24	88	36	225	3.67

Fatigue Failure of Tube Nodes:

In order to verify the possibility of the structural fatigue failure under ice vibrations, estimating whether the cyclical stress of a hot-spot is greater than the fatigue limit stress is needed. Fatigue damage of the platform is induced by cyclical stress of the tube node. The typical deck vibration response and the structural vibrations under typical ice conditions were evaluatied with modeling tools. According to the type of the node and the structural parameters, The Stress Concentration Factors (SCF) of the node is considered based on the criterion promulgated by DNV. In addition, according to the S-N curve of the steel provided by API 2A, the fatigue limit stress is about 41MPa when the limit fatigue life is. As seen on the figure below, the cyclical stress amplitudes of the structure induced by the typical ice condition are greater than the fatigue limit stress amplitude, in one minute the number of times is about 16, considering the SCF. So the cyclical stress induced by the ice forces may cause fatigue damage.



Acceleration Failure mode of Deck:
Sea ice can induce the periodic load and make the offshore jacket structures vibrate with major acceleration. These accelerations can cause several mechanical defect, such a flange loosening, pipe fatigue, bolts un-tensioning etc. Compared with the ISO standard about human body in vibration environment (GB/T 13442_92), it is found that as a living platform, intensive deck vibrations could discomfort the crew members and even affect work efficiency or health. On the following figure the typical daily deck vibrations of ice resistant platforms is shown.



<u>Proposal and consideration for ice-resistant design</u>
The ice conditions and ice-structure interaction play an important role in oil exploitation and production. Although under extreme static ice loads the safety reserves of ice-resistant jacket platforms are greater, and the structures could withstand the push-over ice force. The phenomenon of ice accumulation which can lead to a larger global ice load on the platforms should be considered in the concept design. Both vertical structures and conical structures encounter significant ice-induced vibrations. However the intensive steady-state vibration on the vertical structures is more harmful than the ice-induced vibration on the conical structures. The idea of adding ice breaking cone should be adopted in the concept design. Additionally, in order to promote the bending failure process of ice breaking and decrease the contact area between the ice and cone, traditional ice breaking cone might be substituted by adding attached component on the cone or changing the form of the cone. In order to avoid strong ice-induced vibrations, newly designed ice-resistant structures, such as those are more flexible than existing economical jacket structures, should be presented. These structures should not only resist an extreme static ice force, but also react gently to the ice-vibrations.

Ice-resistant design aspects for the shallow water and moderate ice conditions:

- Perfect geometry to avoid the ice accumulation.
- Ice breaking cone should be adopted.
- Vibration mitigation and control device might be applied.
- Dynamic failure mode of slender ice-resistant structures should be considered.

Ref:	Title:	Author:	Date:
3.14	DNV Recommended Practice for Ice Effects on Offshore Arctic Structures	A.B. Cammaert A.M. Horn	06-2009

Summary:

Relevance to thesis
arctic design codes, DNV, ISO19906, ice loads, arctic design considerations

Introduction
The design of offshore structures in areas of arctic conditions and ice interaction is a discipline that is continuing to develop. There is ongoing research and development into preliminary and detailed design aspects, and a certain level of optimization for projects that are currently being executed. For offshore structures in Arctic areas, the highest load actions are normally caused by ice/structure interaction, and it is of great importance that these loads are accurately addressed.

Over the past decade major initiatives have emerged to develop new and comprehensive codes for the design of Arctic offshore structures. The most important of these, ISO 19906 is intended to harmonize and update existing regional and national codes. DNV has decided to
develop a companion document to the ISO standard, which is intended to comply fully with the
Normative provisions of the Standard. The RP should be considered as a supplement to the Informative provisions of ISO19906 by providing practical design recommendations and case studies.

Understanding of ice effects
Studies indicated that there is a considerable improvement in agreement for loads generated by a level, first-year ice sheet on a vertical-sided structure. There is still a large disagreement in the range of predicted loads from first-year ridges and multi-year floes interacting with a vertical-sided structure. There is a large range of disagreement on predictions of level ice on a conical-shaped structure. The coverage in different codes was judged to differ considerably. Some codes give detailed guidelines while others may just warn of a particular loading condition.

Why DNV recommended practice document?
The Normative part of the ISO Standard represents a very helpful list of items that should be considered when designing Arctic offshore structures, and the Informative part provides suggestions on how the provisions of the Standard may be satisfied. The ISO relies on Recognized Class Societies rules in addressing specific detailed issues, and DNV plays a significant role in developing such rules and standards. DNV publications are divided into three categories; Offshore Service Specification (OSS), Offshore Standard (OS), and Recommended Practices (RP). The OS gives detailed requirements and the RP provides optional or additional proven design aids.

DNV has reached an agreement for the ISO 19906 Standard to start RP-C209. DNV has a strong focus on developing recommendations and guidelines for Arctic Technology in order to ensure safe and sustainable exploration and exploitation of oil and gas in this vulnerable area.

DNV-RP-C209
The RP will identify and discuss issues that should beneficially be addressed in the concept screening or FEED stage. The scope of the proposed RP is to provide practical guidance on key issues related to the following topics:

- Design methodology, particularly relating to safety philosophy and probabilistic design.
- Characteristics, properties and conditions for sea ice and icebergs in selected areas.
- Ice action scenarios and load prediction algorithms for fixed and floating structures.
- Discussion of structure response for key design issues.
- Case studies for fixed and floating structures.

	Structure	Type		Function		Ice Regime				Analysis	
	Description	Fixed	Floating	Drilling	Production	FY floes	FY ridges	MY ridges	Icebergs	Deterministic	Probabilistic
1	Single Leg Jackup	■		■		■	■			■	■
2	Multi Leg Platform	■		■	■	■	■			■	
3	Multi Leg Jackup	■		■		■	■			■	
4	Vertical Caisson	■		■	■		■	■		■	■
5	Sloped Caisson	■		■	■		■	■		■	
6	DP Drillship		■	■		■			■	■	
7	Moored Buoy		■		■	■	■		■	■	

It is intended that there should not be any unnecessary duplication of work in the RP over what has already been done in the DIS for the ISO19906. DNV will likely elect to expand on specific topics, or for very few cases, further research activities. Where a specific topic is well covered in the DIS the RP will only provide a brief summary of the recommendations or ice action algorithms, and the appropriate sections of ISO will be referenced.

Conclusion

DNV has decided to develop a companion document to the new ISO standard ISO19906, which is intended to comply fully with the Normative provisions of the Standard. The RP should be considered as a supplement to the Informative provisions of ISO19906 by providing practical design recommendations and case studies. A Joint Industry Project (JIP) has been initiated, with representation from operators, engineering and shipbuilding companies, and research institutes.

Ref:	Title:	Author:	Date:
3.15	Fixed Offshore Platforms in the Arctic	R.P. Stag	1971

Summary:

Relevance to thesis
arctic structures, construction, design considerations, arctic concepts

Introduction

Due to the current surge of interest in the development of hydrocarbon reserves in the Arctic, a need exists for structural designs which are not prohibitively expensive for fixed structures to support drilling and production operations in the hostile environment. The principal design problems are rather quickly resolved to be definition of design risk level, derivation of loadings suitable to that risk level, and development of structural configurations which will resist those loadings and provide satisfactory operational characteristics.

Loading

One generally thinks of structures sufficiently close inshore to lie within the bounds of shore fast ice as essentially static structures subjected only to loadings induced by thermal expansion and contraction of the ice. In such a location the primary design consideration may well be wave action during the ice free season or ice forces during heavy weather conditions before the ice mass becomes fast to the bottom or after spring breakup starts. In locations further offshore, wave action is still a significant consideration, as a possible maximum loading and as an influence on installation procedures for the structure. Probable sea states at the planned location will affect the installation and could have a profound effect on the design of the structure. The primary lateral loading, however, will likely be imposed by ice in its various forms. It will be necessary to carefully assess the probability of occurrence of loading mechanisms and their intensities for each given location, to prevent over-dimensioning of the structure, which can lead to prohibitive costs. The final selection of design conditions should be made in light of the economic significance and desired life span of the structure.

Materials

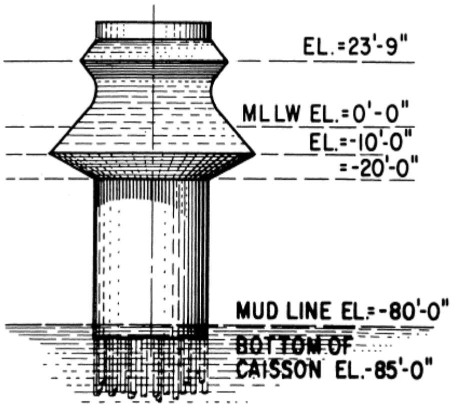
In the Arctic, one would desire a material which provides a high resistance to ice abrasion, low temperature ductility, and a high strength to weight ratio. The strength to weight ratio may not be so important to operational performance, but is important to transportation, installation, and possible salvage at the end of its economic life 15 or 20 years hence. Steel will probably prove to be the most economical material for Arctic structures, with substructures having grouted filled steel cellular exterior hulls to provide local rigidity to ice forces. An alternate substructure material may be prestressed concrete with a steel abrasion face. A prestressed concrete substructure would, however, be heavier than one of steel and may require a longer transportation time due to the resulting less favorable tow characteristics. A self-buoyant concrete structure would certainly have draft limitations during transportation and installation which would be more severe than that of a steel structure.

Foundations

For any transportable structure of reasonable size and mass, the foundation will be required to resist not only bearing loads, but also uplift from the lateral load overturning moment. The foundation must resist lateral movements to within the limitations imposed by well casing and product flowline flexibilities. Mat foundations do not possess the capability to resist overturning uplift. That resistance must come from the mass of the structure. Except in favorable subsurface conditions, mat foundations will not provide bearing capacities in the order of magnitude likely under Arctic structures without pile support. Pile foundations will prove to be necessary as a general rule to support Arctic structures, particularly in deeper water. Pile foundations can be designed to resist overturning couples and lateral shears even in the worst of subsurface conditions. The drawback is that piles will in many locations extend into permafrost. It is feared that the pile will act as a thawing mechanism in the permafrost. The problem is intensified by the probable use of at least some of the piles as well conductors.

Arctic designs

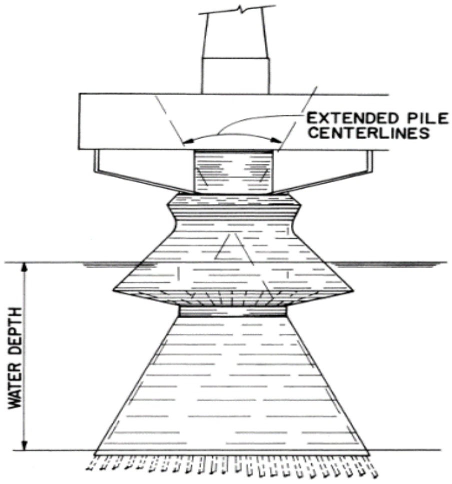
It is obvious that structural concepts which would be successful in one area of the Arctic offshore would yield to other configurations in other locations and loading environments.



The structure in the figure was proposed as a test module to assist in the accumulation of data on pack ice characteristics and forces. It was intended to produce a relatively inexpensive structure to support a sloped icebreaking face. The structure was proposed to be a 50 foot diameter steel caisson of cellular hull construction with a slip-over ice breaker having a water line dimension of 80 feet. The icebreaker position was to be field adjusted to provide an 80 foot dimension at the water line regardless of depth, for depths equal to or less than design. A constant diameter caisson was required to permit the icebreaker to be positioned at any height on the caisson.

Drilling and Production Platform

It is probable that the best configuration for a production platform substructure would be a conical form similar to many lighthouse structures. For somewhat deeper water, however, the volume and surface area of a conical structure becomes extremely large. A stepped hull form such as that indicated in the figure could improve characteristics. The step, or return, in the upper cone provides the possibility of objectionable uplift due to ice pressures on the lower face. The uplift can be minimized, however, by judicious choice of return slope.



DRILLING AND PRODUCTION PLATFORM
FIGURE 2

Conclusion

The economic success of Arctic offshore structures depends on definition of loadings appropriate to a realistic risk level, recognition of the hazard of construction in ice susceptible areas, the limitations of short construction season and difficult logistics. Given these stipulations, it is possible to design platforms to successfully resist Arctic ice loadings. To predict structural configurations without aiming toward a particular set of criteria is valueless, as in the Arctic, more than any other area of petroleum operations, the structural concept will be determined by local probable conditions at the proposed structure's location.

Ref:	Title:	Author:	Date:
3.16	Ice and Offshore Wind Turbines in the Gulf of Bothnia	M. Määtänen	06-2009

Summary:

Relevance to thesis
Gulf of Bothnia, ice loads, offshore wind in ice conditions

Introduction
The Gulf of Bothnia and shallow coastal areas of Finland are good candidates for wind energy farming. Compared to existing offshore wind farms the foundations in the Gulf of Bothnia have to be designed to withstand level ice thickness up to 1.2 m. Beyond the landfast ice zone moving ice can be 0.8 m thick with significant pressure ridges. The trend in wind generator size is now towards larger units, to the capacity range of over 6 MW. Especially at offshore sites where foundations are more expensive it is a must to use large units, to make construction of offshore wind farms cost effective. In Finland the Ministry of Trade and Industry funded research to Explore the potential of offshore wind energy in Finland and what are the implications of moving ice on wind generator foundations. It was learnt that about 70TWh, all of the annual Finnish electricity consumption, could be harvested from the Gulf of Bothnia. In this article, wind, wave, ice and sea bottom conditions in the Gulf of Bothnia are described with an eye on establishing wind parks.

Offshore wind farms
At offshore sites the wind energy production is over 10 % better than inland. The reason is a better shape in the wind boundary layer profile and lower turbulence level in the wind. In many cases also the average wind speed is higher. Adverse effects are wave and ice loads against the foundation. Atmospheric icing on the tower and propeller blades can be more intense. During the winter only thermal ice expansion loads are met. Limited ice action is exerted against the foundations in the landfast ice zone. In the Gulf of Bothnia there is no tide but a storm surge can raise water level over two meters. This allows deeper waves to proceed longer. As water depth decreases waves get higher and steeper.

Wind and Wave loads
Average annual 6 m/s wind speed line follows close to the shoreline along the Finnish side of the Gulf Of Bothnia. Less than 2 km offshore average speed exceeds 7 m/s. Wind generator nominal output is usually referred to about 15 m/s wind speed. As the energy is proportional to the third power of velocity only 15 % of nominal power output is available at 7 mls wind. At higher winds the generator RPM is limited and completely stopped during a storm. Highest measured wind speed in the Gulf of Bothnia has been 39 m/s. There is an ample safety barrier for a typical wind generator design wind gust speed of 55 m/s. Wind load at nominal 15 m/s wind from the propeller and hub is about 280 kN. This results a bending moment of 20 MNm to sea bottom at -10 m depth. For a conical shape at waterline ice load is about 2 MN and results in the same 20 MN moment to the foundation. However, at about 25 m/s the wind load increases over twofold before the rotor is stopped. Hence the wind load will become decisive in foundation design. Significant wave height in the Gulf of Bothnia is less than 3.5 m. For a 4 m diameter cylinder wave loads are about 0.5 MN, significantly less than ice loads. If there is a caisson or conical section underneath the wave loads will increase but the location of resultant is lower. Regardless of these possibilities wave load calculations indicate that wind loads will remain the decisive design factor in the Gulf of Bothnia.
Wave period is dependent on wave height. For significant wave heights the wave periods are always over five seconds, much longer than the longest natural periods of wind generators. Thus no wave load resonance is to be expected either. The main issue due to wave action is to furnish wind generator foundations with adequate erosion protection.

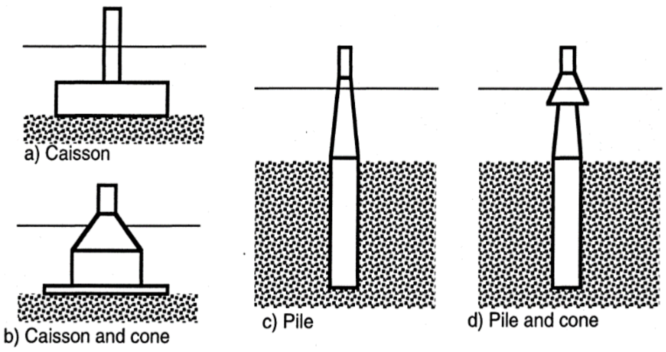
Ice Loads

All possible ice loading types are to be considered when designing a wind generator foundation. Both static and dynamic ice load designs have to be made. Ice adfreeze loads result after ice starts to move after a long and cold period. In the article level ice load, adfreeze ice load and thermal expansion ice loads are discussed and calculations are presented. Conical sections at the waterline with ice failure by bending reduces ice loads from those of crushing. In the landfast ice zone moving pressure ridge loads are not to be expected during the wintertime when ice is thickest and strongest. However, during fall ice formation and spring ice melting period moving pressure ridges can occur. If pressure ridge is moving one has to add also simultaneous parent ice sheet failure load to get the maximum load. Rubble pile-up is likely to occur on the wider and shallower foundation footing. This poses another concern for wind generator foundations, due to blocking the access to the tower.

There are limiting factors for the ice loading scenario's described. Environmental thrust may not be high enough to make the ice move. In the wind generator park an array of foundations will improve the natural locking of landfast ice. Also with more fixing points the oncoming ice can buckle well ahead of the structures and form rubble piles that ground and protect structures behind. It is also possible to make artificial reefs to promote rubble pile-up formation at preferred locations. All site dependent limiting factors should be carefully considered and utilized to reduce ice action against foundations.

Foundation principles

The sea bottom in the Gulf of Bothnia is made up of silt, sand or moraine. Sufficient stiffness allows to use either gravity based caissons or large piles. Both can be furnished with a conical section at the waterline to reduce ice loads and ice-induced vibrations. However, access by boat becomes more difficult with the presence of a cone .

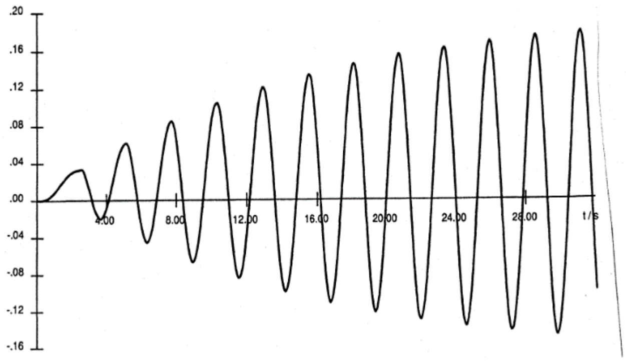


The material of a caisson foundation is normally concrete. Caisson diameter, tentatively over 20 m, is at the same range as what has been used in offshore lighthouses. Stability of the caisson during towing phase allows to assemble also the tower, nacelle and rotor completely ashore. This reduces the required length of the weather window for installation work at sea. Bottom preparation can be made earlier and erosion protection later with less restrictions in weather conditions. The only problem is during the sinking phase when auxiliary stabilization is needed. Steel foundation pile is manufactured in a machine shop or shipyard. The diameter is up to 4 m. As about four times the diameter is driven down into sea bottom the total length is over 20 m. Compared to the caisson foundation there is more installation work at sea but the favoring factor is that neither bottom preparation nor erosion protection is needed. Preliminary cost estimates indicate that the complete cost of foundation and installation of the wind generator is the same within few percents regardless of whether a caisson or pile foundation is chosen.

Dynamic ice loads

First experiences with steel pile as a foundation for lighthouses proved disastrous. After the nature of ice-induced vibrations were uncovered and vibration isolation for lighthouses introduced the steel foundation pile proved to be successful and replaced caisson foundations. Vibration isolation is intended to carry through high vertical and small horizontal loads between the tower and foundation. This function is hard to be combined with high horizontal wind loads. Without vibration isolation there are two ways to mitigate the effects of dynamic ice forces. First the foundation can be made so stiff that foundation displacement response is insignificant. This requirement is likely to increase foundation cost even though with a caisson foundation the stiffness is naturally high. The second is to use a conical section at the waterline that changes ice failure from crushing to bending and reduces ice loads. Then the displacement response reduces as well. Important is that ice failure frequency falls below the lowest natural frequencies of the complete structure. Thus the threat of resonant vibrations is avoided. In design the natural frequencies and modes of the complete structure has to solved, and if needed, structural mass and stiffness changed in such a way that resonance due to propeller blade excitation is avoided. Load cases include transients due to ice edge hit or sudden ice load relaxation, random ice load level variations, and continuous repeating ice load failures. Transient or random loading response calculation is an ordinary practice as the loading function is known.

As an example dynamic analysis response results due to an assumed saw tooth ice loading function are shown in the figures. Nacelle displacement amplitude approaches 0.2 m, which is only about 20 % of maximum wind induced deflection. For a much stiffer corresponding caisson foundation displacement and acceleration response are only about one tenth of those of the pile foundation.



The application example indicates that dynamic ice loads do not become a restrictive factor for wind generators. With cone the repetition rate of ice failures is dependent on ice thickness. Ice failure repeat after ice advances at least a distance of two times its thickness. In the Gulf of Bothnia thick ice velocity never gets over 0.3 m/s. Hence e.g. a 0.8 m thick ice will never fail against a cone at higher frequency than 0.2 Hz. This is well below the wind generator lowest natural frequency, and hence resonant loading is possible only with thin ice and low ice forces.

<u>Conclusions</u>

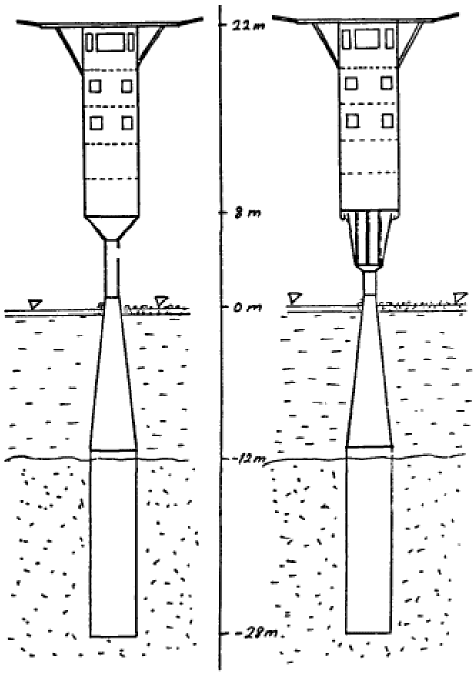
The Gulf of Bothnia offers vast areas of landfast ice zone with reduced ice action against offshore structure foundations. The trend in making larger wind turbine units has increased wind loads acting high above the sea level. Wind moment at the foundation becomes the most important factor in the foundation design. Wave and ice loads are of lower importance. Pile driving or gravity caisson foundations are applicable for wind generator foundations. Both foundation types have their merits and disadvantages. With stiff foundation and/or conical section at the waterline the dynamic response of dynamic ice forces can be made tolerable for wind turbine nacelle and rotor. The cost of wind energy is decreasing by serial production of wind generator components and by constructing large wind energy parks. Shallow offshore sites in the Gulf of Bothnia are promising in harvesting wind energy in the future regardless of long ice covered season.

Ref:	Title:	Author:	Date:
3.17	Ice Forces against a Steel Lighthouse and Proposed Structural Refinements	M. Määtänen	1975

Summary:

Relevance to thesis

dynamic ice structure interaction, ice loads, Gulf of Bothnia

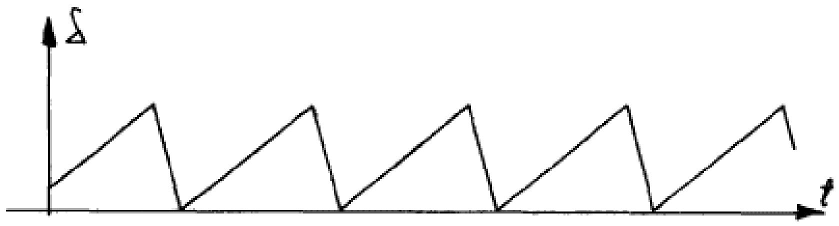


Introduction

The Kemi I lighthouse was situated at the northernmost end of the Gulf of Bothnia. The structure was a tubular steel pile hammered deep into the sand of the sea bottom. The underwater structure was conical, with the neck narrowing to the waterline to minimize ice forces. The above water structure was also a tubular steel cylinder. Compared with concrete caisson type lighthouses, the steel lighthouse was a light, flexible structure. The basic idea of this low-weight steel lighthouse was a cheap and simple structure with a minimal amount of construction work at sea. However, it appeared to be very sensitive to ice-induced vibrations. Even the crushing of a relatively thin ice sheet caused severe vibrations.

Vibration behavior and ice forces

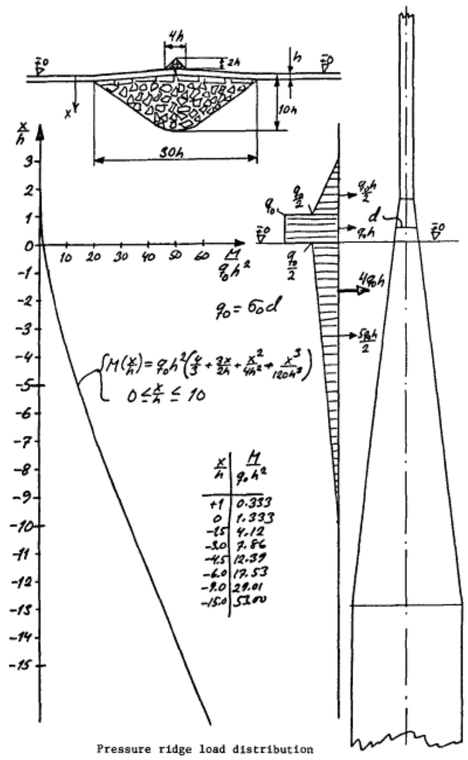
Three types of vibrations were observed: pure vibrations with the first and second natural mode of the structure, and a_combination of these two. The second type could continue unchanged for several minutes. Acceleration levels were high although ice thickness was small. The third type of vibration was a combination of the first and second natural modes. It was more common during observation time than the pure first mode on thick ice. Usually when the ice thickness grew the resonant second mode disappeared and the structure started to vibrate with the first mode and increasing amplitudes. The vibration changed to a combination of the first and second modes and this might continue as long as thick ice or a pressure ridge crushed against the lighthouse. At the beginning of the combined cycle, when the ice failed and crushed, the sudden release of the load caused the structure to spring out of its deflection with all its natural modes. Of these the first two are most dominant, and as the second was four times faster, crushing would start with the second mode. During the return phase of the second mode the foundation pile came loose from the ice edge and later hit against it. At this stage all the energy of the second mode was dissipated and the crushing continued next only with the first mode for the remaining half cycle. A typical double-blow crushing noise was heard during this type of vibration. Later in the motion, when the foundation pile was free of the dynamic effects of upper structures, a fourth type of vibration was observed. The displacements of the foundation pile grew almost linearly with the drifting speed of ice cover. At maximum deflection the ice strength was exceeded and crushing began and displacement sprang back to zero in a very short time. After crushing the foundation pile again stuck to the edge of the ice sheet, starting displacement growth and a new cycle without additional vibrations, as seen below.



The vibrational behavior of the ice sheet and the lighthouse structure is best described as "stick-slip" movement. The stick-period occurs when the pressure of ice against the structure is lower than the ice crushing strength. Once this is exceeded the slip-period will begin. In the combinational vibration of the first and second and fourth modes a periodic damping occurred for the second mode. The energy dissipation during ice crushing plays a major role in the damping. During the combined vibration at the first and second mode the ice thickness did not match with the natural frequencies of the structure. The properties of ice are statistical by nature and so the ice force and crushing will also be random variables causing a random response for the structure.

New design criteria

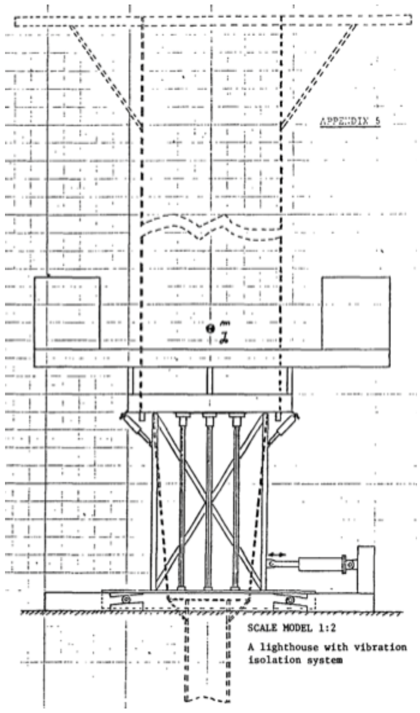
When calculating the ice force the ice crushing strength has to be adjusted according to the pile diameter to thickness ratio. It is advantageous to have a small diameter at the waterline in order to minimize ice forces. The maximum ice load will be due to a maximum pressure ridge. The resultant pressure ridge load will be 2 to 3.6 times the maximum fast ice sheet load. With slender structures as a bottom founded steel tubular, it is also important to know the pressure distribution. A vertical load distribution in a pressure ridge is adopted, as can be seen in the figure. Maximum pressure is at the area of fast ice cover that is lifted about its thickness by underlying ice bricks. On the area of ice bricks nearest the fast ice sheet the pressure is assumed to be half of the maximum, reducing linearly to zero when going to the top of the sail bottom of the ridge regardless of the slender cone shape. Total pressure ridge load will then be four times the fast ice sheet load. The dimensioning of the underwater structures may be carried out using a loading with both static and-dynamic components. The dimensioning of the above water structures will be undertaken with eye on dynamic ice forces.



Pressure ridge load distribution

Vibration Isolation System

In order to obtain vibration levels low enough in above water structures it is more economical to arrange a vibration isolation system rather than to stiffen underwater structures. Dimensioning only against static ice forces yields a too flexible structure with high acceleration values at the top of the structure. A new design for the connection between above- and underwater structures is designed to be flexible, to isolate the vibrations to the underwater structure. During the rapid deflection spring out of the foundation pile during ice crushing the light horizontal spring stiffness of the connection cannot transfer high loads and acceleration values to the upper structures. The supporting elastic beams are designed to give internal damping as well, but there is an additional double shock absorbing system with shock absorbers and stoppers. Relative movements between the upper and lower structures is restricted by using a stopper ring. The design criteria for the vibration isolation system are the amount of permitted relative movement and the amount of energy dissipation capability in shock absorbers during dynamic resonant ice loading. The effectiveness of the vibration isolation system has been confirmed by scale model tests.



Ref:	Title:	Author:	Date:
3.18	Ice Loads for Wind Power Foundations in the Gulf of Bothnia	L. Fransson L. Bergdahl	06-2009

Summary:

Relevance to thesis
ice loads, Gulf of Bothnia, wind power foundation, ice structure interaction

Introduction
Ice loads measured on lighthouses in the Gulf of Bothnia can serve as guidance for design of foundations for wind-power generators. These structures must withstand high pressures from solid land fast ice as well as from ice ridges or other drifting ice masses that are drifting.

Ice conditions in the Gulf of Bothnia
In the Gulf of Bothnia two main types of ice are observed, namely fast ice and moving ice. Fast ice is even level ice covers frozen to the coast and locked in by the extensive archipelago. This ice develops rather fast during the freezing period and will then be rather still during the rest of the ice season. The moving ice in the central area is of dynamic nature and usually deformed. The deformation process causes bands of ice fragments, hummocked ice and ice ridges. The compacted ice pack often freezes together and bands of thick ice, thicker than the snow covered fast ice, are formed.

Ice pressure loads
Static ice loads on a structure will often reach a maximum after the ice has been partly crushed and is about to move. If the contact between ice and the structure is smooth the stress distribution becomes rather uniform after a certain loading time due to viscous creep and creep crushing. According to plasticity theory the highest stress level is a function of yield strength of the ice and the degree of confinement around the structure. Static ice pressure is most likely independent on size of the pressure area if the confinement is constant.

If the driving force is sufficient, ice floes are crushed against vertical structures when they are moving. The driving force in the Gulf of Bothnia comes from the wind and the drifting velocity is about 3% of the wind velocity, usually less than 0.6 m/s. The prevailing low-saline ice is extremely brittle even close to the melting point and thus brittle ice crushing is the most common failure mode. Fracture mechanical behaviour implies that the process is highly dynamic causing substantial vibrations to almost any structure in interaction. These vibrations may lead to ice induced resonant oscillations on flexible structures. Such oscillations are only limited by the damping in the system and may cause a total collapse of an otherwise stable structure.

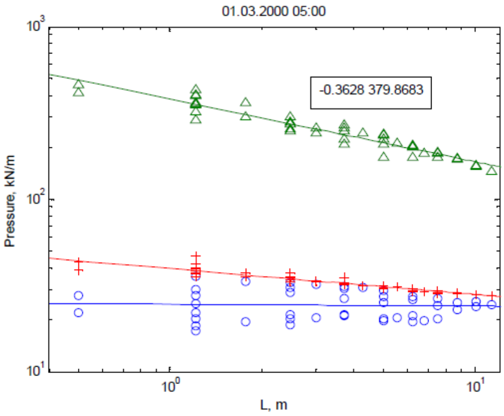
It has been shown that high-pressure zones develop at the centre of the contact area. The maximum pressure in these small zones is probably limited only by pressure melting. Average pressure over a large contact area is typical less than 1/10 of these peak pressures. Major fracturing is only one of many mechanisms that are involved. For narrow structures the aspect ratio is the most important factor and must always be considered when selecting the effective pressure. Wide structures imply that a larger volume of ice is involved in the crushing process and one might expect some type of size effect. It is also possible that the ice thickness has an effect on the effective pressure, and thus linked to the influence of pressure area.

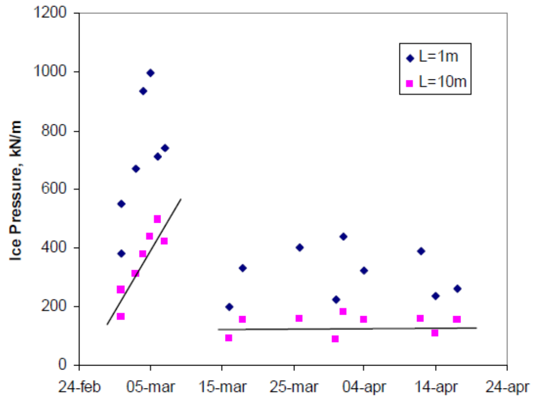
Static pressure measurements
Ice loads on the lighthouse Norströmsgrund in the Gulf of Bothnia were measured simultaneously on nine panels covering about half the periphery (LOLEIF database). It was

found that the highest pressure was 625 kN/m, measured at the onset of ice movement. The local ice thickness was measured to 0.7 m in direct contact with the lighthouse foundation.

Ice crushing

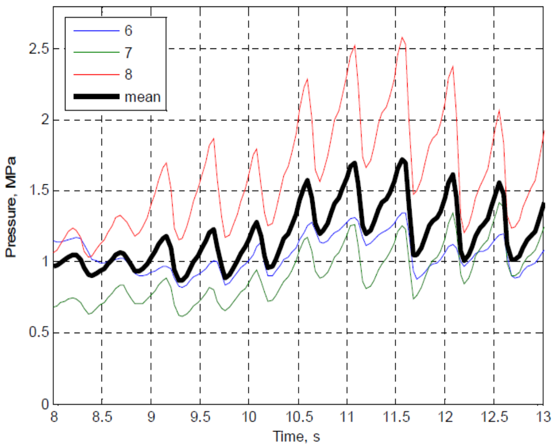
Results from LOLEIF also showed that the dynamic ice loads most of the time were uncorrelated on pairs of load panels that were separated from each other. An overview of measured ice pressures is shown in the figure as a function of contact width L. A maximum pressure of 380 kN/m was estimated, whereas the pressure decreased to 165 kN/m for 10 m contact width. As can be seen there is a substantial scatter of the individual panel pressures around the perimeter of the foundation and the local pressures are somewhat underestimated.



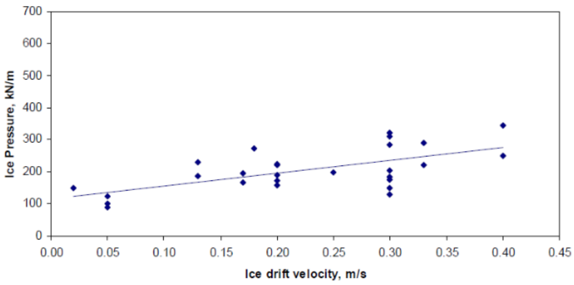


Ice-induced vibrations

Measured ice pressure and corresponding lighthouse displacement were often small and limited by bending, splitting of floes or collapse of weak ice or inhomogeneous ice. When the moving ice floes were thick and strong enough and the velocity was over a critical value, continuous ice crushing resulted in vibrations of the structure. Measured oscillating pressures are characterized as a saw-tooth curve where the force dropped faster than it was build up. For wider structures this high frequency variation was superposed a quasi-static load level referred to as ice extrusion pressure. The structure was then always in contact with the ice edge.

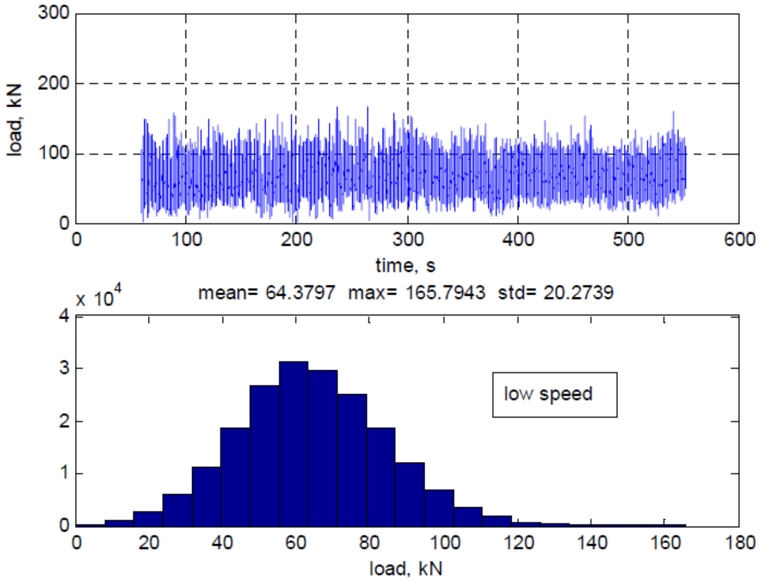


It was not possible to trace any clear dependence of ice drift velocity on the effective pressure even though the ice induced vibrations were triggered above a critical velocity. When the total load was divided only with the actual contact width there was a clear trend shown in the figure.



High-speed ice crushing

At high penetration speed most of the experienced rate effects originate from indentation tests where the structure instead of the ice sheet has been moved. These findings are not directly applicable because of the different inertia effects but comparisons can be made. In one of the tests series the velocity was kept as constant as possible and the steel pile was pushed for 10 minutes in smooth and uniform level ice. This test procedure was repeated at three different velocities at different dates with changed ice conditions. Load record and corresponding distribution are shown in the figures below. The recorded ice load was characterized as a harmonic vibration at about 40 Hz when the steel structure was pushed in 0.25 m thick level ice at a speed of about 0.3 m/s. Average load level, standard deviation and maximum load is given in the figure for the period when the speed and thus the vibration was relatively uniform.



Discussion

Ice strength usually decreases with increasing ice thickness and the average ice temperature in the thick ice become close to zero. Several dynamic effects made the thicker and older ice-cover in the Gulf of Bothnia less homogeneous and many crack systems were kept unfrozen. In a more severe winter, ice may grow to its maximum thickness without these flaws. For design it is therefore not motivated to use a lower effective pressure or compressive strength for thick ice in the northern parts of the Baltic Sea. It is then important that the selected design ice thickness is based on good statistics of the thermally grown ice cover and not on measured ice thickness that may include rafted or hummocked ice. The results from the icebreaker indentation tests indicate a general trend of increasing mean load levels with speed but the maximum load did not always follow the pattern. Snow on the ice or changing ice brittleness was a factor that may have affected the fracturing mechanism and thus the velocity trend.

Conclusion

For the purpose of design, effective pressure as well as compressive strength is assumed to be independent of ice thickness. Structures should be designed for dynamic ice loads that are dependent on natural frequency of the structure and ice drift velocity. Increased effective pressure has been indicated for high speed ice crushing. Ice load measurements on lighthouse Norströmsgrund support the suspicion that also design ice loads should increase with drift speed. This rate effect and other uncertainties about the worst scenario for ice-induced vibrations suggest a more conservative design of wind-power foundations inside the dynamic ice zone.

APPENDIX D – SUMMARY OF ARTICLES RELATED TO OFFSHORE WIND ENGINEERING

Ref:	Title:	Author:	Date:
4.01	Conceptual designs for large scale offshore wind farms – DOWEC Final Results	M.B. Zaaijer H.B. Hendriks	2005
Summary:			

Relevance to thesis
offshore wind farm development, offshore wind research, offshore wind concepts, economics

Introduction
The offshore environment imposes new and more complicated requirements on the application of wind energy. Additional external influence is present through hydrodynamic loading, a corrosive environment and the possibility of seabed erosion around the structure. Energy transmission, support structures and maintenance are generally more complex and have higher costs, complicating economic exploitation. Copying onshore wind energy technology and practices of the offshore oil and gas industry is therefore not necessarily the best solution for offshore wind energy. The intention of the DOWEC project was the development and integration of the necessary knowledge, design tools and competence to build reliable and commercially attractive offshore wind turbines and wind farms. The project included the design of a 6 MW wind turbine, optimized as part of the offshore wind farm. A baseline wind farm was designed and evaluated, including all main hardware components, installation and operation. The baseline wind farm and wind turbine were used as a reference for over forty conceptual and parametric variations. This paper summarizes the achievements of the research, an overview of the adopted approach, the used models and an evaluation of the designed solutions.

Design Case
The most important parameters that were obtained from site-specific datasets were:

- 3-dimensional scatter diagrams of wind speed, significant wave height and zero-crossing periods for fatigue analysis.
- Extreme values of wind speed and wave height for ultimate limit state calculations.
- Wind climate for energy yield estimation.
- Weather windows for assessment of operations.
- Description of borings in the targeted area.
- Bathymetry surveys.

The most important parameters for foundation design that were determined for the two sites were the soil type, the occurrence of boulders, saturated unit weight, undrained shear strength and friction angle. Typical heat conductivity and convection of the wide graded dense sands and sea temperature at the seabed were assessed, to calculate the maximum electricity cable capacity.

Large-scale wind turbines
Power performance and load sets were determined for a reference rotor and 22 variants to investigate the rotor design. The aero-elastic design code was extended with a model for blade pre-bending in flap wise, upwind direction, which is common for large blades. The following conclusions were drawn:

- Reduction of the blade-chord of an ‘ideal’ rotor by up to 20% resulted in a reduction in aerodynamic loads that outweighs the decrease in power.
- Twist of the outer part of the blade could be increased slightly. The reduced angle-of-attack gave enhanced aerodynamic damping of edgewise blade vibrations.
- Smaller maximum lift coefficients gave some benefit through smaller blade loads.
- Increased blade stiffness resulted in decreased fatigue in edgewise direction, but increased fatigue in flapwise direction.

With a diameter of 6 m, a steel monopile foundation was still an option for the 6 MW turbines in 21-36 m water depth. For the monopile the following variants were investigated: with and without scour protection, two alternative transition pieces to facilitate installation and pre-stressed concrete. As alternatives, tripods with driven piles and with suction piles were analyzed, focusing on feasibility, optimization of the main dimensions and adjustment of the natural frequency. Several designs of scour protection with dumped rock were made for the monopile. Large cost-savings were obtained when the protected area was reduced and shear failure was allowed. Of four alternative concepts, only rock dumping in a scour hole could be a more economic, feasible option. Integrated geotextile with concrete block mattresses, a protection wall with concrete filling and seabed improvement by gluing were too expensive, technically difficult and there was too little experience with the concept.

The need for preventive and corrective maintenance was determined. Maintenance procedures were defined for four categories: lifting of heavy components with an external crane, lifting of heavy components with a built-up internal crane, lifting of small parts with a permanent crane and man-carried parts and equipment.

<u>Large-scale wind farms</u>
Three promising electrical infrastructure systems were chosen for evaluation: constant speed, individual variable speed and park variable speed. For each of these options three cable layouts with varied spacing were evaluated: the string, star and octopus. Investigations regarding the length of offshore cables revealed that a distance to shore of 100 km was still feasible.

An installation procedure was developed in which most of the activities took place on land. Tower, nacelle and rotor were assembled on temporary foundations in the harbor before transport to their offshore location. The monopile and transition piece were installed by the same vessel or a separate pile-driving vessel. With 60% workability installation of the 80-turbine wind farm in one season was only possible when two vessels were deployed. An installation yard was required for operations and storage. Based on method statements a budget model was established that was used to calculate costs for different park layouts. Several alternative installation procedures for the turbines and the cable connections were assessed, including omission of a transition piece, one-step installation of the entire turbine, sub-sea power connections and an offshore workspace.

<u>Wind turbine and farm concepts</u>
Levelised production costs (LPC) were identified as the leading criterion in the overall assessment. A cost model was developed. The cost items and power performance characteristics could be fixed values, values that differ per concept or trends of main parameters. The designed baseline wind farm was characterized as a ‘best practice’ wind farm. It was expected that the baseline wind farm had a moderate to low development risk and moderate costs per kWh. The main features of the baseline wind farm were: 3-bladed, variable speed, pitch to vane turbine, with gearbox and doubly-fed induction generator and rotor diameter of 129 m; a small internal crane, that can hoist a larger built-up crane; one service visit per year and an overall failure rate of 1.55 failures per year; a tubular tower, connected to a monopile foundation with grouted transition piece; scour protection by rock

dumping in a reduced area around the pile; single-lift installation on pre-installed piles, using one vessel and two seasons; an electrical infrastructure of three interconnected strings, each with a separate AC line to shore; maintenance from a supplier, retrofit and overhaul every four years. Assuming an operational lifetime of 21 years and a real interest rate of 5%, levelised production costs of the baseline were 5.54 € ct/kWh. A breakdown of the LPC is given in the table below. The energy yield over the lifetime of the wind farm equaled 34,816 GWh.

Component	Unlevelised costs (M€)	Percentage of LPC	Energy yield / Efficiency	(-)
Wind farm design	13	1.2	Electric transmission	0.961
Hardware	576	50.8	Electric infrastructure	0.980
Transport and installation	132	11.1	Aerodynamic farm efficiency	0.917
Yearly O&M	26	28.1	Farm availability	0.985
Four-yearly overhaul	30	7.5	Turbine availability	0.915 - 0.97
Decommissioning	41	1.3	Annual yield (GWh)	1.698

Single-objective concept variations were designed, aiming at reduction of the LPC through one specific aspect of the wind farm. No concept changed the LPC by more than plus or minus 5%. The influence of some governing parameters, such as the number of turbines, water depth and rotor diameter, proved to be large.

<u>Conclusions</u>
An integrated approach with partners from different fields of technology resulted in a high number of investigations into different subjects needed in the design of offshore wind farms. This knowledge was applied to generate an optimized design of a 480 MW wind farm. It can be concluded that design variations improving the efficiency and reliability turn out to be economic despite the additional investment costs. The effect of conceptual changes on the LPC tends to be small compared with the expected accuracy of the cost estimates. The baseline wind farm proves to be already fairly optimal, due to pre-selection of concepts based on engineering intuition.

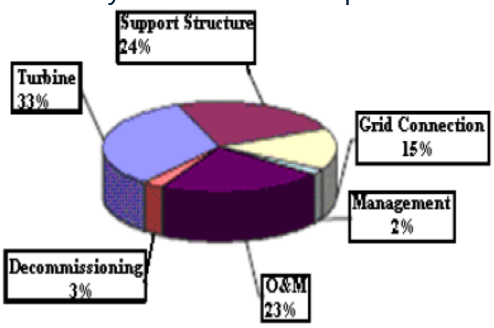
Ref:	Title:	Author:	Date:
4.02	Monopile foundations for Offshore Wind Turbines	V.J. Kurian C. Ganapathy	2010

Summary:

Relevance to thesis
offshore wind energy, monopile foundation, wind turbines, environmental load.

Introduction
Wind has been established in modern times as a source of renewable energy to generate electricity through the use of wind turbines. Wind flows over the airfoil-shaped blades of wind turbines, causing lift, causing the turbine blades to turn. The blades are connected to a drive shaft that turns an electric generator to produce electricity. Offshore winds are less turbulent and they tend to flow at higher speeds than onshore winds, thus allowing turbines to produce more electricity. Increased wind speeds of only a few kilometers per hour can produce an exponentially larger amount of electricity.

Studies indicate that the cost of offshore wind turbine systems is significantly more than land based systems because of the higher cost of foundations, installation, operation and maintenance. The breakdown of the costs for a wind farm in shallow water is shown below



Offshore wind technology
Once a suitable place for the wind facility is located, piles are driven into the seabed. For each turbine, a tower is installed on the pile foundation for supporting the turbine assembly, for housing the remaining plant components and for providing sheltered access for personnel. A matrix of fiber glass mats impregnated with polyester or epoxy is used for making the rotor blades. The turbine consists of a rotor with blades, connected through the drive train to the generator. After the turbine is assembled, the wind direction sensors turn the nacelle to face into the wind and maximize the amount of energy collected. Offshore turbines have different technical requirements compared to onshore turbines due to the climatic environmental exposure. Design modifications are required to suit the different environmental conditions. Offshore turbines are typically equipped with built-in service cranes, corrosion protection, and internal climate control and high grade exterior paint. To minimize expensive servicing, offshore turbines have automatic greasing systems to lubricate bearings and blades. Also, they have pre-heating and cooling systems to maintain gear oil temperature within a narrow temperature range.

Offshore wind turbine pylons
Tapered steel tubes formed from seam welded rolled plates with flange bolted connections at the terminations are used for constructing majority of offshore wind towers. Taller towers are built up from separate lengths determined by limitations of transport and lifting. The portion between the nacelle and the level of the highest wave crest is called pylon. Steel monopiles have natural frequencies falling between the blade passing frequency (2 s) and the wave excitation zone (6 s). When taller towers with larger and heavier turbines are used, the natural periods of oscillation are likely to fall into the wave excitation zone (6s to 20 s) and therefore great care is to be taken to prevent the dynamic amplification of responses.
Offshore wind foundations
Three different types of foundations have been used to support the offshore wind turbines. They are monopile foundations, torpid foundations and gravity based caisson foundations.

Monopile Foundations

A simple design in which the wind tower is supported by the monopile either directly or through a transition piece. The monopile consists of a steel pipe pile up to 6 m in diameter with wall thickness as much as 150 mm. Depending up on the subsurface conditions, the pile is typically driven into the seabed by either large impact or vibratory hammers, or the piles are grounded into the sockets drilled into rock. Compared to the gravity base foundation, the monopile has minimal and localized environmental impact. The monopile is the most commonly used foundation for offshore wind turbines in shallow water depths. When the water depth increases, they have to be stiffer to avoid large natural periods. Therefore, this type of foundation has a water depth limit of about 30 m.

Torpid Foundations

The tower is pinned by three-legged or four-legged steel jackets to small diameter steel piles or caissons. This foundation is suitable for deeper waters and has great scope for future development. Tripods are also under development, using suction piles.

Gravity Based Caisson Foundations

The principle of gravity based foundation is an in-place mass sitting on top of the soil to prevent the monopile from moving. The size of the tower and gravity base can be increased to satisfy the design requirements corresponding to the turbine size and tower height. Steel gravity foundations are easier to transport and install because they are lighter than concrete caissons. Gravity foundations, whether made of concrete or steel, are much costlier than monopile foundation.

Comparison of the three types of foundations and found that the monopile foundation has the longest lifetime, but the torpid and gravity based foundations have more lateral strength. The main disadvantage of the monopile foundation is that it requires more time and cost to construct and position them and that it can be used only for shallow water depths up to 30m.

<u>Loads on monopile foundation</u>

Wind Loads

The wind load applied on the turbine tower comprises of the effects of the direct wind pressure on the tower and the wind turbine. The wind turbine loads have two components namely stationary and cyclic. The cyclic loads are aerodynamic loads from a uniform, steady wind speed and the stationery loads arise from the centrifugal forces. A stationary but spatially uneven flow field over the swept areas causes cyclic load changes on the turning rotor. The inertia forces that result from the rotating rotor blade masses cause periodic, non-stationery loads. In addition to the stationary and cyclic loads, the rotor is exposed to non-periodic and random loads caused by wind turbulence. The variables to be considered are direct wind pressure, gust factor and force coefficient.

Wave and Current Loads

Wind towers at sea are subject to forces from waves, and water currents. When the waves act against structures, their energy is transferred as loads on the structure. The wave loads comprise of the inertia component and the drag component and they depend on the wave height, wave periods and water depth at the location. The shape of the structure influences the drag and the inertia coefficients. The wave loads decrease exponentially towards the sea bottom. The loads due to the water current are dependent on the square of the velocity of the current.

Loads from Wind Rotor

The static and dynamic reaction components from the rotor on to the wind tower have to be properly accounted for as they will produce axial force, shear force, overturning moment and twisting moment on the foundation. Special wind rotors that transfer minimum reactions on to the tower have been developed recently.

Dynamic Behavior
The dynamic characteristics of the tower have to be examined with the help of simulation or modeling to understand dynamic properties of the tower. It is necessary to understand the extent to which the flexibility in the foundation plays a role as a design parameter in influencing the dynamic behavior of the tower. The dynamic magnification effects can directly influence the fatigue loads to be considered in the tower design. The tower frequency should be designed such that it avoids excitation of the resonant oscillations that result from rotor thrust fluctuations at the blade passing frequency or at the blade rotational frequency. Larger and heavier turbines will inevitably experience longer periods of natural oscillation. Offshore wind turbines are also bigger than onshore turbines.

Pile Soil Interaction
The interaction between the monopile and the soil around has to be properly accounted for by incorporating the measured soil properties in to the calculation of the immersed weight, lateral soil pressure, soil stiffness and the soil friction. The details depend up on the assumptions made about soil properties.

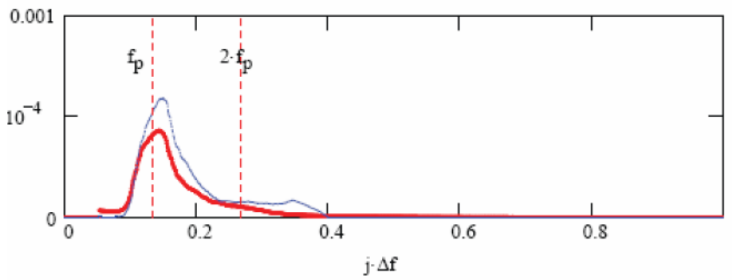
<u>Possible useful reference:</u>
Article contains a calculation example on the described monopile foundation loads, based on a case in the Malaysian waters. Could be useful for load determination during modeling phase of thesis.

Ref:	Title:	Author:	Date:
4.03	Waves for design of wind-power plants in shallow seas	L. Berghdal L. Fransson	06-2009
Summary:			

Relevance to thesis
wave loads, wave conditions, offshore wind support structure loads

Introduction
Most wind-energy plants are intended for water depths less than 20 m. A concept for assessing design waves at a near-shore site is to transform the offshore wave spectra to the target site by a model for spectral wave-energy transfer over the actual bottom topography. The inshore spectra can be used for linear statistics of extreme waves and design wave loads can be produced. For the design of structures offshore or near-shore against wave loads it is necessary to have some realistic design waves. These could be regular design waves for extreme loads or irregular waves for dynamic load cases and fatigue problems. Based on measurements the TMA shallow water spectrum is recommended for assessing irregular waves. The TMA spectrum is a modified JONSWAP spectrum.

Waves were measured at Bockstigen on with a pressure and directional bottom mounted equipment and with a wave-radar. Analysis of records from the same occasion shows that the pressure equipment mounted at 6 m water depth gives inaccurate information of the second-order double frequency waveform due to the attenuation of the dynamic pressure with depth, because, when amplifying the attenuated pressure signal by dividing with the attenuation factor, noise will also be amplified. The wave-radar gives the actual geometric waveform directly, however, with some inaccuracies at peaked, breaking waves. In both measurements it is difficult to differentiate between first-order and second-order waves at the same frequency. Measuring in one point the wave celerity cannot be evaluated.



Standard Wave Spectra
There are many wave spectra used for waves offshore in deep water, i.e. when the wavelength is smaller than twice the water depth. A fundamental spectrum is the Pierson-Moscowitz spectrum, which should describe wave spectra for fully developed sea, or fully arisen sea (FAS), when a constant wind blowing infinitely long cannot increase the energy in the waves, but the energy transfer is balanced by dissipation. This spectrum is a one-parameter spectrum completely described by the wind speed:

$$S_{PM}(\omega) = \alpha g^2 \omega^{-5} e^{-0.74(\omega_s/\omega)^4}$$

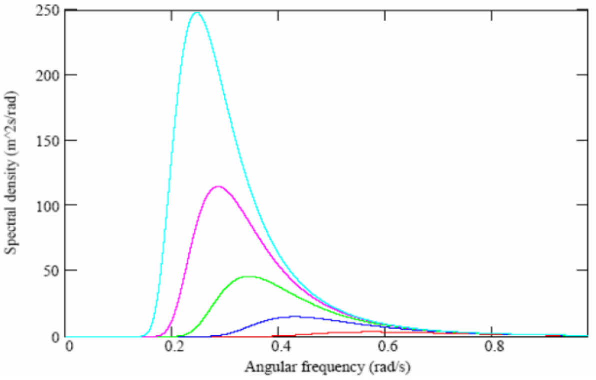
In this spectrum the significant wave height, H_s, is used instead of the wind speed or mean period.

where $\alpha = 0.0081$ is Phillip's constant,

g the earth acceleration,

$\omega_0 = g/(U_{19.5})$ and

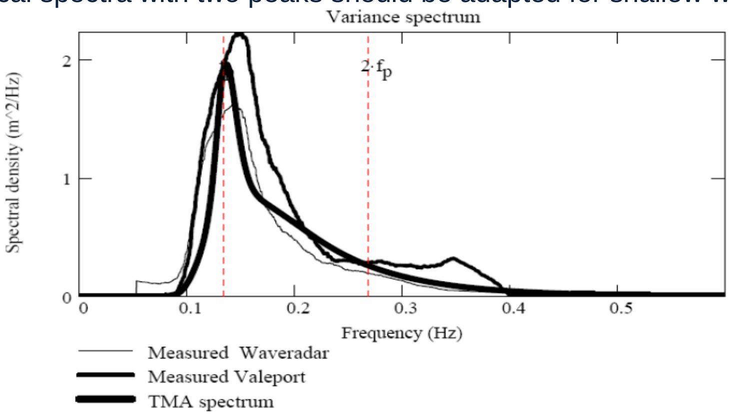
$U_{19.5}$ = the wind speed at the height 19.5 m above still water level.



Mostly the sea state is, however, not fully developed as the wind speed and direction change, the fetch is too short, or the duration is not long enough, especially for strong winds and high waves. Then two-parameter spectra for developing seas can be used, some in which the wave height and frequency are the parameters. This offers more flexibility, because the energy of the spectra can be placed at arbitrary locations on the frequency axis with the demanded significant wave height. While the JONSWAP spectrum originally was developed for developing sea in deep water, the waves in shallow areas are often waves coming in from deeper areas into an area where the waves are much affected by the limited water depth. A modified JONSWAP spectrum in shallow water called the TMA spectrum is presented. It is based on the fact that low-frequency or, equivalently, long-period waves must have a limited height in shallow water. Therefore the spectrum is multiplied by a function for limited depth.

Comparison with measured spectra

The measured spectra, from the wave radar and the Valeport measurements are compared with the TMA spectrum using the recommended parameterisation with input significant wave height. It is observed that only the TMA spectrum, of the spectra investigated, is capable of reasonable approximation of this sea state at the Bockstigen site. The conformity between the measured spectrum and the TMA spectrum may be improved if the parameters are adjusted for each measured spectrum. Spectra from 58 one-hour wave radar measurements have been compared with TMA spectra withstandard parameterisation and input significant wave heights, Hs, and peak frequencies, fp, estimated from the measurements. One can conclude that for high waves (> 1.5 m approximately) originating from steady winds in one direction the TMA spectrum gives a good fit. For lower waves the fit is poorer. For waves originating from turning or strongly changing winds with two spectral peaks, theoretical spectra with two peaks should be adapted for shallow water.



Ref:	Title:	Author:	Date:
4.04	Modelling offshore wind resources - Comparison of a mesoscale model and measurements from FINO 1 and North Sea oil rigs.	E. Berge ø. Byrkjedal	2008

Summary:

<u>*Relevance to thesis*</u>
wind measurement, comparison of models, wind loads

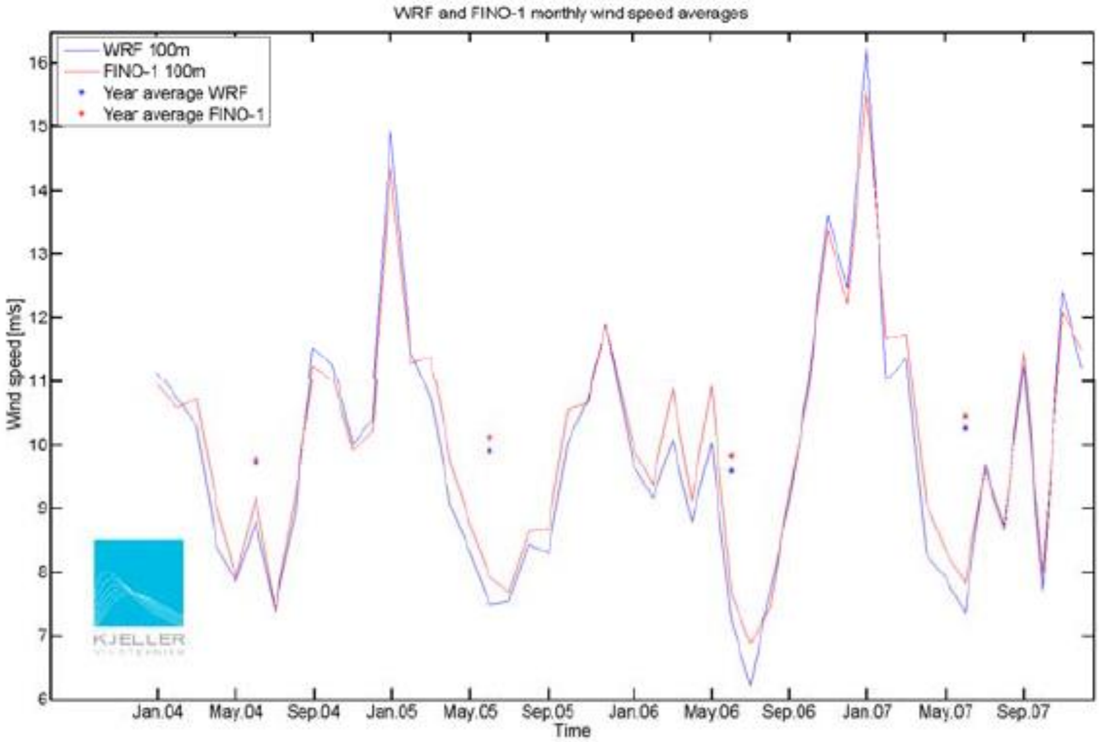
<u>Introduction</u>
The meso-scale meteorological model WRF (Weather Research and Forecasting) has successfully been applied to onshore wind resource assessment in Norway. Annual average wind speeds are typically predicted within ± 10% of observed values in 50m high measuring masts for coastal mountains. For more homogeneous areas lower deviations are found, and for offshore regions even more accurate predictions may be expected. The aim of the performed research is to develop wind atlases for the Irish Sea, the North Sea and the Baltic Sea. The model has been run for four years for the North Sea, and wind speed and wind direction statistics have been generated based on output from the model. Detailed vertical wind and temperature data are available which have be used to analyze the WRF model results. Meteorological measurements from the oil rigs in the Norwegian sector of the North Sea are also compared with the model calculations.

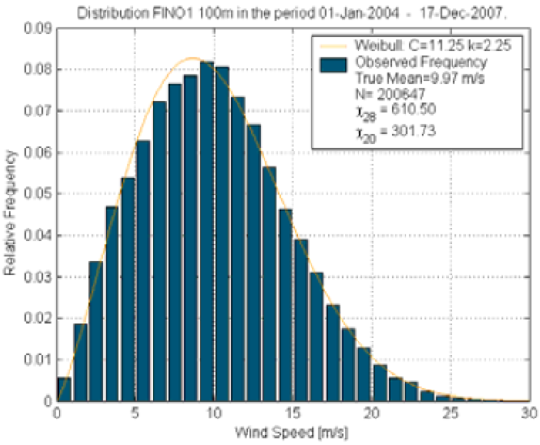
<u>Measurement data</u>
In the present analysis wind speed data from the levels 60m, 80m and 100m have been utilized. The wind speed data have been corrected for mast effects by employing Lidar measurements. Furthermore, wind direction data are from 90m, while the temperature data utilized are from the levels 30m, 40m, 50m, 70m and 100m. The data set is considered to have high quality compared to for instance wind measurements at oil rigs.

<u>Meso-scale meteorological model</u>
The Weather Research and Forecast (WRF) model is a meso-scale numerical weather prediction system, aiming at both operational forecasting and atmospheric research needs. The global data are analysis based on observational data for the time-frames 00, 06, 12 and 18 UTC. The global data have been interpolated to the WRF-grid. The lowest layers in the model are at approximately the heights 20m, 60m, 115m and 190m. The model has been run for four years (2004-2007) to cover the measuring period. Hourly data in each grid-point and for each vertical level is stored from the runs. Thus a large database is available. The sea is characterized by a low roughness value. This roughness is, however, dependent on the state of the sea surface, wave heights and pattern etc., which is dependent on the surface stress.

<u>Comparison of results with measurements</u>
On an annual basis the differences are small between the model and the measurements. On average the model yields 0.1 m/s lower wind speed than measured during the four years period. The average wind speed values for this period were 10.0 m/s and 9.9 m/s based on the measurements and the WRF-model respectively. On a monthly basis the deviations are larger and up to 0.5m/s. The hourly correlation between the model and the measurements is 0.92. The model and the measurements follow each other closely most of the time with a few exceptions where rather large deviations occur. Also the modelled Weibull distribution fits very well with the observed distribution, though the model overestimates the occurrence of wind speed in the range 8-10m/s with about 1%. Finally, the average wind shear is presented in Table 1. The measurements indicate an increasing wind shear factor from 0.05 between 80m and 100m to 0.08 between 60m and 100m. On the other hand, the model

data indicate a reduction of the wind shear moving from the layer 80m-100m to the layer 60m-100m, which may appear somewhat unrealistic. The vertical resolution is low in the model for such detailed comparison and inaccuracies in the vertical interpolation could also affect the results. It is important to be aware of that atmospheric stability effects also could play a role. It is therefore recommended to analyse the wind shear data more closely together with the stability data. All this date can be found in the figures below.





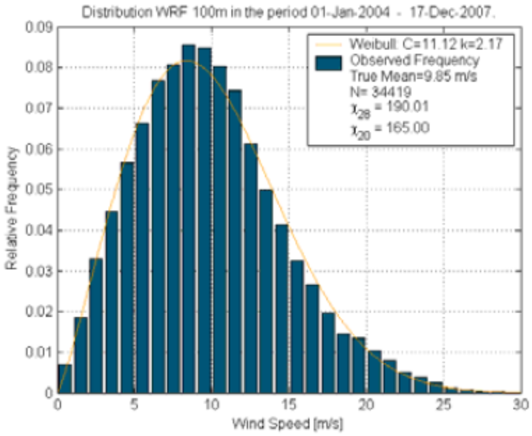


Table 1. Average wind shear for the period 2004-2007 at Fino 1.

Wind shear	100m-80m	100m-60m
Fino 1	0.05	0.08
WRF	0.07	0.06

The overall impression is that the model is very capable of generating the average wind conditions. It is recommended that the model data is utilized for offshore wind resource assessment and preliminary energy estimates and wind farm layout. The model should also be well suited as a tool to develop offshore wind atlases of the Irish Sea, the North Sea and the Baltic Sea.

Wind shear and atmospheric stability

The modeled temperature follows the measured temperature closely, but the model is slightly biased toward too low temperatures. This could be linked to too low sea surface temperatures of the model. The offset is typically 0.5 - 1.0 ºC. Most of the time the temperature drop over the 70m is in the range -0.5 ºC to -1.0 ºC, which corresponds to near neutral stability conditions. The relatively warm sea surface in January gives rise to a well-mixed near surface boundary layer. Actually, the model tends to give a ~ -0.7 ºC temperature drop over the 70m during long periods corresponding closely to neutral conditions. In the measurements we note a couple of incidents of strong vertical stability, which are not captured by the model. We also encounter a few cases of rather strong vertical instability which is not picked up by the model either. The vertical profiles of temperature are in the model parameterized and thus forced to follow more closely a standard profile. Instantaneous mixing also will take place within the vertical layers in the meso-scale model, thus smoothing out vertical differences to some degree. In addition, any turbulence on a sub-grid horizontal scale (below ~ 2 km) is also parameterized in the numerical model, which in turn will contribute to a smoothing of spatial and temporal differences in the physical quantities.

Conclusion

Monthly and annual average wind speeds from the WRF model compares very well with the observations. Also the four year Weibull distribution and wind rose from the model correspond well with the observed values. The model is a reliable tool for characterizing the average offshore wind conditions, at last in the south eastern part of the North Sea. However, for the temporal variations of vertical stability and wind shear larger deviations between the model and the measurements are encountered, and before the model data are applied to for example wake modeling a more detailed study of the statistical properties of the model data is recommended. Comparison of the average wind speeds of the WRF model with data from four oil rigs in the Norwegian sector of the North Sea indicate that the measurements could overestimate the annual wind speeds with as much as 5-10%. Thus, the oil rig data should be applied with care in wind power studies, unless overestimation of the offshore wind energy potential could result.

Ref:	Title:	Author:	Date:
4.05	Comparison of Design Guidelines for Offshore Wind Energy Systems	R.K. Saigal D. Dolan	05-2007

Summary:

Relevance to thesis
offshore wind design guidelines, comparison of design codes

Introduction

This article provides a general comparison of different guidelines that may be used for the design of offshore wind turbine support structures. The intent of this article is to describe the range of applicability of the different design guidelines and to illustrate how these may be compared to assess their applicability to the design of OWT support structures for wind farm applications in the United States. The codes and guidelines that have been developed for the design of land-based wind turbine structures have been adapted to address the issues associated with the marine environment. These additional requirements have focused primarily on the loads that are generated from waves and currents and the effect of these loads on the design of the support structure and its foundation.
API RP-2A provides a basis for the design of offshore structures subject to wave, wind, current and earthquake loading conditions; however, it does not address the scope and range of all conditions that are required for the design of wind turbine support structures. API RP-2A would have to be adapted or supplemented with other standards if it were to be used as the basis for wind turbine design. Guidelines that have been developed for the design of offshore wind turbine generators, such as IEC 61400-3, have utilized offshore guidelines similar to API RP-2A as the basis for the development of OWT marine requirements. Guidelines such as the IEC 61400-3 and API RP-2A may therefore include similar design requirements for wave and current loading conditions. However, a direct comparison of the IEC and API requirements show that there are some specific differences. The IEC uses a 50- year return period for the definition of extreme environmental design conditions. API RP-2A includes three levels of design requirements based on the platform type and its failure consequence. API RP-2A uses a 100-year return period for the definition of design conditions for high consequence platforms.

Development of Guidelines for Offshore Structures

Design guidelines relevant to offshore wind turbines and other offshore structures have four main origins; Industry developments, Governmental initiatives, Classification societies and from International developments.

American Petroleum Institute (API)

The API recommended practice for offshore platforms (API RP-2A Working Stress Design) is used for the design of various types of structures that have been designed using RP-2A ranging from major multi-level platforms installed in very deep water to minimal structures located in shallow water. Structures that have been designed using API RP-2A are located in areas that are dominated by extreme storms, hurricanes, earthquakes and ice. Therefore, API RP-2A provides a valuable experience base that can be used for the design of structures operating in harsh marine environments. API RP-2A categorizes structures into three levels of exposure based on specific life safety and consequence of failure. These exposure categories may be used to define environmental design criteria. While RP-2A does not include specific provisions for wind turbines, the guideline does include a wide array of technical information required for the design of offshore structures that are applicable to OWT support structures.

International Electrotechnical Commission (IEC)

Technical Committee TC-88 of the International Electrotechnical Commission has compiled the international guidelines for wind turbines. IEC 61400 is developed specific to the design

and assessment of wind turbines. IEC 61400 comprises ten guidelines, covering a range of topics from safety and design requirements to performance assessments of prototype turbines. Of these, 61400-1: “Design Requirements” and 61400-3: “Design Requirements for Offshore Wind Turbines” contribute the most to the design process. IEC 61400-3 specifies the requirements for the definition of site conditions and, together with IEC 61400-1, provides essential design requirements for of offshore wind turbines. The guideline is intended to provide an appropriate level of protection against damage from all hazards during the planned lifetime of the structure.
IEC 61400-3 focuses on the engineering integrity of the structural components of an offshore wind turbine but also provides requirements for subsystems such as control and protection mechanisms, internal electrical systems and mechanical systems. One of the most valuable aspects of IEC 61400-3 is the rigorous specification of design load cases that address all operating conditions in combination with applicable external loads. The standard allows for the use of other industry design guidelines, such as GL, DNV and API. IEC specifies that when partial safety factors from national or international design codes are used together with partial safety factors from IEC 61400-3.

Germanischer Lloyd (GL)
Germanischer Lloyd (GL) on the basis of the Guidelines may carry out certification of offshore wind turbines for the Certification of Offshore Wind Turbines. The GL guideline for the Certification of Offshore Wind Turbines provides a complete set of rules for the certification of offshore wind turbines and offshore wind farms. The guideline covers requirements for the support structure, turbine machinery and blades. The COWT includes a clarification of certification extent, loads, materials, structures, machinery, rotor blades, electrical systems, safety systems and condition monitoring systems. The GL safety philosophy is derived from onshore turbine experience. The load factors are harmonized with IEC 61400-1/3 and the material factors are comparable but specified in greater detail than the IEC guidelines.

Det Norske Veritas (DNV)
The DNV offshore wind turbine guideline DNV-OS-J101 provides principles, technical requirements and guidance for design, construction and in-service inspection of offshore wind turbine structures. The guideline may be used for the design of support structures and foundations of offshore wind turbines, as well as the design of support structures and foundations of other structures within an offshore wind farm, such as transformer stations and meteorological masts. DNV-OS-J101 is intended to be used for the design of support structures and foundations for offshore wind turbines. For structural design of wind turbine components for which no DNV guidelines exists, reference is made to the IEC61400-1 guideline.

International Organization for Standardization (ISO)
ISO standards relevant to offshore technologies are contained within the ISO 19900 – 19909 series. While these standards do not specifically address offshore wind turbines, considerable guidance is given for the design of offshore structures in general, particularly with regard to structural integrity. As is the case with API RP-2A, the ISO standards contain general guidance on the design of offshore structures in general but do not include specific provisions for the design of OWT support structures. Relevant ISO standards include:
· ISO 2394: General principles on reliability of structures
· ISO 4354: Wind actions on structures
· ISO 19900: General requirements for offshore structures
· ISO 19901: Specific requirements for offshore structures
· ISO 19902: Fixed steel offshore structures
· ISO 19903: Fixed concrete offshore structures

Provisions for Fatigue Conditions in Guidelines

An important distinction between offshore wind turbines and offshore structures used for oil and gas production is the fatigue demand. Conventional oil and gas platforms are subject to cyclic loading primarily from waves. The support structures for OWT will experience wave induced cyclic loads as well as substantial cyclic loading due to the wind load and rotor rotation. The relative significance of the wave and wind fatigue demand will depend upon specific environmental conditions. Wind induced fatigue is a primary design driver for offshore wind turbines in relatively mild ocean environments.

Provisions for Extreme Load Conditions in Guidelines

API RP-2A specifies a return period of 100 years for the environmental conditions such as wind, wave and current for design of offshore structures. Criteria are typically developed for 100 year wave heights with concurrent wind and current conditions. The ISO 19902 standard for fixed steel offshore structures also specifies a return period of extreme external conditions of 100 years. Inherent in the IEC 61400-3 guideline is an assumed safety level for offshore wind turbines that is equal to the safety level for onshore wind turbines specified by IEC 61400-1. For design load cases that feature normal design situations the extreme external conditions are specified with a return period of 50 years. In the case of an offshore wind turbine, wind and waves are important sources of loading and therefore the combination of extreme wind and wave conditions is specified such that the global extreme environmental action has a combined recurrent period of 50-years. Both the GL and DNV guidelines adopt the basic assumption of a 50-year return period of extreme external conditions for ultimate load cases.

Comparison of Inherent Reliability

A straightforward way to compare inherent reliabilities of IEC 61400-3 and API RP-2A is to generate separate designs of a structure using each guideline and then assess and compare the respective reliabilities of the two designs. To provide a broad comparison of the two guidelines, this exercise would need to be repeated for a large number of structural types and environmental/load conditions. A simpler approach is to compare the two guidelines without considering a specific design structure. This approach is possible by eliminating structure-dependent coefficients in the design or reliability formulations.

Conclusions and Future Work

The results provide an initial indication of the comparison of the API and IEC guidelines. The review of the existing guidelines has shown that each one addresses different issues and provides a unique perspective on the design of OWT support structures. Extra studies will help to identify a set of guidelines that will provide design requirements specific to OWT support structures and meet the levels of reliability required by all parties involved in the development of the offshore wind resources. (ie. regulatory, public and private).

Ref:	Title:	Author:	Date:
4.06	Design and Construction Considerations Offshore Wind Foundation	S. Malhotra	2008

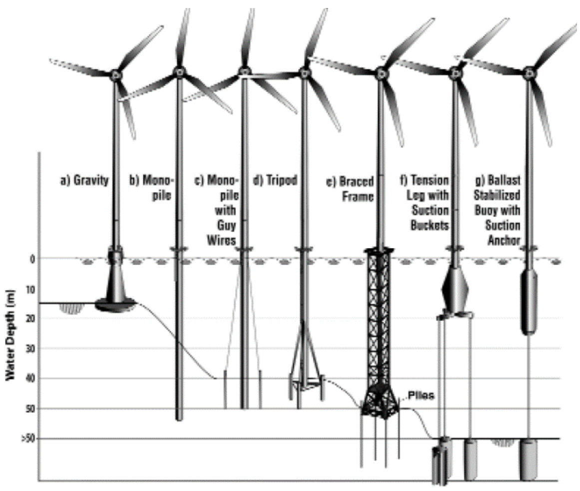
Summary:

Relevance to thesis
offshore wind foundations, support structure concepts,

Introduction
The next generation of wind turbines that are on the drawing boards are getting bigger in size, making them more cost-efficient, but also putting large demands on their support structures and foundations. As an increasing number of wind farms are being planned offshore in water depths of over 40 m, the combination of water depth and increased windmill tower heights, turbine weights, and rotor blade diameters create loads that make foundation design very complex. This article summarizes various relevant foundation and geotechnical issues for offshore wind turbine tower foundations. Offshore foundations are exposed to additional loads like ocean currents, storm waves, ice and potential ship impacts.

Wind Turbine Tower System Configuration
The components of a wind turbine system include the: Foundation system, Transition piece, Tower, Nacelle, Rotor blades.

Typical Support Structures
Support structures for offshore wind towers can be categorized by their configuration and method of installation. These foundations and associated water depths are shown in the figure. Typical sizes for offshore foundations and the construction sequence are presented in the table.



Type of Foundation	Size (m)	Weight (ton)	Typical Water Depths (m)	Construction Sequence
Gravity Base	12 - 15	500 – 1000	0 – 15	(a) Prepare seabed (b) Placement (c) Infill ballast
Monopile	3 - 6	175 – 350	0 – 30	(a) Place pile (b) Drive pile
Monopile with Guy Wires	3 - 6	175 – 350	20 – 40	(a) Place pile (b) Drive pile
Tripod	15 – 20	125 – 150	20 – 40	(a) Place frame (b) Insert pile (c) Drive pile
Braced-Frame with Multiple Piles	10 – 15	200 – 400	20 – 50	(a) Place frame (b) Insert pile (c) Drive pile
Suction Bucket	10 – 20	150 – 400	0 – 30	(a) Place base (b) Suction installation
Tension Leg Platform	10 – 20	100 – 400	>50	(a) Drive anchor pile or suction bucket (b) Float tension leg platform (c) Install anchor cables

Gravity Structures: These foundations resist the overturning loads solely by means of their own gravity. They are typically used at sites where installation of piles in the underlying seabed is difficult, such as on a hard rock ledge or on competent soil sites in relatively shallow waters. Gravity caissons are typically concrete shell structures. These structures are competitive when environmental loads are low and the dead load is significant, or when additional ballast can be provided at a reasonable cost.

Monopile: The wind tower is supported by the monopile either directly or through a transition piece. Depending on the subsurface conditions, the pile is typically driven into the seabed by either large impact or vibratory hammers, or the piles are grouted into sockets drilled into rock. Compared to the gravity base foundation, the monopile has minimal and localized environmental impact. The monopile is the most commonly used foundation for offshore wind turbines. The limitation of excessive deflection of a monopile in deeper waters is overcome by tying the monopile with tensioned guy wires.

Tripods: Tripods can be used to limit the deflections of the wind towers. The pre-fabricated frame is triangular and consists of steel pipe members connecting each corner. A jacket leg installed at each corner is diagonally and horizontally braced to a transition piece in the center. The tripod braced frame and the piles are constructed onshore and transported by barge to the site. These foundations are placed over small piles prepared on the seabed.

Braced Lattice Frame: A modification of the tripod frame, the lattice frame has more structural members. The jacket consists of a 3-leg or 4-leg structure made of steel pipe that is interconnected with bracing to provide the required stiffness.

Suction Buckets: This design consists of a center column connected to a steel bucket through flange-reinforced shear panels that distribute the loads from the center of the column to the edge of the bucket. The steel bucket consists of a steel skirt extending down from a horizontal base resting on the soil surface. The bucket is installed by means of suction and behaves as a gravity foundation, relying on the weight of the soil encased by the steel bucket.

Floating Tension Leg Platforms: These structures are floated to the site and submerged by means of tensioned vertical anchor legs. The base structure helps dampen the motion of the system. The structure can be floated to the site and connected to anchor piles. The structure can be subsequently lowered by use of ballast tanks and/or tension systems. The entire structure can be disconnected from the anchor piles and floated back to shore for major maintenance or repair of the wind turbine.

Typical Foundation Concepts

Gravity Caissons: For economical fabrication of gravity caissons one requires a shipyard or a dry-dock near the site so the massive foundation structures can be floated out to the site and sunk. Site preparation and placement required for gravity caissons typically involves dredging generally soft seabed sediment and replacing it with compacted, crushed stone in a level bed.

Driven Pipe Pile: The driven steel pipe pile option is an efficient foundation solution in shallow to deep waters. The typical method of offshore and near-shore installation of piled structures is to float the structure into position and then to drive the piles into the seabed using hydraulic hammers. The handling of the piles requires the use of a crane of sufficient capacity, preferably a floating crane vessel. Use of open-ended driven pipe piles allows the sea bottom sediment to be encased inside the pipe, thus minimizing disturbance. The noise generated during pile driving in the marine environment might cause a short-term adverse impact to aquatic life.

Post-Grouted Closed-end Pile in Predrilled Hole: A closed-ended steel pipe pile is placed into a predrilled hole and then grouted in place. It offers significant advantages over the cast-in-place drilled shaft option, including advance fabrication of the pile, better quality control, and much shorter construction time on the water. This option requires a specially fabricated large diameter reverse circulation drill. Closed-end piles can be floated to the site and lowered into the drill hole by slowly filling them with water.

Drilled Shafts or Bored, Cast-in-Place Concrete Pile: The installation of bored, cast-in-place concrete pile requires driving a relatively thin-walled casing through the soft sediment to the underlying denser material, then drilling through and below the casing to the required base elevation. Bending resistance is provided by a heavy reinforcing cage utilizing high strength, large diameter bars. The casing provides excavation support, guides the drilling tool, contains the fluid concrete, and serves as sacrificial corrosion protection. This approach requires a large reverse circulation drill.

Suction Caissons: These caissons are installed by sinking them into the seabed and then pumping the water out of the pile which creates a pressure difference across the sealed top, pushing the pile to the design depth. These foundations cannot be used in rock, in gravel or in dense sand. Suction caissons are less expensive to install because they do not require underwater pile drivers. At the end of a wind turbine's life, a suction caisson can be removed completely from the seabed, unlike piled foundations.

General construction characteristics of the various foundation types are presented in the table.

Construction Phase	Gravity Base	Monopile	Tripod/Braced Frame	Tension Log Platform
Onshore Fabrication	On land and close to site to be economical	No constraint	On land and close to site to be economical	No constraint
Transport Offshore	Float to site or on barge	Float to site or on barge	On barge	Float to site or on barge
Pre-placement Activities	Seabed preparation required	None	None	None
Placement	Lift or float over	Lift and sink	Lift and sink	Lift and sink
Fixing Tower to Substructure	Bolt to substructure	Grout to piling	Grout to tripod central member	Tie to tension cable
Installation of Tower and Turbine	Requires specialized cranes and large barges	No hindrance to lifting	Requires specialized cranes	No hindrance to lifting

<u>Conclusions</u>

The increasing windmill tower and turbine sizes and installations in deeper waters have demonstrated a need for more innovative and cost-effective foundations. The need for high-capacity foundations that can be installed in deep water with limited accessibility and with little disturbance to the existing environment can also be fulfilled by new technologies and process improvements. Environmental impact can be mitigated by the use of geotextiles for scour protection, and the use of a bubble curtain for noise mitigation.

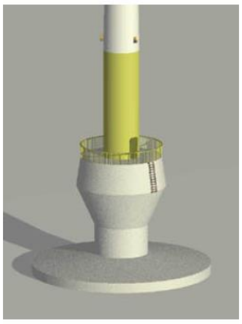
Ref:	Title:	Author:	Date:
4.07	Design Concepts, Methods and Considerations Offshore Wind	T. Ashuri M.B. Zaaijer	2009
Summary:			

Relevance to thesis
design requirements, design solutions, analysis tools.

Introduction
The objective of this article is to perform a literature review of the design process in which an OWT is developed. At first a brief overview of the requirements that an OWT should fulfill will be presented. Then different solutions that are currently available to satisfy the needs will be reviewed. The next step is to review the tools that are used to verify the proposed solution. The guidelines used for the overall design of OWTs are discussed. Based on this investigation the modifications to current concepts, knowledge and tools are outlined to pave the road to achieving large scale OWTs.

Requirement of OWT
The design of OWTs has many similarities to those of land based turbines, but there are a number of differences as well as additional considerations such as:
- The combined effect of the wind and the waves on the load spectrum.
- OWT's are operating as wind farms and are grid connected systems, part of a bigger grid network.
- For an offshore location, the poor access and extreme weather condition can influence the maintenance. A higher demand for Reliability, Availability, Maintainability and Serviceability is required in order to decrease the overall cost of generated electricity.
- Because of a limited time for working offshore a higher demand for fast OWTs installation.
- High level anti-corrosion systems are required
- Additional design requirements and cost increase due to bigger turbine sizes on support structure, transportation and installation.

Support Structure
The foundation supports the tower, the rotor and the nacelle and resists against loading from wind and waves. Offshore bottom mounted support structures are classified according to three basic properties that are: installation principle, structural configuration and foundation type. Classification of support structures is based on the water depth that each concept can be used economically, and gravity base, monopile, tripod and floating support structures are reviewed.

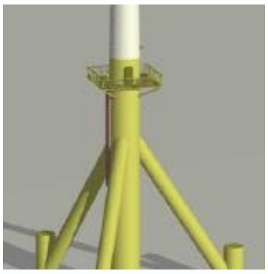


Gravity Base Structures
From structural point of view, a GBS is a monotower that is fixed at the top of a gravity base foundation. The foundation consists of a large flat base to resist overturning loads imposed by the wind and wave, and a conical part at the water surface level to break the ice and reduce the ice load by causing the ice sheets to bend downwards and break-up as they contact the conical section. In order to keep the attachment between the GBS and the sea bed, ballasts are laid on the flat base. In this way, the foundation always remains in compression under all environmental conditions.
Monopile

The monopile support structure consists of a steel pipe as a foundation which is driven or drilled into the soil. The monopile is equipped with a transition piece to absorb tolerances on the inclination of the monopile and to reduce the assembling time required at sea. The steel pipe transfers all the loads by means of vertical and lateral earth pressure to the ground. Therefore, both uncertainties in the ground properties and scour holes can lead to a structure with a quite different structural frequency than designed for.

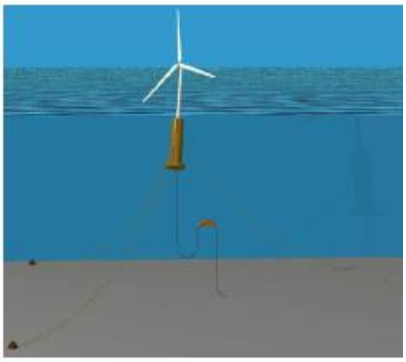
Tripod

The tripod consists of a central steel shaft and three cylindrical steel tubes with driven steel piles. The central part distributes the loads to the cylindrical tubes and acts as a transition piece for the tower. The cylindrical tubes give additional stiffness and strength and increase the capacity of the structure to support additional overturning moments. The foundation has the advantage that it requires less protection against scour than the monopile, which generally has to be protected against scour in sandy sea beds.



Floating

Current fixed-bottom technology has seen limited deployment to water depths of around 30m. The floating support structure consists of a floating platform and a platform anchoring system. The platform has a transition piece to install the tower on top of that. The platform can have several topologies such as single and multiple turbine floaters. The anchoring system fixes the platform and can be gravity base, drag embedded, driven pile, suction anchor type.



<u>Current Offshore Wind Technology</u>

The dominant rotor configuration is the variable speed three bladed upwind with a collective pitch and the yaw system. The most used concept for the drive train is the geared drive train, with three stages gearbox and a doubly fed induction generator. Besides economical point of view, the design drivers for selecting a support structure are mainly governed by water depths, soil conditions and the turbine size. Therefore, for the Baltic and North see waters with sandy bedplates and water depths below 30, the monopile is the most common used support structure, except in the shallowest water depths (up to max. 10 m) where the GBS is preferred.

<u>Design Verification</u>

The behavior of an OWT is made up of complex interactions of subsystems and analyzing this behavior requires the skill of a multidisciplinary team in areas such as meteorology, rotor aerodynamic, control and electrical engineering, structural and civil engineering. To analyze such a complex system, it is necessary to use computational design codes capable of performing complete simulations of the behavior of wind turbines over a wide range of different operational conditions. In addition to stated design codes, general insight in an OWT is obtained by finding the relation between a number of important parameters that govern the turbine characteristics.

Ref:	Title:	Author:	Date:
4.08	DNV Design Standard Offshore Wind Structures	T. Feld	2007
Summary:			

Relevance to thesis
design standard, DNV design code, model testing, offshore wind design, concepts

Introduction
One of the major drawbacks in using offshore wind farms has up to recent been the extremely high support structure cost (up to 50% of the total investment for an offshore wind farm project). In order to make the projects economically viable the wind energy industry requires cost-effective design for offshore wind turbine structures. Offshore structures are generally subject to complex loading from waves, wind and current, and, when placed near shore, also to impact from ice loading. These structures suffer unusually high levels of horizontal load and moment due to the combination of significant wind load from the elevated wind turbine and the loads from waves and current. A new offshore standard Design of Offshore Wind Turbines Structures, DNV-OS-J101, specific developed and applicable for offshore wind turbine structures. The standard covers a set of state-of-the-art design rules required to be fulfilled in order to achieve a complete certification and approval of an offshore wind turbine structure, including: Wind Turbine, Support Structure, Foundation, Site-specific approval of Wind Turbine Structures. The DNV offshore standard is based on a life cycle approach starting from site investigations and ending with decommissioning of the structure.

It is generally recommended to analyze and design any support structure using a coupled analysis of the foundation and its superstructure. The analyses should include both extreme event and fatigue analyses. The data necessary for modeling of the wind turbine is required as basis for the design. This comprises data for wind loads, geometry and dynamic behavior of the wind turbine. There are several critical issues in the design phase of a wind turbine structure such as establishment of soil design parameters, establishment of design waves and wave kinematics, establishment of combined loads on wind turbine structure (wind-waves, wind-ice), fatigue calculations of steel tubular joints, design of grouted connections in steel mono-piles, design of pile to jacket grouted sleeve connections in tripods and jackets and design of steel tube to concrete gravity foundation connections.

Design Principles and Safety Level
The standard provides an overall safety level corresponding from low to normal safety class, accounting for the fact that the structures are unmanned and the risk for pollution of the environment is limited. This makes the DNV-OS-J101 a cost effective design standard while at the same time living up to safety levels required.

Site Conditions
For economical design of offshore support structures it is of greatest importance to assess the site conditions like design soil parameters and design wave height. Site conditions for offshore wind farm projects consist of all site-specific conditions which may influence the design of wind turbines, support structures and foundations that together constitute a wind farm. The site conditions include meteorological conditions, oceanographic conditions, soil conditions, seismicity, biology and various human activities. The wind and wave climates are the most important site conditions for the loading of the wind farm structures.

Soil
For design and construction purposes the stratification of the individual soil units, the site-specific soil strength and deformation properties are of particular interest. Soil investigations

shall provide relevant information about soil to a sufficient depth, which depends on the foundation type. A model with geological description, geotechnical strength and deformation parameters can be identified for the entire project area.

Design Waves

For wind and wave climate representation, the intensities of the wind speed and wave height processes, the 5-minute mean wind speed and the significant wave height, respectively, are of particular interest.

Loads

Typically loads to be considered includes breaking waves and ice loads in addition to normal wind, wave and permanent loads. Wind loads generated from the wind turbine rotor are most often determined before the support structure and foundation have been designed. Thus, the wind loads must to be recalculated based on the site-specific layout and stiffness of the wind turbine structure. The combination of e.g. wind and wave loads must be
established in a consistent way.

Structural Design

The structural design of an offshore wind turbine requires optimization in order for the projects to be economically viable. Design of offshore wind turbine support structure covers geotechnical design and structural design for all relevant load situations in all limit states such as ultimate limit state, fatigue limit state, serviceability limit state and accidental limit state. The interaction between structure and foundation is essential in the determination of the design conditions for the entire structure composed of wind turbine, support structure and foundation.

Fatigue design of offshore steel structures

Fatigue is often a design driver for the structural design of offshore wind turbines and their support structures due to their flexible structural performance and exposure to highly dynamic loads from wind and waves combined with the corrosive environment at sea.

Grouted connection

The grouted connection has turned out to be a cost-effective solution for monopile foundations and has been applied on a number of offshore projects. Since the governing load from the wind turbine is the overturning moment, the loads can fundamentally be transferred as a force-couple in the top and the bottom of the grouted region, minimizing fatigue damage in the grout, monopile and transition piece due to omission of shear keys. This also minimizes or eliminates installation induced fatigue damage on critical elements such as flanges of the transition piece.

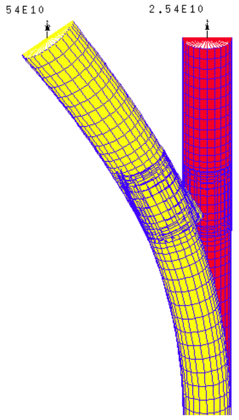
Concepts for OWT Support Structures

Design conditions are primarily the soil condition, water depth, possible erosion, size and type of wind turbine type and environmental conditions (wave height, current, ice etc. The selection of concept is highly influenced by a keen desire to achieve the lowest cost development, and a choice has to be made regarding the expenses spent in the design phase versus the expenses during operation and maintenance.

Piled Foundations

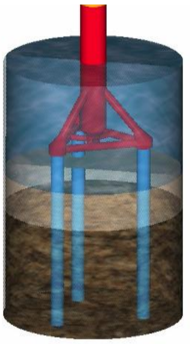
Piled foundations make up the most common form of offshore foundations. The structure can be configured as a mono pile, a tripod structure, or have piles that are driven through sleeve elements and are attached to the main structure by either a grouted or swaged connection. Piles are inexpensive to produce and provide a least cost manufacture option. The piles are typically either driven or vibrated into the seabed.

Monopile Concept



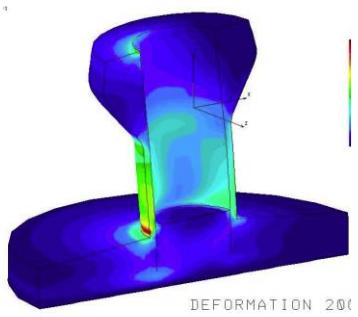
The freestanding monopile is one of the simplest foundation types used for large wind turbines. The steel monopile transfers the loading on the wind turbine to the supporting soils by means of lateral earth pressure. The monopile must therefore have a certain length depending on the soil strength in order to have sufficient capacity. The interface between the lower part of the monopile and the tower will typically be a welded flanged connection or a grouted flanged connection. The monopile may either be driven or vibrated into the seabed using a suitable hydraulic hammer/vibrator, or it may be drilled into the seabed and then grouted. Scour protection is typically required for the monopile solution at sandy locations. The monopile solution is currently the preferred solution and has been applied for many projects.

Tripod Concept



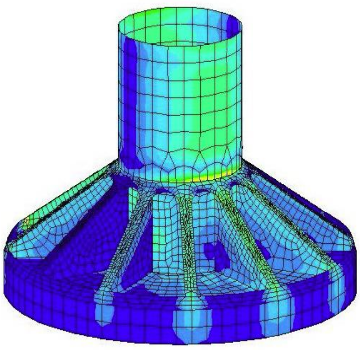
The tripod concept consists of a standard 3-leg structure, made of cylindrical steel tubes with driven steel piles. The concept is developed based on the simplicity of the monotower and enhanced by the additional stiffness and strength from the braced structure. The central steel shaft of a tripod structure provides a basis for the transition to the wind turbine tower. The base width and pile penetration depth can be adjusted to suit the actual site conditions. The tripod solution is expected to be economical and technical feasible at offshore wind farms at deeper water depths.

Gravity Based Concept



The gravity based concept is from a structural point of view a mono tower fixed at the top of a gravity base, thus reducing the free-standing or cantilevering part considerably The gravity foundation is designed to avoid tensile loads between the gravity base and the seabed, by providing sufficient dead load to stabilize the structure under overturning moments resulting from wind, wave and/or ice. The foundation can be vulnerable to erosion and scour, and require extensive scour protection. Based on the actual soil conditions sea bed preparation should performed.

Bucket Concept



A novel concept for offshore wind turbine structures is the bucket foundation. The suction is used for installation of the bucket - after installation the foundation will act as a skirted foundation a hybrid of a traditional pile and a gravity based foundation. The dynamic peak loads are partly taken by the suction effect. For design of the structure it will be necessary to perform FE analyses for determination of stress levels in ultimate and fatigue loading scenarios. Refined modeling is required in regions with high stresses. It seems a very cost-effective way of obtaining high bearing capacity and horizontal stiffness, suitable for application in soft soil, shallow waters and harsh environments.

Project Certification

To assure the required quality of the offshore wind farm project certification has been initiated within the offshore wind marked, verifying that the project complies with chosen standards and project specifications. The project certification is carried out as a review of the design documentation submitted by the manufacturer. It is generally recommended to analyze and design any support structure using a coupled analysis of the foundation and its superstructure excluding inaccuracies and uncertainties originating from assumed simplified interfaces. Certification is recommended to commence already at the time for data acquisition for soil, wind and wave site specific investigations, as an early consensus on the site specific loads will have beneficial impact on the project costs avoiding redesign due to revised loadings caused by the site
conditions.

Conclusions

The wind energy industry requires cost-effective design for offshore wind turbine structures in order to make the projects economically feasible. The newly issued DNV standard for Design of Offshore Wind Turbine Structures fills a gap within the offshore industry being specific developed and applicable for offshore wind turbine structures. Extensive experience from previous offshore wind farm projects as well as experience from maritime and offshore oil & gas projects is adopted in the offshore standard. The standard includes novel design and design calculation methodology for offshore wind turbine support structures, tower and foundation structures. The foundation structures include new designs and design methodology for suction bucket foundations, tripods, grouted mono-pile foundations etc. The DNV standard is based on a life cycle approach starting at site conditions and ending with decommissioning of the structure. The new design standard will allow for developing and optimizing new designs for offshore wind turbines and their support structures, being within the framework of a sufficient standard and quality level, and help to bring down the cost for offshore wind turbine support structures.

Ref:	Title:	Author:	Date:
4.09	Bottom Founded Steel Support Structure for Offshore Wind Turbines in deep water North Sea	H. Subroto R. Narold	2004

Summary:

Relevance to thesis

Offshore wind Energy, deeper waters, tripod, jacket, monopile, OWT support structures.

Introduction

Parts of the North Sea, with a depth range of 30-50 meters, have a large potential for the implementation of offshore wind energy. In the near future these 'deeper water' locations are expected to play a significant role, due to the available space and the wind regime. On the other hand the deeper location of the sea will give rise to specific requirements regarding the design, installation and manufacturing of the Offshore Wind Turbine (OWT) support structures. This will probably lead to an important cost impact. The widely implemented configuration for the OWT support structure, i.e. monopile and gravity based, are designed for depths up to 20-25 meters, and are therefore less suitable for the aforementioned 'deep water' areas. Consequently, alternative configurations have to be found and analyzed to meet the deep water requirements as best as possible. The cost efficiency of generating electrical power from wind energy increases with the implementation of larger turbines, both in size and power, and the installation of these in large numbers. This has directly led to the rapid increase in size and power of wind turbines. Nowadays, prototypes with a rated power in the order of 5 MW are being tested. The increase of the turbine weight, which causes a significant load on the tower top, is a matter of concern. The influence of this load on the design of the support structure will therefore also need to be taken into account.

Design Considerations

The OWT is an advanced system which, according to the actual design standards, has to operate in a hostile offshore environment, sustaining a high degree of operational reliability. Implementation of the 'integrated design' concept is a major requirement. The OWT's main components, such as rotor, turbine, support structure and foundation, should not be treated separately in the design phase. There is a high degree of interaction between these main components, which compels to consider and design the OWT as one system.

The first step is in the design phase is to choose three locations in the North Sea, for which the environment data will be determined. Three support structure configurations will then be designed for each location. One of those should be the mono-pile as a reference. Consequently, detailed design of all configurations will be performed. Finally the best design for each location will be determined, and furthermore sensitivity analyses on each remaining configuration will be done.

Environmental data and Load Cases

To perform realistic load simulations it is required to obtain environmental data of the chosen locations. For this purpose both in-house database of the participants and the commercial ARGOSS database have been used. Available location specific data, such as water depth, soil structure, wind speed , turbulence intensity, wave height and current will be implemented. The part and the format of the large set of required environment data that depend strongly on the set of the chosen load cases. Additionally, the description of the chosen load cases depends on which regulations will be utilized.

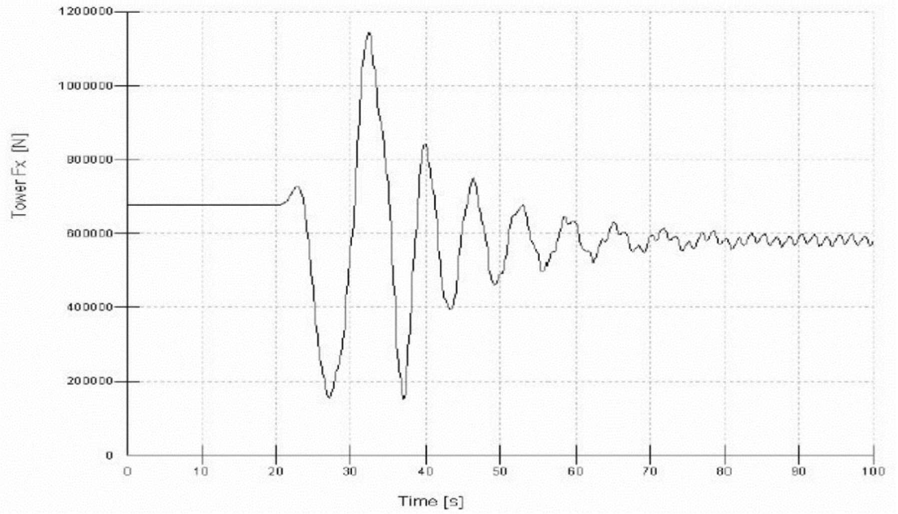
The following load cases have been selected:

Load nr.	Category	Design situation	Wind condition	Wave condition	Tide / Current	Add. info	DNV / IEC load nr.
1	Ultimate Limit State	production	Vr = 12 extreme turbulence, **ETM**	Hs-10yr	MWL/max	WT Class C turbulence	3 / 1.3
2	ULS	production	Vhub = 10 , 12, 14. extreme coherent gust with direct. change,**ECD**	Hmax-10yr	MWL/max	with direction change	2 / 1.4
3	ULS	production	Vr = 12, extreme operating gust with extreme wind shear, **EOG + EWS vertical**	Hs-50yr	HAT / min		**Not a standard** case !!
4	ULS	parked	Extreme Windspeed Model, **EWM**	Hs-10yr	HAT / min		10 a / 6.1
5	ULS	emergency shutdown	Normal Turbulence Model, **NTM**	Hmax-10yr	MWL / min	Brake performance defined by GEWE	9 / 5.1
6	Fatigue Limit State	production	Hs - Vw	Hs - Tz	MWL / max		12 / 1.2
7	FLS	normal shutdown	Hs - Vw	Hs - Tz	MWL / max	1000 x per 20yr	15 / 4.1

The chosen set consists of five Ultimate Limits State (ULS) and two Fatigue Limits State (FLS) load cases. For the preliminary design of the support structure, the largest tower top aerodynamic loads have to be determined. All of the chosen load cases are standard DNV.

Determining the extreme aerodynamic loads by simulations

After the determination of the set of extreme loads and acquiring the data of the turbine, an OWT model can be constructed using special programs like ‘Bladed’. Simulations of each of the chosen extreme load cases can then be performed. In this preliminary design phase the extreme loads are determined using simple PI-controller that is available in Bladed. This will cause higher aerodynamic loads on the rotor and support structure, and therefore result in a conservative design, which is preferred in this design phase. The extreme loads cases will generate maximum forces and moments on the tower top, which are used as the design input to determine the dimensions of the three support structures.



Support Structure Designs

Considerations regarding design complexity, material, fabrication, transport, installation, appurtenances and scour protection have been evaluated. After comparison, a tripod and a four legged jacket as the most promising alternatives. Results of the preliminary design of the determined configurations are showed in the table below.

Description	Monopile	Tripod	Jacket	Guyed monopile	Truss tower
Design	++	+	-	++	-
Material	-	+	++	-	++
Fabrication	++	+	-	++	-
Transport	++	-	-	++	-
Installation	-	-/+	-/+ *)	-	-/+ *)
Appurtenances	-	++	++	-	++
Scour protection	-	++	++	-	++

The advantages of the monopile concept are its simple design, easy manufacturing and easy transport. The disadvantages for use in deeper water and high tower top loads are the required large amount of structural material and large required tubular diameters, pulling this concept beyond the limits of feasible design. The tripod has reasonably good evaluations in many fields, except for transport and installation. Another point of concern is the design of the bracing connections to the main column. Especially the fatigue behavior of this connection is of significant importance. As for the tripod, the four legged jacket requires a complex and fatigue sensitive design for the connection of the jacket legs, with small diameter, to the main tower, with large diameter. A main disadvantage of the guyed mono-tower is that the guy wires have to be maintained in the same level of tension at any time. Also additional piles have to be placed to anchor the guy wires. The full truss tower has its drawbacks regarding the complex design, fabrication and transport. The preliminary design of these support structures is based on the maximum quasi static loads on the tower top. A concise summary of the preliminary design main results are showed in the table below.

Design parameter	Type		
	Monopile	Jacket	Tripod
Hub Height [m]	95	95	95
Water Depth [m]	40	40	40
Pile diameter [m]	7	1.83	2.13
Pile Length below Sea Bed [m]	54	41	41
Total Weight [ton] (pile+tower)	2496	1030	982
1st Eigenfreq. [Hz]	0.25	0.36	0.30
2nd Eigenfreq. [Hz]	0.81	1.38	0.93

Conclusion

The chosen locations are realistic for the implementations of offshore wind energy in deeper waters, and the differences in soil specifications are expected to have significant influences on the dynamic behavior of the support structures. After performing the preliminary design the conclusion can be drawn that the monopile concept comprises the use of much more steel material than the tripod or jacket. Nevertheless, this concept has its own specific advantages, such as easy transport, design and manufacturing. In the detailed design phase, when performing load simulations, the output of the sensors/channels representing the loads in certain directions of a specific location of the structure, will be combined to determine the maximum resulting forces and moments, and also taking into account their phase differences.

Ref:	Title:	Author:	Date:
4.10	Foundations for offshore wind turbines	B.W. Byrne G.T. Houlsby	2003

Summary:

Relevance to thesis
foundations; offshore wind turbines; renewable energy

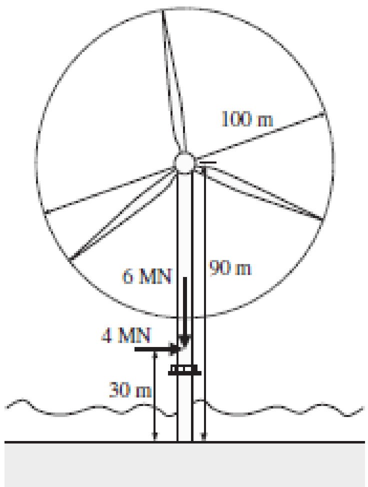
Introduction

One of the most promising renewable energy sources is wind energy: electricity realized through the use of large wind turbines. There is significant pressure, however, to put wind turbines offshore. By moving offshore, larger structures can be developed which allow a much greater power output. It should be noted that offshore winds are not necessarily stronger, but are usually more consistent. The disadvantage is that the environmental (wind and wave) loadings on the larger structures lead to greater forces in the structure. The foundation of the structure transfers the forces from the structure to the surrounding soil.

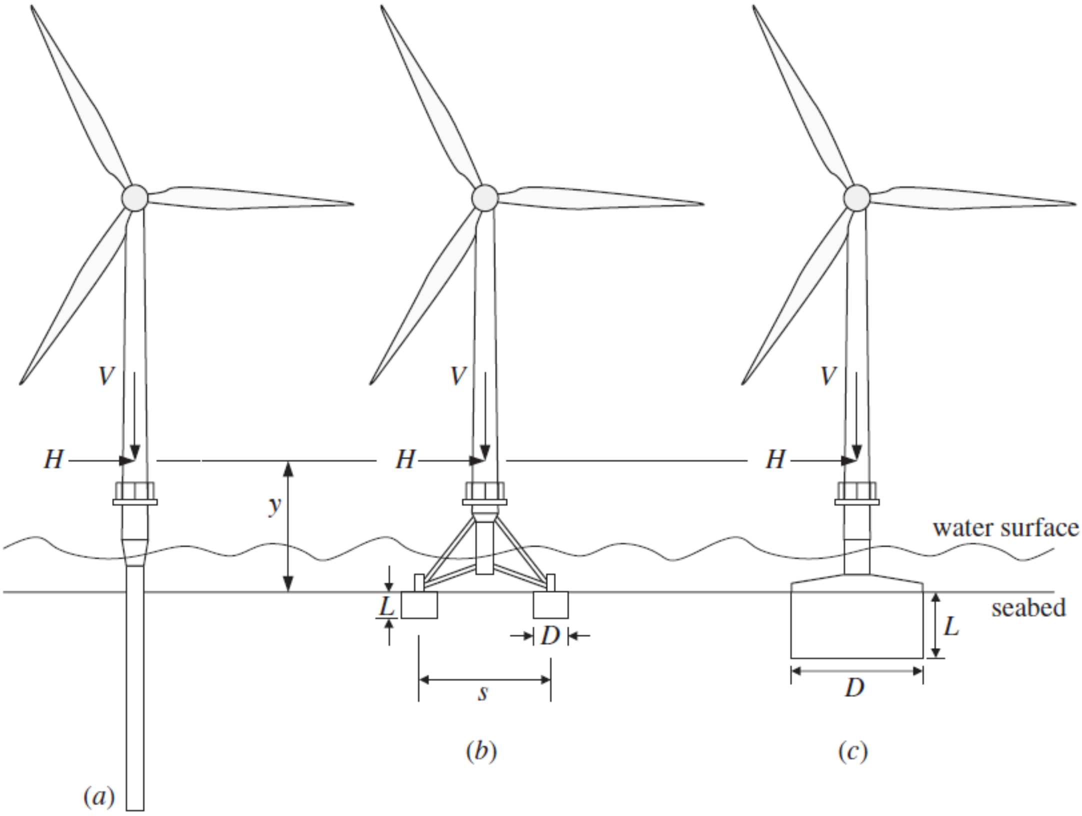
Foundation Design Considerations

For a wind turbine the foundation may account for up to 35% of the installed cost. Currently the cost for each such turbine is estimated at €1.8 million per megawatt, which compares with onshore turbines at €0.65 million per megawatt. The weight of each structure is relatively low, so the applied vertical load on the foundation will be small compared with the overturning load from the wind and waves. Further, it will be necessary to have a single design that can be mass-produced for use over a whole wind farm site. This shows that the design of the foundation becomes crucial to the economics of the project.

The following figure give estimates of the values for an anticipated 3.5MW design offshore wind turbine. The loads are comprised of wind and wave loads and are cyclic in nature. The worst load case is usually when the turbine is operating in moderate winds while the sea is in an extreme state. The combination of extreme sea and wind states is generally not critical, as the blades are fluttered during extreme winds to reduce the blade load and therefore the probability of blade damage. Furthermore, the wave direction may not be coincident with the prevailing wind direction. Therefore, the loads (moment and horizontal) acting on the foundation may not be coincident. Note that the wind force contributes ca. 25% of the horizontal load but ca. 75% of the overturning moment, because it is applied at such a high level.



One foundation concept is to use conventional methods such as driven monopiles (Type A). However, at some sites it may prove more economical to use foundations that bear only on the surface sediments, and, in particular, foundations with perimeter 'skirts' embedded into the sea floor so that the effect of scour is mitigated. In Type B the overturning loads applied by the wind and waves are resisted predominantly by a 'push–pull' action, involving equal and opposite vertical loads at foundation level. In Type C, the overturning load is applied directly to the single large foundation, and the foundation responses to an overturning moment will be critical.



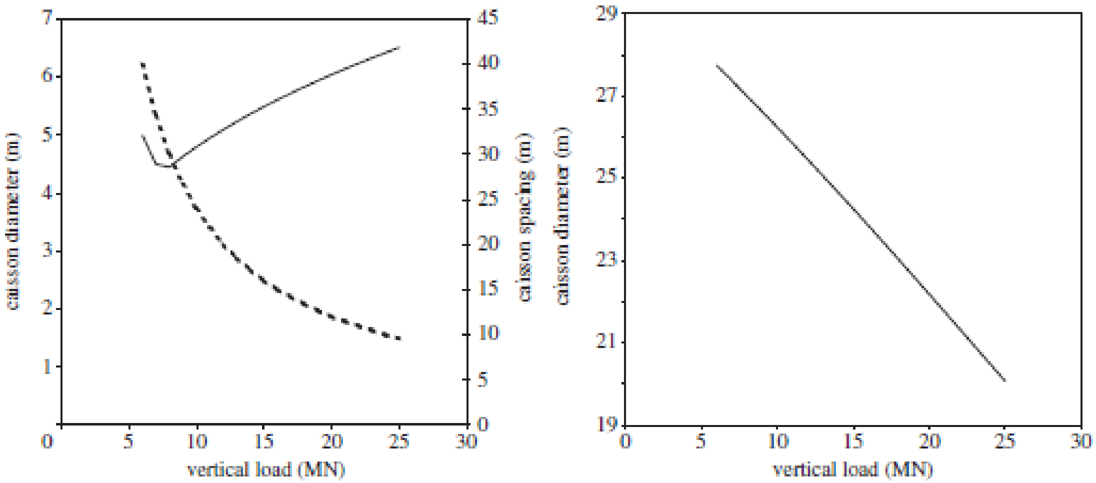
These skirted surface foundations, usually called ‘suction caissons’, are a novel design. They can be installed very quickly with the aid of suction. By comparison with traditional foundation systems, such as piles or massive concrete bases, large savings can be made on installation time and materials. The first of these can be very important to the overall budget, as offshore construction equipment is very expensive to hire. The skirted foundations have the added advantage that they can be removed easily by reversing the suction process.

Foundation Design Methods

The problem with foundation design is known as the bearing-capacity problem. The action of a moment and horizontal load as well as a vertical load significantly complicates this bearing-capacity problem. The aim of the design study is to investigate the effects of typical foundation sizes and spacing (in the case of foundation Type B), and the effect of critical parameters, such as vertical load, on the capability of the foundation to sustain the horizontal and moment loads. There are two facets to the design: the separation of the foundations and the dimensions of the foundations.

The critical calculation for establishing the separation of the footings relates to the case where the structure rotates about two downwind foundations. The restoring moment will consist of the vertical load acting through the center of gravity of the structure. To simplify the calculation it is assumed that the upwind foundations cannot provide any tensile resistance. This is a conservative assumption, as the foundations may be able to sustain tension through friction along the skirts. The critical calculation for the capacity relates to the case where the wind direction is such that only one foundation is downwind. Note that there will be no difference in the size of the caisson foundations for tripod and quadruped structures as the vertical load is the same in both cases. A secondary calculation for this design case is used to check that the horizontal capacity is sufficient.

As the vertical load increases, which could be the result of adding ballast, the size of them structure could be reduced. Interestingly, the size of the foundation initially reduces as the horizontal loading dominates, but then increases as the vertical load becomes critical. Adding ballast is clearly favorable up to about V = 15 MN, after which there are diminishing returns.



Type C is difficult to evaluate, as there are currently no standard design calculations that can be adopted. There is an approximately linear relationship between M and V at low vertical loads. It is clear that the increase in vertical load, say through ballast, is very beneficial for the design. A controlling factor on the aspect ratio for this type of caisson will be whether enough suction can be generated for the caisson to be installed.

Computational modeling

The optimal structural configuration will only be achieved by accounting for the complex interaction of the structure with the wind, wave and soil. This can be achieved by using numerical-analysis techniques. Fatigue of structural components and of the foundation, as well as the ultimate capacities, are just some of the issues to be addressed. The dynamic excitation forces will consist of the waves on the structure, the wind on the turbine blades and the interaction between the blades and the structure as the blades rotate. These will all affect the loading of the foundation on the soil. The structural configuration will be important, as it will be important to design the structure so that its natural frequencies are such that resonance with the frequencies of the excitations can be avoided. Computational analyses of offshore structures requires: the modeling of the structural response, including dynamics, of the structure; the evaluation and modeling of the wind, wave and current environment; and the accurate modeling of the interaction of the structure with the ground through the foundation.

Ref:	Title:	Author:	Date:
4.11	Comparison of monopile, tripod, suction bucket and gravity base design for a 6 MW turbine	M.B. Zaaijer	2005

Summary:

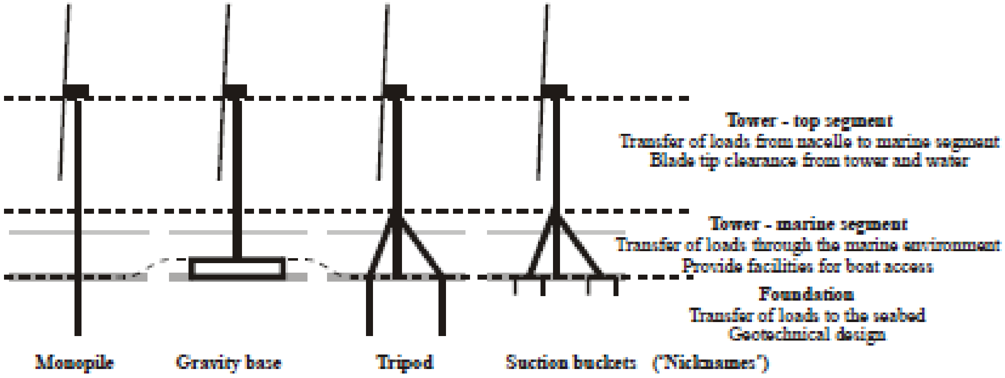
Relevance to thesis

Introduction

The tendency toward larger sized turbines and hostile locations will continue, as large-scale implementation of offshore wind energy proceeds. The subject of this article is the comparison of support structure concepts for these very large turbines. Monopiles and gravity base structures are used in current offshore wind farms, but monopiles tend to become extremely wide as turbines grow and gravity base structures are known to experience very significant heave forces at exposed sites with intermediate water depths. To overcome scaling problems of monopiles, several planned wind farms have already proposed to use tripod structures. Due to its expected installation benefits, a full scale prototype suction bucket foundation has recently been developed. In this article the fundamental principles of the concepts and the design drivers are brought together and compared.

Analyzed concepts

This article treats two concepts for the marine segment of the tower and three foundation concepts. The combinations of these concepts that are explored are in the figure below. All concepts are combined with the same conical top segment that starts at 9 meters above mean sea level.



Comprehension of important design drivers and feasibility of concepts are considered more important than obtaining fully optimized and approved solutions for this study. The loading conditions during the lifetime of an offshore wind turbine are diverse and depend on the instantaneous conditions of wind, wave and operational status and on dynamic response.

Tower and top segment

The top segment of the tower, extending from 9 m above MSL to the yaw system, is a tapered cylindrical tower, similar to its land-based counterparts. Although above sea level, hydrodynamic loading may also cause stresses in this part of the tower, due to dynamic response of the structure. For soft structures fatigue damage of the top segment due to hydrodynamic loading may even be in the same order of magnitude as below sea level. The diameter and wall thickness vary with steps at small height intervals.

Hydrodynamic loading

Hydrodynamic loading complicates the design of a gravity base severely, as it requires a simultaneous hydrodynamic and geotechnical analysis. The design of a foundation pile is much easier separated from the hydrodynamic analysis of the marine segment of the tower. Heave force on the (smaller) topside of suction buckets is expected to be absorbed by the dynamic suction effect that is discussed later.

Soil mechanics

The dominating geotechnical principles are very different for the four foundation concepts: the laterally loaded monopile, the axially loaded piles of the tripod, the sealed suction bucket and the gravity base foundation under combined loading.

- The lateral loads on the monopile are counteracted by a pressure difference between both sites of the pile that is initiated by a displacement of the pile. The bearing capacity of an axially loaded pile comprises shaft friction and pile point resistance. In case of hollow piles the soil inside the pile contributes to the bearing capacity by friction with the inner wall, or by point resistance of the soil plug at the pile tip.
- The type of suction bucket considered is a cylinder with a cap that is sealed after installation. Since no active suction is applied after installation of the bucket, the geotechnical principles of axially loaded piles also apply here: skin friction and point resistance. The point resistance of the pile tip is typically negligible, but the cap of the bucket causes very significant bearing capacity by pressing on the soil plug inside the bucket. Under tensile loads, the vertical displacement of the cap will result in a pressure reduction below the cap. During longer tensile loading the suction area below the cap will be drained and only skin friction will remain.
- The gravity base must provide sufficient resistance against sliding and sufficient vertical bearing capacity. The required sliding resistance determines the minimum weight of the system. The bearing capacity of the gravity base is checked for many phases of the incoming wave, due to its sensitivity to the ratio between vertical and horizontal loading.

Installation

- Tripod piles are of similar type and size of conventional offshore structures and the installation of these are currently routine work.
- Monopiles for 6 MW wind turbines have much larger diameters than current piles, which may cause practical problems. The ratio of diameter to wall thickness of the tripod piles and monopile are fixed at 60 and 100, respectively, as a preliminary criterion to avoid buckling during pile driving.
- For suction buckets the installation process is a significant factor for the structural design. The driving force during installation of the suction bucket is the hydrostatic pressure difference over the cap and the deadweight of suction bucket, ballast and preassembled parts of the tower. It has been assumed that the pressure inside the suction bucket can be reduced to zero, although in reality this may cause liquefaction of the soil at the point of critical suction. A “highest expected” skin friction and end resistance are used to determine the resistance during installation, while “most probable” values are used in the calculation of bearing capacity.
- -For gravity bases the installation process may result in requirements for the structural design for practical reasons, such as the capacity of the installation vessel or the size of the workspace.

Dynamics

The dynamic behavior of the support structure is an important design driver for offshore wind turbines. The foremost criterion is avoidance of resonance at wave excitation frequencies, the rotor frequency and blade passing frequencies. As turbines get higher, the natural frequency of monopiles comes down into the high energy part of the wave spectrum. It is expected that the stiffer tripod suffers less from wave-resonance and provides more opportunities to tune the natural frequency.

Scour

Due to changed currents around the structures, erosion of the seabed will occur. Due to the scour hole that originates from this process the soil supporting the foundation starts at a lower level and the overburden pressure on deeper layers reduces. As a consequence, bearing capacity and resistance of the foundation reduces and the natural frequency drops. Initially, protection of the seabed against scour is assumed, for instance by rock dumping. For the gravity base and suction buckets scour is expected to be unacceptable, due to their high reliance on near-surface soil. On larger scale natural sediment displacements may result in rise or drop of the entire seabed around the structure. The magnitude is independent of size of the construction and can be several meters at some North Sea sites. These sites are particularly unsuitable for gravity bases, suction buckets and to some extent piled tripods.

Concepts designs

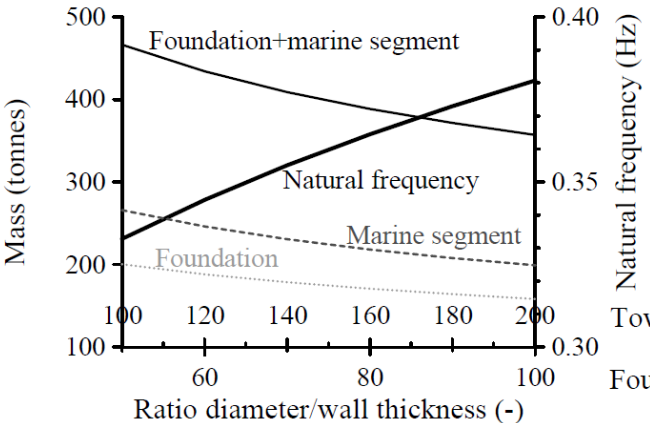
Monopile

The design freedom of the monopile is very limited. The main parameter that can be influenced is the ratio between diameter and wall thickness. Increase of this ratio results in a lighter construction, but buckling risk imposes a limit. The table below gives the dimensions of the monopile for the more or less optimum ratios.

Variation of the ratio between diameter and wall thickness is also a means to adapt the natural frequency of the monopile support structure. The effectiveness of this means is shown in the following figure, together with the effect on structural mass.

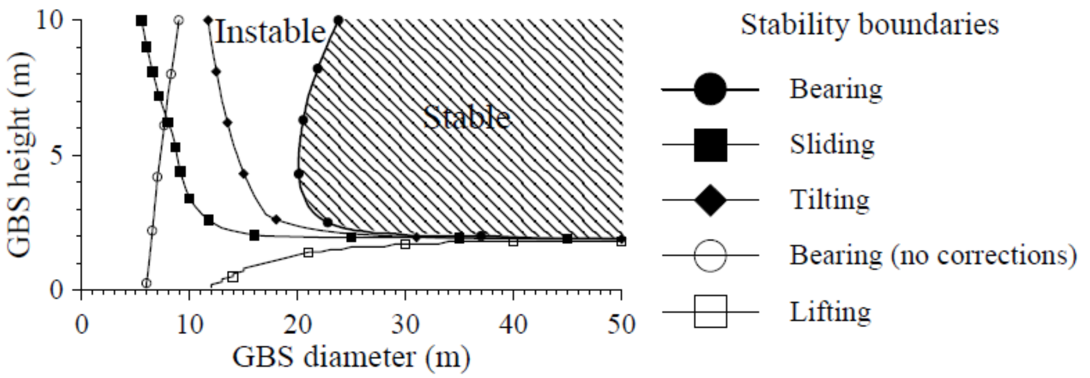
Marine segment	Mass (kg)	$158 \cdot 10^3$
Height above seabed	**Diameter (m)**	**Wall thickness (m)**
30 (= 9 m above MSL)	6.1	0.030
20	6.3	0.032
10	6.6	0.033
0	6.9	0.035
Foundation pile	Mass (kg)	$199 \cdot 10^3$
Penetration depth (m)	**Diameter (m)**	**Wall thickness (m)**
26	5.6	0.056

When no scour protection is applied, a scour hole of approximately 1.5 times the pile diameter is expected. The foundation pile has to be adapted to this hole by increasing diameter and wall thickness with 7% each and increasing pile penetration with 4.8 m, resulting in an increase of mass by approximately 35%. Additionally, a means to cross the scour hole with the electricity cable has to be provided.



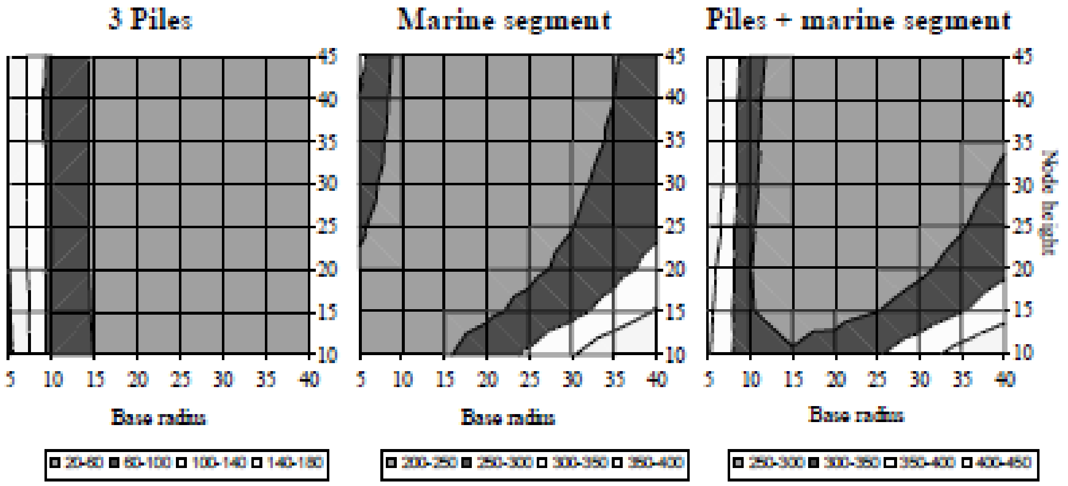
Gravity base structure

The marine segment of this concept is nearly equivalent to that of the monopile, being cut-off at the GBS top surface. Considerations of manufacturing, installation and dynamic behavior may result in differences, but the basic design principles are the same. The weight of a gravity base has to be sufficient to avoid uplift, tilting and sliding, while at the same time avoiding failure of the subsoil. The figure below shows which gravity bases provide a stable foundation and where boundaries of failure mechanisms occur. Heave force on the gravity base are more dominating than the large overturning moment due to aerodynamic loads.



Tripod

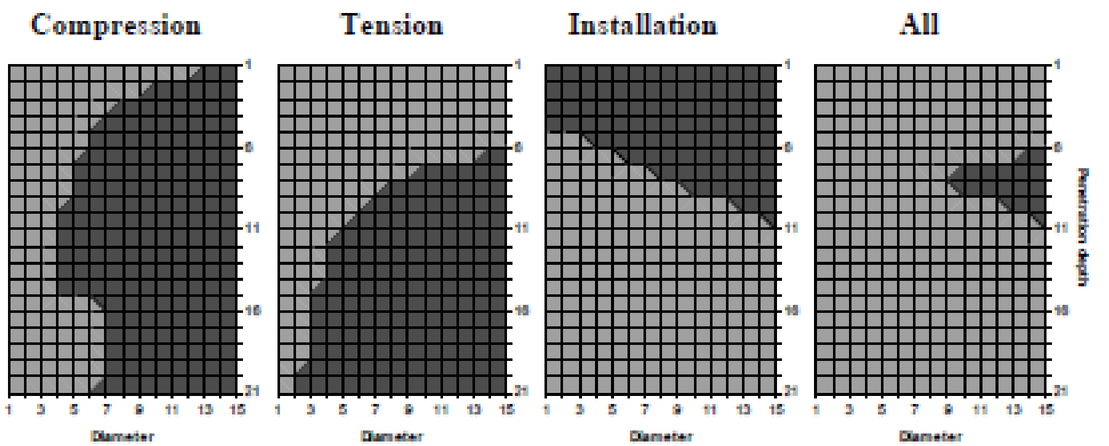
The main design parameters for the tripod are the height of the joint and the base radius. Only main member-forces are determined, using a statically determinate beam model. The resulting mass for the marine segment and piles are shown in the figure below.



Variation of the ratio between diameter and wall thickness does not have a significant effect. Considering corrosion, maintenance and wave impacts, the splash zone is an unfavorable location for the tripod joint.

Suction buckets

There are two basic requirements for the suction buckets: installation has to be possible with the achievable hydrostatic force and resistance to operational loads has to be sufficient. The main dimensions that can be varied are the bucket diameter and penetration depth. The figure below shows feasible buckets for this design case. In this study the tripod is connected to the three suction buckets during installation, providing some additional deadweight.



Drainage currents are known to reduce the resistance during installation. Previous studies indicated that suction buckets are more economic in clays than in sandy soils. In clays the margin between “most probable” and “highest expected” resistance is smaller, resulting in a smaller margin between the expected undesired installation resistance and desired operational resistance. Furthermore, the skin friction in clay is already fully available at small penetration depths, whereas skin friction in sand builds up with penetration.

Conclusions

The table below summarizes the structural masses found in this design study. The piled tripod is the lightest structure, due to the light foundation piles. This conclusion still holds when no scour protection is applied. However, fabrication of the tripod is likely to be more costly than the monopile and requires more space. Optimization of the manufacturing process is therefore a beneficial and essential task for tripods. The costs and duration of the installation, as well as the availability of equipment will play an important role in the selection between monopiles and piled tripods.

Table 6 - Structural masses for foundation and marine segment (in 10^3 kg)

(Top segment	226)	(Mono) pile	(Tripod) piles (3)	Suction buckets (3)	Gravity base
		199	43	150	4100
Single column	158	357			4258
Tripod	216		259	366	

As known and shown, the installation requirements of the suction bucket tend to result in wide, shallow foundations. Because the pile-soil friction for cohension-less soils increases with penetration depth, suction buckets require a larger surface than driven piles. This is only partly compensated by the smaller wall thicknesses that are required for the benign installation procedures of suction buckets. Therefore, the tripod with suction buckets is the heaviest all-steel construction. Although slightly different conditions may render this structure lighter than the monopile, fabrication will be even more costly and spacious than that of the piled tripod. The largest benefit of this concept is expected from its suitability to install the support structure with a preassembled turbine. The gravity base structure is more difficult to compare with the other structures, due to the very different type of material and manufacturing process. Installation, seabed preparation, scour-protection and non-technical issues also differ significantly from those of the steel structures.

Adaptation of the first natural frequency in the design phase has a smaller impact on structural weight for the tripod than for the monopile, but the range of variation is smaller than expected. The second natural frequency of the tripod can be more easily adapted. The counter effect is a larger sensitivity of the tripod’s second natural frequency to scour.

Ref:	Title:	Author:	Date:
4.12	Integrated Support Structure Design Analysis	T. Feld J. Waegter	2003

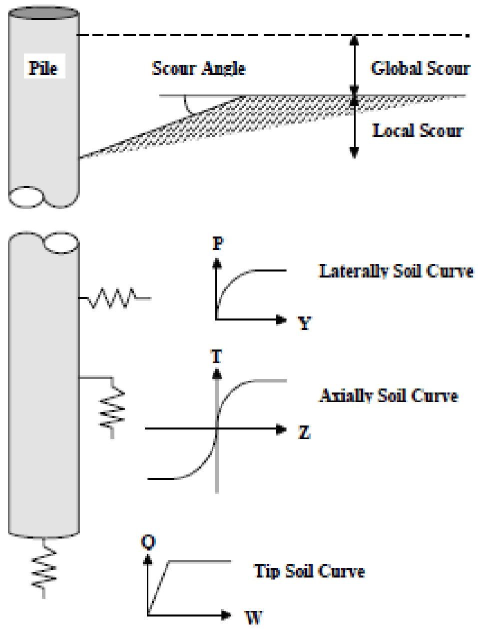
Summary:

Relevance to thesis
Support structure design, fatigue, load analysis

Introduction
Offshore structures are generally subject to complex loading from waves, wind and current, and, when placed near shore, also to impact from ice loading. Such structures call for a rather careful analysis and design especially when used to support offshore wind turbines. These structures suffer unusually high levels of horizontal load and moment due to the combination of significant wind load from the elevated wind turbine and the loads from waves and current. It is generally recommended to analyze and design any support structure using a coupled analysis of the foundation and its superstructure. The analyses should include both extreme event and fatigue analyses.

Structural Analysis
During design the analysis model should be used with different levels of sophistication adapted to suit the specific requirements of different types of structure and of analysis. On shallow water breaking waves may be a design consideration of either global or local nature. Since non-linearity's rarely are significant for fatigue load levels, most fatigue analyses are performed on a linear structural model with a linearized foundation. Based on the properties of the soil layers the foundation piles are automatically subdivided into a suitable number of elements. The soil-pile interface is described as a coupling between the nodes of these elements and the surrounding soil in terms of soil curves.

Piled foundation
Piled foundations make up the most common form of offshore foundations. The standard method of installation is to drive the pile into the seabed using a steam or hydraulic driven hammer. It is considered that the vibrations resulting from the piling operations would present too great a risk to component parts of the mechanical and instrument equipment housed in the nacelle, and as a result piling would need to take place prior to placement of the nacelle.



The foundation structure can be configured as a mono pile or as a tripod structure. For the tripod the piles are driven through sleeve elements and are attached to the main structure by either a grouted or swaged connection. In both cases the pile provides the means of transferring both tensile and compression loads from the structure to the seabed. The figure shows the analysis model for pile-soil interaction.
Scour
When using a piled foundation there is an option, either to design against erosion or include any possible scour in the design. When designing monopiles or tripod structures at sandy

locations seabed scours are accounted for in the design. In general scour is included in the design as a reduction in the effective stresses along the pile. Local scour is included as a conical loading, with a reduction in the vertical stress.

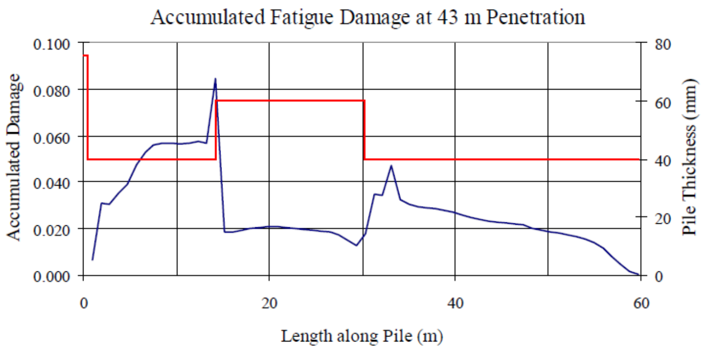
Design Codes

Offshore pile design procedures have evolved from onshore experience and theory, resulting in generally accepted procedures such as the API guidelines for piles. Offshore wind farms shall obtain a standard endorsement before installation; consequently the safety level reflected in the design calculations must be based on the existing codes, as described in design regulations for offshore wind farms. Structural members as well as tubular joints must be checked for both strength and fatigue in accordance with established codes.

Design Analysis

Analyses of support structures for offshore wind turbines are performed based on limit state requirements. Ordinary strength aspects are considered in ULS and FLS, while esthetical and performance requirements are considered in SLS. Extraordinary strength aspects such as ship impact analysis and other accidental load limit states are considered in ALS. Flexible structures may require dynamic analyses covering both parking and production phases.

Fatigue from the installation phase should be derived from drivability studies and included in the total fatigue damage. Fatigue damage from installation in the pile can be determined. The total fatigue damage in the pile is the sum of the fatigue damage from in-place phases plus the accumulated fatigue in the pile caused during the driving process.



Conclusions

It is generally proposed to analyse and design any support structure by applying a coupled analysis of the foundation and its superstructure. The analysis should include both extreme event and fatigue analysis. The integrated support structure design analysis is described, emphasizing the capabilities and advantages of this type of analysis to more simplistic design methods. The main benefit of the proposed approach is to obtain a correct soil-foundation-structure interaction, thus excluding inaccuracies and uncertainties originating from more or less arbitrary chosen simplified interfaces.

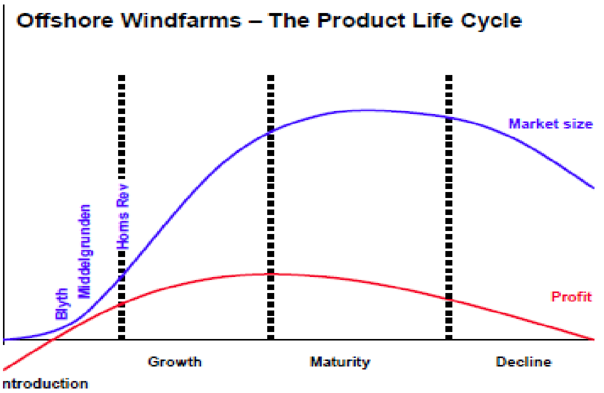
Ref:	Title:	Author:	Date:
4.13	Offshore Foundations for Offshore Wind	Ballast Nedam	11-2004

Summary:

Relevance to thesis
offshore wind farms installation, support structure concepts

Introduction

In terms of the product life cycle, offshore wind farms are situated somewhere between the latter stages of the introductory phase, and the start of the growth phase. The introductory phase is more concerned with developing awareness about offshore wind farms, than with generating turnover and profits. Market size and growth are both small, while Research & Development costs are substantial. This is demonstrated in the adjacent diagram which shows a negative result in terms of profit.



Main characteristics of the introductory phase:

- Small number of turbines per offshore wind farm
- Small size of individual wind turbines
- Relatively close to shore
- Limited water depths
- Sheltered sites
- Close to existing grid connection

However, these characteristics change when you move into the growth phase. Typical developments include the presence of more turbines in an individual wind farm, as well as larger turbines. Furthermore, the overall character of the wind farm will change as the offshore wind farm matures. For example, a mature offshore wind farm could easily consist of 100 wind turbines, each 6-7 MW, 130 -140 meter rotor diameters, 40 km from shore where the water is 35 meters deep. This will have an impact on all aspects of the offshore wind farm. However, this article will focus on the foundations and on the working methods involved.

Foundations

As the wind farm gets larger, its foundations will have to grow accordingly. In terms of the weight, the tripod is the most favorable design, followed by monopile foundations, and finally by mainly concrete solutions like the concrete monopile and the concrete GBS. GBS are most effective in up to 10 meters of water depth, monopiles are the best solutions in water depths of between 10 to 25 meters, while in water depths of more than 25 meters, tripods seem the best solution. However, production costs are also a deciding factor, and can vary considerably. Steel production costs for monopiles are four to five times higher than prefabricated concrete production costs per tonne. The cost of producing steel structures like tripods can be three times greater again than the cost of steel monopiles, working out between 10 to 15 times more expensive than production costs for the concrete foundations. Concrete prices show a much more stable price level compared to the rising steel prices. This reduces the risks substantially. The result is that, even in deep water, the GBS can prove a cheaper foundation type than the tripod or even the monopile. In the table on the next sheet a small comparison is made between the different concepts.

Offshore Wind Turbine Foundations (weight in tonnes)	6 MW Turbine	
Type *water depth >*	water depth -20	Water depth -35
Tripod and piles (3)	388	525
Suction bucket and tripod	606	-
Monopile (steel)	591	775
Monopile (steel, excl. scour protection)	733	971
Monopile (concrete)	-	2,400
Gravity-based Structure (concrete)	-	7,200

Installation

The present methods being used for offshore wind farms will not be able to cope with the future demands of the offshore wind energy industry. Most of the existing types of equipment cannot handle heavyweight foundations, while the production of these foundations demands new production techniques. Existing equipment for offshore wind farms has reached the limit of its capacity. Self-elevating platforms are limited when dealing with water depths and hoisting capacity, while sheer legs are limited in hoisting capacity and their working ability is restricted at certain wave heights. Specialized equipment for offshore wind farms is designed mainly for installing the tower and turbine, and not the foundation. Heavy lift vessels originating in the oil and gas industry are considered not suited for serial installation, largely because of cost criteria. These factors mean that in the future, full size offshore wind farms will have to rely on scarce equipment for the installation of offshore foundations.

Working methods

Technologies used in the construction of foundations for large offshore bridges can be transferred effectively to the production and installation methods for laying the foundations of offshore wind farms. As has been noted, concrete foundations are a competitive alternative to steel structures. The main advantage of these concrete foundations is that they can be manufactured at onshore sites near to the offshore wind farm. By comparison with steel, concrete is likely to have a shorter delivery time, while there is almost no problem with availability. By creating production lines, the foundations can be delivered on schedule to a pier which is suitable for a Heavy Lift Vessel. From there the HLV can lift the foundations, sail to the offshore site and place the foundations on prepared foundation beds.

Design and Engineering

The design and engineering of Offshore Wind turbine foundations is a process where wave, wind (turbine), material and seabed parameters have to be combined with offshore logistics and working methods. In the opinion of Ballast Nedam this integrated path is the only way that leads to optimal foundation solutions. Besides the integrated approach, Ballast Nedam uses the construction experience of Ballast Nedam to achieve creative and practical design solutions. The scope of Ballast Nedam Offshore Energy also includes geotechnical analysis, design and engineering activities starting from conceptual design up to and including detailed design, material specifications and construction drawings, static, dynamic and fatigue calculations incl. FEM calculations, Risk assessment and risk management.

Ref:	Title:	Author:	Date:
4.14	Structural and Economic Optimization on Offshore Wind Support Structures	T. Feld J.L. Rasmussen	2000

Summary:

Relevance to thesis

support structure design, tripod, suction buckets, design analysis

Introduction

The use and development of wind turbines has been a hot topic in the debate of energy political and environmental issues for the last couple of years. It has been shown that the use of offshore wind turbines can assist to the energy supply. One of the major drawbacks in using offshore wind turbine farms been the extremely high foundation cost (¼ of total cost). Installation of the offshore parks is approximately 50-100% more costly per installed rotor area as compared to conventional onshore projects. The reasons for this are primarily the added complexity of having to install foundations and power cables offshore and secondly the increased costs of the foundation itself. As a result an R&D project was initiated aimed at developing new foundation concepts in order to reduce the foundation costs and thus the overall costs of the offshore wind turbines.

Foundation Concepts

The project consisted of three foundation concepts; gravity based foundation, mono pile foundation and tripod foundation. Two preferable design locations are considered, namely Horns Rev and Rødsand. The R&D project revealed a number of conclusions and observations:

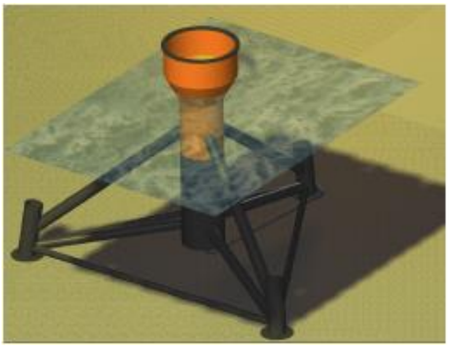
- All three concepts are preferred to be steel concepts. The primary draw backs of the concrete structures are the overall weight which complicates transport and installation operations, and the requirements to build the structures at a temporarily established construction yard close to the final location of the park which imposes restrictions on weather.
- The study resulted in reduced estimated foundation costs (16% of total costs) compared to the experienced 23% of total costs at the existing wind turbine farms.
- A rather weak dependency of depth, for all three concepts, disqualified the expected “quadratic rule”, which forecasts the costs of the completed foundation to be approximately proportional with the water depth squared.
- The bigger the turbine – the smaller the relative foundation costs.
- While most of the differences in costs between the three concepts analyzed lies within the tolerance/uncertainty, the tripod concept seems to have the lowest costs at greater water depth. Likewise the gravity structure is the cheaper concept on shallow water with ice.

Foundation type	Advantages	Disadvantages
Gravity steel structure	No piling Can be removed completely and possibly repositioned All parts visible for inspection	Seabed preparations required Time consuming welding details Space requirements at construction site
Mono pile steel structure	Simple No preparations of seabed Insensitive to scour	Requires heavy duty piling equipment Not suited for geotechnical location with large boulders
Tripod steel structure	Adaptable to increased water depth Low blocking effects A minimum of preparations required at site prior to installation	Specialised fabrication methods Not suitable for geotechnical location with large boulders Not suitable for shallow water depths (< 6 m)

Tripod Steel Pile Solution

The concept consists of a steel space frame transferring the sectional forces from the tower to primarily bending moments, tension and compression loads in three hollow steel piles

driven into the seabed. Each leg frame consists of a pile, a pile sleeve and two braces. The legs are interconnected above the seabed by three mudbraces giving the tripod its characteristic triangular base. The tripod is placed on the seabed.



Tripod Bucket Foundation

The wind loads on a slim structure such as the offshore wind turbines give rise to a constant average load, combined with a variable load changing between positive and negative peak values. Traditionally the foundation of the wind turbines is designed to withstand the maximum load at all time. Thus the foundation will generally be designed for too large a load. A possible solution to the problem is using a foundation based on suction buckets. At a load compression situation the foundation would work as a normal foundation. In case of load tension, the buckets would work by a combination of skin friction on the inside and outside of the buckets, and the suction due to negative pore pressure under the lid could withstand the brief peak values. Thus the design load could be diminished, as the suction would carry part of the peak values.

Three buckets replace the three foundation piles. By the use of buckets rather than piles it is possible to remove some of the geometric constraints that formed the structure before. It is possible to extend the center column to seabed and then use the base of the column as one of the buckets. The center column and the buckets on the supported frames will be penetrated to the same depth below mudline by means of suction. Due to the reduction of the maximum capacity of compression when having a bending moment the structure is optimized in a way that the bending moment is reduced. The removal of some of the frames reduces the amount of steel. Scour protection around the buckets is necessary in frictional materials.

To enable the penetration of the bucket it was a condition that the required suction to penetrate the soil was less than or equal to the critical suction. By applying suction less than critical suction no cavitation during installation will occur. Critical suction can be defined as the maximum possible partial vacuum applied on a bucket without soil plug lifting or dilating. The pullout force was investigated and calculated using the general bearing capacity formula for clay. The formula for clay was used on sand, as well. The internal frictions in the sand was equalized with an undrained shear strength from the assumption that sand will act as an undrained material with undrained shear strength for quick, short duration peak loads. The pullout force was estimated to be in the order of 4MN

Concept Comparison

The new optimized structure founded on buckets has been compared to the steel pile tripod, especially with respect to structural and economic impact. As the structure has been changed relative to the steel pile tripod the amount of steel was significantly reduced. The difference in amount of steel between the two concepts is estimated to be 5% to 35%, depending on soil and loading conditions. For dense sandy soils, rather large buckets are required to provide capacity. The price of steel will change when going from piles to buckets, as the buckets require more welding during fabrication. The figures below show the distribution of the individual parts in percent of the total price. The price for the geotechnical investigations and detailed design together with the installation is unchanged between the steel pile tripod and the steel bucket tripod, even though a bucket foundation requires shorter geotechnical borings.

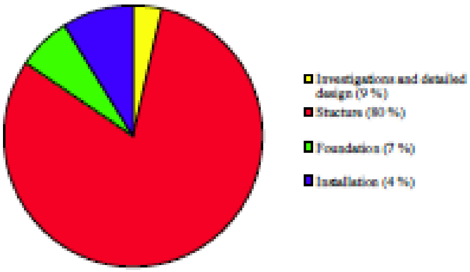


Figure 5.1 The steel pile tripod – Horns Rev.

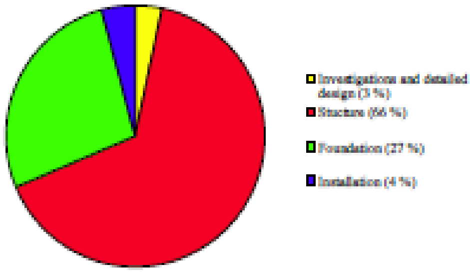


Figure 5.2 The steel bucket tripod – Horns Rev.

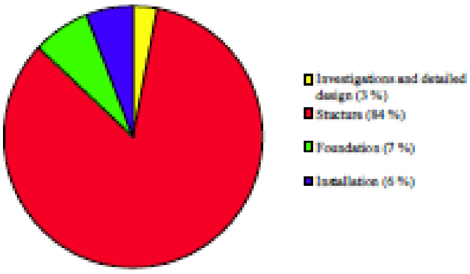


Figure 5.3 The steel pile tripod – Rødsand.

Figure 5.4 The steel bucket tripod – Rødsand.

<u>Conclusions</u>

The comparison between the two concepts revealed the following results:

- A general saving on the amount of steel for the structure, corresponding to 10% at Horns Rev and 25 % at Rødsand.
- A 61% saving on the amount of steel for the foundation at Rødsand, and a 6% increase at Horns Rev.
- A general steel weight saving between 6 and 34 %.

Due to the difference in steel prices (including welding during fabrication), the two foundation concepts revealed approximately the same price at Horns Rev and a large saving at Rødsand.

Installation-wise the suction bucket tripod is appealing, as the installation time is substantially reduced and less resource demanding.

Generally the new bucket tripod foundation is economically and environmentally attractive in clay and soft soils. In dense sand as found at Horns Rev, the advantages are less, when dealing with lighter offshore structures such as wind turbines. However other investigations indicate saving of 5% for dense sand and 15% at cohesive soils, when platforms are founded on buckets instead of driven pile.

APPENDIX E – SUMMARY OF RESEARCH AND THESIS REPORTS

Ref:	Title:	Author:	Date:
5.01	Analysis of Lifetime of a Tubular Research Structure on Antarctica	C. Saltner W.D. Keij	06-2002
Summary:			

<u>*Relevance to thesis*</u>
(ant)arctic environments, low temp. structural engineering, lifetime analysis in the (ant)arctic

<u>Summary</u>
In this study the deformation of a tubular structure in ice has been modeled for the Neumayer Station at the Ekström Ice Shelf. The model has been focused on the deformations of the tubes in cross section, as this was seen to be the most important issue by the station operators. The conclusion of this project points out the end of the lifetime of Neumayer Station under given limitations. The scope of this project was to focus on the deformations of the base and derive an estimate of the lifetime through an analytical model of the phenomena involved in deformations in ice.

<u>Contents</u>

Chapter 1 – Introduction
Chapter 2 – Research in Antarctica
Chapter 3 – Structures in Snow and Ice
Chapter 4 – The Neumayer Station
Chapter 5 – Problem Statement
Chapter 6 – Deformation on the Neumayer Station
Chapter 7 – Model Concepts for Tubular Structures
Chapter 8 – Physics of Snow and Ice
Chapter 9 – Construction Parameters at Neumayer Station
Chapter 10 – Survey of the Deformations of Neumayer Station
Chapter 11 – Modeling Deformations of a Tubular Structure in Ice
Chapter 12 – Analysis of Lifetime for Neumayer Station
Chapter 13 – Recommendation for a Replacement of Neumayer Station
Chapter 14 – Conclusions and Recommendations

Ref:	Title:	Author:	Date:
5.02	Arctic Offshore Technology Assessment	X. Shi W. Rodriquez	06-2011

Summary:
<u>*Relevance to thesis*</u> *arctic environment, operating arctic facilities, maintenance, safety and environmental impact* <u>Summary</u> This report addresses the various aspects of construction, installing and operating offshore oil and gas platforms in arctic environments. It focuses on assessing and determining of the environmental conditions in certain areas of the arctic. The abilities and limitations of current offshore equipment is examined in light of these environmental conditions. Also the possibility of support vessels and support operations during installation and operation of offshore arctic facilities is reviewed. Furthermore, safety, health and risk is evaluated, and considerations presented. Last, the environmental impact during operations or accidents is examined and evaluated. <u>Contents</u> Section 1 – Assessment of Environmental Conditions Section 2 – Study of Abilities and Limitations of Equipment used to Transport Platforms Section 3 – Support Operation Assessment Section 4 – Personnel and Safety Equipment Considerations Section 5 – Helicopter Operations Review Section 6 – Diesel Spill Risk Assessment

Ref:	Title:	Author:	Date:
5.03	Arctic Workabilty	L. Burg	08-2007
Summary:			

<u>*Relevance to thesis*</u>
arctic environment, ice conditions, ice features

<u>Summary</u>
Studies underscore the significant reserve potential of the Arctic region: an estimated 25 percent of potential oil and gas reserves, onshore and offshore, is believed to be located in the Northern Hemispheres Arctic region. Although these areas already have been under consideration for over 30 years, technical difficulties have put a threshold on these developments. Natural conditions like low visibility, extreme colds and ice make it nearly impossible to navigate and therefore restrict workability immensely. This thesis will focus on the occurrences of certain concentrations of sea ice, air temperatures and their combined events. Based on these findings a probabilistic approach allows the definition of risk features over defined spatial and temporal domains.

An extensive analysis has been performed on environmental and ice measurement datasets. Efforts have been made to structure and validate the ice concentrations into a reliable, weekly standardized database. Linear regression analyses on ice extent have been performed for different regions and during different periodes of the year. The probabilities of occurrence for sea ice concentrations above 0% and 30% have been determined by calculating the relative frequency over 33 years. To analyze the effect of air temperatures and ice existence on navigability and operability, occurrences of both surface air temperatures and sea ice have been determined. A combined analysis has been performed on sea ice and air temperature conditions and in the Bering, Chukchi and Beaufort Seas.

<u>Contents</u>

Appendices B, E and H are proven to be relevant for future reference.

Ref:	Title:	Author:	Date:
5.04	Characterizing and Reconstructing 500 years of Climate in the Baltic Sea Basin	C. Eriksson	2009

Summary:

<u>*Relevance to thesis*</u>
climate change, Baltic Sea, atmospheric circulation, statistical modeling, sea ice

<u>Summary</u>
The regional climate of the Baltic Sea Basin has been analyzed using relevant climatic time series for the past 100–500 years. The time series used in the thesis describe parameters such as station-based and gridded air temperature, sea level, ice cover extent, river ice break-up dates, and river runoff. To describe the atmospheric circulation over the area, gridded sea level pressure data have been used to construct time series describing the occurrence of high and low-pressure systems as well as westerly and northerly winds.

The definition of climate was analyzed and a proper climate averaging time was found. The winter climate of the past five centuries was examined through a comprehensive analysis of the longest time series, describing winter severity, available for the Baltic Sea Basin. The covariation of several climatic variables was examined using new statistical techniques.

Two reconstructions have also been made, describing the past evolution of maximal ice cover extent in the Baltic Sea and river runoff from the Baltic Sea drainage area. Statistical modeling was used to link atmospheric circulation parameters to changes in ice and river runoff. High ice coverage in the Baltic Sea was demonstrated to be closely associated with high-pressure circulation and easterly winds, while low ice coverage was associated with westerly winds and low-pressure circulation. Runoff information was developed from three different models, each formulated to describe one of the three sub domains (north, south, and Gulf of Finland) using atmospheric circulation and temperature.

<u>Contents</u>

Ref:	Title:	Author:	Date:
5.05	Feasibility of New Terminal in Arctic Russia - MSc Thesis		

Summary:

Relevance to thesis
arctic environment, arctic design considerations, feasibility study of arctic structures

Summary
The Northern Sea Route (NSR), a sea passage that goes through the arctic waters adjacent to the northern coast of Russia, is the shortest seaway to link the Atlantic and Pacific Oceans. Despite the much shorter distance, the NSR is not frequently used for transshipment between Europe and Asia. This is caused by the extreme natural conditions in the eastern part of the Northern Sea Route. The growth of the Russian economy and the exploration of new oil and gas fields in north Russia make it very interesting to study the feasibility of new import and export terminals along the NSR. However, the arctic waters are characterized by very harsh conditions. One of the major problems is the presence of ice during most of the year. The forces of the ice on the ship's hull and the structures at the terminal can be severe and must be taken into account.

The Russian economy has been growing during the past years and will most likely continue to do so in the future. This causes the import and export flows to grow accordingly. Plans for development of the large oil and gas reserves in Northern Russia demand extra export capacity. In order to bypass the pipeline system, which has limited capacity and is in a deteriorating state, interest has raised in new export terminals in the Russian arctic. Development of these industries might increase the demand for products from Europe in this region, which calls for enough import capacity to be available. This region however has to cope with arctic conditions that may have serious influences on the port processes and the terminal layout design. The project will picture the cargo flows to and from the Russian Federation in the presence and the future. The analysis as a whole will shed more light on future terminal design and construction in the arctic regions.

The objectives of the study are:
- Master planning of the import and export facilities in the Russian Federation on a national level.
- Provide insight in the operational aspects of arctic terminals.
- Explore the required technical specifications of terminals under arctic circumstances.
- Generate a rough evaluation model to assess the financial feasibility of new terminals under arctic circumstances, based on investment costs.

Contents

Section 1 – Subject of Research and Scope
Section 2 – The Russian Economy
Section 3 – Arctic Port Planning
Section 4 – Terminal Expansion Arkhangelsk
Section 5 – Arctic Quay Wall Design
Section 6 – Expansion Feasibility
Section 7 – Conclusions and Recommendations

Ref:	Title:	Author:	Date:
5.06	Ice Management in Arctic Offshore Operations and Field Developments	K.J. Eik	2010

Summary:

Relevance to thesis
ice management, arctic environment, ice conditions, ice features

Summary
The intent of this thesis is to gain increased knowledge about ice management in general and to transfer the knowledge from practical experiences into statistical design frameworks. The work is presented through nine papers each dealing with different elements of ice management.

In order to include ice management in statistical frameworks for design calculations, a number of building blocks need to be in place. Examples of such building blocks may be; “ice detection models”, “ice and iceberg drift forecasting models”, “models for calculations of managed ice” and “models for iceberg deflection success”. With respect to ice intelligence, which is the first activity required in ice management operations, it was decided to look closer at the ability to detect ice features from the bottom side. Reasons for this was that novel technology such as AUVs and multi beam echo sounders is considered promising with respect to future ice management operations while more traditional intelligence means such as marine radars and satellites already have been considered for most ice management operations.

Despite the number of similarities between sea ice management and iceberg management, it was decided to treat each of these subjects individually. Thus, all information on iceberg management is found in Chapter 4 while all information on sea ice management is found in Chapter 5. Both of these chapters close with papers on how the management systems may be incorporated into the design process. Section 4.4 and Section 5.3 address iceberg management and sea ice management respectively. The bricks required for iceberg management evaluation such as iceberg drift, iceberg deterioration and iceberg deflection are presented through four papers in Sections 4.1 to 4.3. Corresponding bricks for sea ice management such as ice load models and ice load variability are presented in Section 5.1 and Section 5.2 respectively. Each paper in this thesis includes both conclusions and references. However, some general discussion of the total work and main conclusions of the thesis have been included in Chapter 6.

Contents

Ref:	Title:	Author:	Date:
5.07	An Overview of First-Year Sea Ice Ridges	G. Timco K. Croasdale	08-2000

Summary:
Relevance to thesis *ice ridge load prediction, ice ridge properties and geometry, ridge load modeling* Summary This report presents an overview of several aspects of the engineering properties of first year sea ice ridges. The report focuses on first-year ridges in temperate climates, and is sub-divided into 4 main sections that deal with the various aspects of ridges. These subjects correspond with the contents of the report. Measurement on ice ridge properties are performed and analyzed. Processes such as ridge formation Contents Chapter 1 - Introduction Chapter 2 - Morphology of ridges Chapter 3 - Physical and mechanical properties of ridges Chapter 4 - Measured ridge loads on offshore structures Chapter 5 - Methods for predicting ridge loads

Ref:	Title:	Author:	Date:
5.08	Dynamic Ice to Structure Interaction	E. Eranti	1992
Summary:			

<u>Relevance to thesis</u>
ice structure interaction, dynamic aspects, dynamic ice load modeling

<u>Summary</u>
A theory of dynamic ice-structure interaction is described with transverse and torsional vibrations included. The theory is applicable to cases of pure crushing of ice against vertical structures as well as combined crushing and shearing of ice against inclined structures. The zonal ice failure approach is adapted, the structure being locally in contact with solid and broken ice alternately. Simple rules are given for the development of the zonal ice force in the interaction process. The structural response, the zonal ice force components and the global ice force are found in an iterative procedure based on the development of the theoretical distance between the zonal contact point and the ice edge.

Ice interaction test were performed. The mass and the stiffness of the vibrating system, pushing velocity, aspect ratio, shape and inclination of the contact face were varied. Highest effective ice pressures were measured for flexible systems. Interaction coefficients are obtained from the test results.

The study concludes that the common practice of using aspect ratio curves or pressure-area curves to predict the effective ice pressures caused by columnar grained level ice is generally invalid and sometimes dangerous. Every situation is a unique dynamic ice-structure interaction and the effective ice pressure and the structural response depend strongly on the geometric and dynamic properties of the structure.

<u>Contents</u>

Ref:	Title:	Author:	Date:
5.09	First-Year ice ridge scour and some aspects of ice rubble behavior	P. Liferov	2005

Summary:

Relevance to thesis

first year ice ridges, scouring mechanism, ice ridge loads, ridge properties, rubble build-up

Summary

This thesis deals with two separate but closely connected subjects. The process of first-year ice ridge scour with an emphasis on physical modeling and the mechanical behavior of ice rubble. When drifting into shallow waters, ice ridges may scour the seabed and create a significant threat to all seabed installations such as pipelines, cables, wellheads etc. Better understanding of the scour process will enable to determine the pipeline burial depth more accurately. Field experiments, examination of previous research and numerical work have been performed. Two in-situ medium scale ice ridge scour tests and one keel shear-off test have been carried out in the Van Mijen fjord on Spitsbergen. The tests on ice rubble that have been conducted during the last three decades have been reviewed and compared with respect to characteristic behavior, mechanical properties and scaling. Laboratory punch tests on ice rubble have been analyzed using finite element method to assess rubble behavior and to derive its mechanical properties. A pseudo discrete continuum model has been developed to simulate the micro-mechanical behavior of ice rubble.

The two ice ridge scour tests revealed, under given conditions, the steady state scour process. Experiments showed that the two main competing mechanisms that result in the steady state scour are the heave of the ridge and the destruction of the keel. Another mechanism, the compaction of the keel, could also be of importance though it is less in magnitude. Keel failure appeared to be not simultaneous, but progressive. A number of different tests on ice rubble were done during the last three decades. An extensive review and analysis of some of these tests have been performed to examine the characteristic features of ice rubble behavior. Particular attention has also been focused on scaling of the ice rubble strength in the reviewed tests. The primary and the secondary failure modes were outlined. The primary failure mode is associated with breakage of the initial rubble skeleton and was studied with the custom-developed pseudo-discrete continuum model. Finite element analysis of the laboratory punch tests on ice rubble has been used to simulate the tests conducted in the laboratory and to derive the material properties. The simulations showed that the bending effect and consequently the tensile strength of ice rubble are of importance in punch tests the way they were performed in the laboratory. Direct comparison of the laboratory and the in-situ punch tests is thus not entirely correct and requires accounting for the complex deformation modes under certain boundary conditions at the laboratory testing.

Contents

Chapter 1 – Introduction
Chapter 2 – Review of Design Issues for Pipelines subjected to First Year Ice Ridge Scour
Chapter 3 – In-Situ Ice Ridge Scour Tests
Chapter 4 – On Ice Rubble Behavior and Strength
Chapter 5 – Conclusions and Recommendations

Ref:	Title:	Author:	Date:
5.10	First-year sea ice features - Investigation of ice field strength heterogeneity and modelling of ice rubble behaviour	S. Shafrova	08-2007

Summary:

<u>*Relevance to thesis*</u>
first-year sea ice features, ice rubble behavior, ice loads, ice field properties and strength

<u>Summary</u>
For the nearest years the design load level for offshore structures in Arctic regions is likely to be controlled by first-year sea ice ridges and rubble fields if the icebergs are not present in the area. Drifting ridges may hit fixed or moored surface structure such as platforms or ships, or they may gouge the seabed endangering pipelines and wellheads. Both the temporal and spatial properties of the consolidated layer and the unconsolidated part (the ice rubble) of the ice ridge are important input into ridge load models. A better understanding of the ice rubble behavior will enable us to determine the ice-ridge load more accurately. This thesis deals with two separate but connected subjects, namely: the ice strength field heterogeneity of both first-year sea ice ridge and level ice and the mechanical behavior of the ice rubble.

Field mechanical testing of first-year sea ice by uni-axial compression has been done in order to improve the knowledge of the ice fields strength heterogeneity. The in-plane ice strength non-homogeneity of different ice fields on the landfast level ice in the Spitsbergen fjords were investigated. Special Finite Difference program “Inhomogeneity” was used to study the influence of the ice strength heterogeneity on the ice loads. It was shown that the ice heterogeneity might be one of the reasons for the scale effect. In order to investigate the nature of freeze bonds between the ice blocks, series of field and laboratory small scale tests were conducted with submerged ice blocks. The temporal development of the freeze bonding strength and the local strength of the ice blocks in the ice rubble, their changes with block size, confinement and ice properties were studied. A pseudo-discrete continuum model has been developed to study the behavior of the ice rubble and in particularly its initial failure mechanism that is associated with the breakage of the freeze bonding contacts (rubble skeleton). The model provides a possibility to simulate the contacts between the ice blocks. A parametric analysis simulating 2D direct shear tests shows that the pseudo-discrete continuum model is very sensitive to both strength and morphology of the freeze bonds between the ice blocks.

<u>Contents</u>

Ref:	Title:	Author:	Date:
5.11	Ice forces on structures	[-]	08-2002

Summary:
<u>Relevance to thesis</u> *ice loading, ice structure interaction, ice failure modes, aspect ratio* <u>Summary</u> This report estimates ice forces on the basis of ice mechanics for its failure in various modes, as well as on empirical values of effective pressure measured on full-scale structures. For ice crushing, which induces the highest effective pressure on a structure, the effective pressure depends on the indentation speed and the aspect ratio (*D*/*h*). Most of the codes take these factors into account for estimating ice forces on structures. When an ice sheet fails in modes other than crushing, the effective pressure is generally less. <u>Contents</u> Chapter 1 – Introduction Chapter 2 – Mechanical Properties of Ice Chapter 3 – Environmental Forces Chapter 4 – Forces limited by Ice Forces Chapter 5 – Forces limited by Momentum of an Ice Feature Chapter 6 – Canadian and American Codes Chapter 7 – Vertical Ice Forces Chapter 8 – Summary

Ref:	Title:	Author:	Date:
5.12	Nonlinear finite element simulations of ice forces on offshore structures	B. Sand	2008

Summary:

Relevance to thesis
finite element structure modeling, ice loads, ice failure modes, ice sheet modeling

Summary
This report focuses on the development of nonlinear finite element simulations by means of obtaining ice forces on structures. The effects of material nonlinearities and friction between ice and structure are taken into account. The key ingredients of the approach are; a realistic representation of the complex constitutive behavior of ice, accurate tracking of contact between the ice and the structure including coulomb friction sliding, and an automatic procedure for computation of buoyancy forces on a partially or completely submerged ice features.

A new three-dimensional constitutive model for ice is developed and the formation of crushing and cracking is treated as phase change. In this approach the material changes from being solid ice to a granular material. In this manner, the mechanical behavior of ice is approximated from the brittle end and it is treated as a rate-independent, elastic-brittle material. An algorithm for automatic calculation of the buoyancy forces on partially submerged bodies has been developed. This procedure has been implemented into a general finite element to include buoyancy and gravity forces on isoparametric, hexahedral elements.

Several realistic examples of ice-structure interactions have been studied to demonstrate the use of the present computational techniques and include ice sheet or multi-year ice ridge interaction with sloping structure, upward and downward bending cones and a cylindrical structure. In the numerical studies, the structures are considered fixed and rigid. Contact kinematics based on finite sliding is applied to describe precise tracking of contact nodes and surfaces in order to define clear and unambiguous contact conditions. Contact forces can be split into normal and tangential components, the latter being a result of friction that arises as the deformable ice meets and slides along the surface of the rigid structure. The computation of friction forces is based on the Coulomb friction law. The numerical results obtained for the chosen examples are compared with well- established analytical methods, numerical results reported in the literature and in some examples, published experimental data. Although there is some discrepancy between these methods, the numerical and analytical results are in relatively good agreement, but the results are not excellent.

Contents

Ref:	Title:	Author:	Date:
5.13	Evaluation of Canadian Artificial Islands	M.J. Jansen	08-1999

Summary:

Relevance to thesis
ice loading on granular material, arctic environment, ice load definition

Summary

Artificial islands are sometimes chosen to function as drilling platforms in Arctic regions, because of the easy construction methods and high resistance against ice loads. In this report a study is performed of the artificial islands designs in severe Arctic conditions. The extreme environment creates special design considerations and construction techniques. Purpose of this study is to determine what the maximal lifetime expectancy is of the artificial exploration island designs. Furthermore a number of production island considerations are studied and evaluated. The islands considered are islands with a granular fill material. The side slopes of these granular fill artificial islands are under the influence of wave and ice loading. The wave loading results in erosion of the fill material. The morphological changes of the slopes are evaluated using a FEM model.

Contents

Ref:	Title:	Author:	Date:
5.14	Friction of Sea Ice on Various Construction Materials	R. Frederking A. Barker	11-2001

Summary:

Relevance to thesis
ice friction forces, materials under ice loading, test set-ups

Summary

A series of tests was performed at the Canadian Hydraulics Centre to investigate friction between sea ice and various materials such as concrete, steel, wood and ice. The tests examined the effects of the change in the friction coefficient corresponding with the deterioration of material surface, speed, temperature, surface wetness and normal pressure. A carriage translated an ice specimen back and forth relative to samples of various construction materials fixed to the tank floor, while measuring the normal and tangential forces between the ice and the sample surface. Results from the test series indicated that friction was higher at lower speeds and also on rough materials. There was a great deal of variability observed in the instantaneous values of the coefficient of friction. Temperature had a weak effect on the friction coefficient, with slightly higher values of friction at higher temperatures, and there was a weak trend of lower friction with higher contact pressures. The average coefficient of friction of sea ice on smooth concrete, painted steel and sea ice was about 0.05 for speeds greater than 5 cm/s and increased to about 0.1 at 1 cm/s. The average coefficient of friction of sea ice on rough concrete and corroded steel was about 0.1 at speeds greater than 10 cm/s and increased to 0.2 at 1 cm/s.

Contents

Ref:	Title:	Author:	Date:
5.15	Ice Actions on Offshore Structures	M. Bjerkas	05-2006

Summary:

Relevance to thesis
ice loading, ice-structure interaction, dynamics ice effects, structure concepts, ice ridge forces

Summary

Ice actions on offshore structures are one of the main concerns for engineering activities in cold areas with ice-infested waters. This report deals with three aspects of ice actions, namely design ice loads from level ice, dynamic ice actions of resonant character, and the actions caused by ridged ice.

An existing design code was found to fit well for the widest structures and dramatically over-predict ice loads for structures of widths less than four meters. The present work was concerned with the analyses of full-scale data from the Norströmsgrund lighthouse conducted in the LOLEIF and STRICE projects (1999-2003). Analyses of time records from ice crushing indicate that the effective structural width should not be reduced from full width when predicting design ice loads.

New applications of continuous wavelet transforms have been presented using the Morlet wavelet for the detection of intervals with ice loads of resonant character. Ice loads of resonant character were found to occur more frequently the warmer the ice. A critical speed was also found. This critical speed seemed to be higher the thicker the ice. Studies of the initial phase of intervals with ice-induced vibrations also revealed two mechanisms that could cause steady-state vibrations, namely circumferential cracking and internal cracking.

Four different ice ridge failure modes were detected together with an insignificant influence from the increasing keel depth on the highest measured loads.

In-situ and laboratory measurements were conducted on ridged and level ice from the Barents Sea and the Van Mijen fjord on Svalbard where the level ice generally was found to be stronger than consolidated ice in ridges. Vertical samples with ice columns in the loading direction were found to be stronger than horizontal samples. Consolidated ice from ridges had an equal hardness to level ice, but was harder than ice rubble.

Contents

Ref:	Title:	Author:	Date:
5.16	Recommendations for design of offshore foundation exposed to ice loads	L. Fransson L. Bergdahl	04-2009

Summary:

Relevance to thesis
ice load design considerations, design offshore foundations, design ice load estimation

Summary

A good understanding of ice conditions and ice loads is essential in order to make proper construction of foundations for offshore wind power in the Baltic Sea.

Assumed ice action is based on experiences from damages on Swedish and Finnish lighthouses as well as on resent full-scale measurements in Sweden.
The applied practices and basic assumptions behind design of bridge pears, lighthouses and offshore constructions were originally created without much knowledge of ice mechanics. Now when these guidelines have been applied for a long time they have become valuable from an empirical point of view.

Because of the stochastic nature of ice, loads on conical foundations have not been reduced to the low levels that many recent investigations have indicated. The uncertainty lays in the question whether a bending failure of the ice sheet always will take place. In general, it is difficult to establish relevant ice conditions and ice scenarios associated with design loads.

A recommendation for better estimations of ice loads on offshore wind power generators is presented together with informative sections on ice loading mechanisms and statistics on ice conditions in Swedish seas. When the foundations are designed horizontal and vertical loads from the ice sheet shall be calculated based on ice thickness, ice strength and properties of the structure. It is then important to distinguish between ice conditions in the landfast ice zone and the more dynamic ice situation further out from shore. As far as measured ice loads on vertical structures are available the probabilistic effective ice pressure (load divided with ice thickness and foundation width) shall serve as guidance. Ice loads against sloping or conical structures can be calculated using plasticity theory only if it is plausible that the ice fails by bending. That is not always the case in areas of pressure ridges or compacted ice. Offshore wind power generators shall be checked for oscillating ice loads if its main frequency can be assumed to be close to the natural frequency of the structure. This applies to both conical and vertical foundations.

Contents

Ref:	Title:	Author:	Date:
5.17	Static and dynamic response of a structure subjected to ice forces: Evaluation of a lighthouse overloading event	V. S. Bjoland	06-2010

Summary:

Relevance to thesis
finite element analysis, dynamics ice-structure interactions, ice forces, ice overloading

Summary
Exploitation of areas and natural resources in arctic and sub-arctic areas makes guidelines for designing structures exposed to ice-forces a necessity. Ice actions on a structure include both static and dynamic components, and methods to calculate the magnitude of the ice loads are given in several common design codes. The static load component is constant and dependent on structure geometry and ice thickness, while dynamic loading is given in the design codes as time varying forcing functions.

In the winter of 1985 Björnklacken lighthouse, located north in the Bothnian Bay, was overloaded by ice forces and displaced along the seabed. A numerical model has been created using the FEA software package ABAQUS to determine the static response and the structural properties of Björnklacken. The structural properties have further been used in the analysis of a single degree of freedom (SDOF)-system to determine dynamic response.

The static and dynamic ice load components given by common design codes have been applied to both the numerical model and the SDOF-system. Initial calculations revealed large differences between the predicted loads from the different codes. Dynamic analysis showed that the response caused by a harmonic forcing function was significantly higher than that which was caused by a sawtooth forcing function.

Results also showed that the amplitude of the dynamic forcing function is reduced if the structure's velocity at loading point is scaled as a ratio of the ice velocity. The reduction is more severe with lower damping, resulting in higher reductions in systems with low damping fractions. Given the close relation between velocity at waterline and dynamic response, a recommendation is that guidelines for velocity scaling should be included in all of the design codes.

Contents

Ref:	Title:	Author:	Date:
5.18	Adapting offshore wind power foundations to local environment	L. Hammar S. Andersson	05-2010

Summary:

<u>*Relevance to thesis*</u>
offshore wind foundations, environmental effects, mitigation measures

<u>Summary</u>
The aim of this report is to provide an environmental perspective regarding the choice of foundations for offshore windpower, suggesting that differences in environmental impact should be involved in decision-making and development concerning future offshore windpower foundations. The study focuses on three different types of foundations; gravity- monopile- and jacket foundations. Also tripod- bucket- and floating foundations are mentioned. The different characteristics of the foundations are discussed based on their environmental impact in five different areas; 1) epifouling and reef-effects, 2) operational noise, 3) changes in hydrographical conditions, 4) noise during construction, and 5) dissolved sediment during construction.

Regarding epifouling, it is noted that the surface texture of the foundation is of less importance in the long run since the initial substrate soon will be covered with organisms, creating a rugged surface for later colonising organisms. It is rather the level of salinity, distance to shore, exposure, depth and turbidity of the water that decide which organisms that will dominate the different foundations after a few years. Operational noise from offshore windfarms has been shown to initially affect some organisms during experimental studies in small containers. Based on a limited number of measurements it seems as if gravity and monopile foundations emit noise of similar amplitude, but the frequency range of the gravity foundation is generally lower. The local conditions of the seabed have a large impact on the propagation of the noise, where shallow water and hard substratum allow the sound to propagate longer distances. During the construction period extreme noise levels may occur, especially during pile-driving which is needed for most foundations except for gravity foundations. The noise level depends on the diameter of the piles that are driven into the sediment as well as the piling method.

The result of this study is to be applied on local at every specific site, hereby indicating what type of foundation to prefer from an environmental point of view, and also to state what technical as well as planning adaptations that ought to be applied.

<u>Contents</u>

Ref:	Title:	Author:	Date:
5.19	Alternatives and modifications of Monopile foundation or its installation technique for noise mitigation	Z. Saleem	04-2011

Summary:

Relevance to thesis
Environmental effects, noise mitigation, monopile installation

Summary

This report reviews and proposed alternatives and modifications for the steel monopile foundation and its current installation technique for noise mitigation. The report identifies a number of different engineering solutions that are divided into two categories, solutions that can be used with the current installation techniques (i.e. modifications) and solutions that change the current methods (i.e. alternatives).

Based on measurements the noise emissions for the installation of a 6 m diameter monopile using hydraulic impact hammers reach sound exposure levels of 174 dB re 1μPa at a distance of 500 meters. This value is above the Temporary Threshold Shift (TTS) of pennipeds (163 dB) and very close to that TTS of cetaceans (183 dB). Moreover prolonged exposure to TTS sound levels can cause Permanent threshold Shift (PTS). The marine mammals depend heavily on their hearing to survive. Damaging the hearing of these animals can make it harder for these animals to survive and in extreme cases make it impossible.

Methods that do not completely change the current pile driving methods are interesting as these procedures can be applied in the short term. These include changing of pile-toe shape, use of contact damping, skirt-pile support, modification of the parameter for pile stroke and sound isolation/damping. The noise reduction from these modifications is achieved either by reducing the sound at the source, for example changing the pile stroke parameter or by isolating/damping the sound, like using sleeves.

Alternatives for current techniques require a major modification either of the installation procedure or of the monopile itself. Alternative for hydraulic impact hammer include the use of Vibratory hammers and drilling, while the alternatives for the monopile foundation include, guyed support structure, concrete/drilled monopile, screwpile, jacket structure, gravity based supports structures (GBS), tripod/tripile foundation, floating structures and suction caisson.

Even the best solution for a significant noise reduction is useless in the short term if it will take decades to implement. Therefore solutions with the quickest implementation time need to be considered and applied to reduce the harmful effects of impact pile driving in the near future. This will slightly lower the noise disturbance in the short-term while giving more effective solutions, time to be developed and tested.

Contents

Ref:	Title:	Author:	Date:
5.20	Design of Offshore Wind Turbine Support Structures	C. LeBlanc	2004
Summary:			

<u>Relevance to thesis</u>
support structure design, wind loading, monopile foundations, soil mechanics

<u>Summary</u>
Offshore wind power is a domestic, sustainable and largely untapped energy resource that provides an alternative to fossil fuels, reduces carbon emissions, and decreases the economic and supply risks associated with reliance on imported fuels. The overall aim of this Ph.D. thesis was to enable low-cost and low-risk support structures to be designed in order to improve the economic feasibility of future offshore wind farms. The research work was divided in the following four selected research topics:

1. Long-term response of monopiles: Offshore wind turbine support structures are subjected to strong cyclic loading, originating from wind and wave loads. The aim of the research work was to improve the current design guidelines for prediction of the accumulated rotation of an offshore wind turbine in response to cyclic loading.
2. Modeling of advanced geotechnical problems: Numerical methods provide an important tool for investigating soil-structure interaction and optimizing the design of support structures. The aim of the research work was to develop a engineering tool for exploring the responses of offshore support structures subjected to cyclic loading.
3. Interpretation of piezocones in silt: Piezocone data give important information on the soil parameters required for the design of offshore wind turbine support structures. However, interpretation of piezocone data in silt sediments is conceptually difficult, as the measured response is affected by the degree of pore pressure dissipation during cone penetration. The aim of the research work was to establish a methodology for interpreting piezocone data in silt sediments.
4. Buckling loads of bucket foundations: Bucket foundations have the potential to be the cost-effective option for future offshore wind farms, if suction assisted penetration is employed. However, the structure is particularly exposed to structural buckling due predominantly to the hydrostatic loading during installation. The aim of the research work was to reduce the risk of buckling failure during installation of future bucket foundations.

<u>Contents</u>

Ref:	Title:	Author:	Date:
5.21	Dynamic Response Calculations of Offshore Wind Turbine Monopile Support Structures	D. J. C. Salzmann	02-2004

Summary:

Relevance to thesis
dynamic analysis, monopile foundation, wind and wave design loads

Summary
The increasing demand for energy and a growing concern on the environment have led to the development of renewable energy sources. Within this development, wind turbines have proved to be one of the most promising, but onshore they are known to cause resistance due to noise nuisance and aesthetic issues. Taking these wind turbines offshore therefore seems an ideal solution, especially when considering the higher wind speeds at sea; an explosive growth of offshore wind energy parks can therefore be expected in the near future. However, the offshore wind turbine (OWT) concept is relatively new and is still to be optimized; especially a reduction in its costs is essential to guarantee it a successful future. Less expensive OWT support structures can be realized through accurate insight in the environmental loads on an OWT and the structure's response. Simulations of an OWT in the preliminary design phase calls for a program that requires only the most basic input data.

In this thesis project, the objective was to develop a computer program that can calculate the environmental loads on an OWT as well as the dynamic response of its monopile support structure, with the use of a limited amount of input data.

The latest theories on wind turbine foundation design were merged into a new computer simulation program called RECAL (Response Calculator). RECAL proved that it was possible to create a computer simulation program for the mentioned purposes using only a restricted amount of input data; the assumptions made in RECAL resulted in a minor influence on the output results compared to the results of simulation programs with extensive input demands. However, more extensive testing of RECAL is advised to validate its use for design purposes.

Contents

Ref:	Title:	Author:	Date:
5.22	Gravity Base Foundations for Offshore Wind Turbines	L. van Kessel	[-]

Summary:
Relevance to thesis *gravity bases foundations design, cost effective design, wind and wave loading* Summary In this report a design procedure for a concrete Gravity Base Foundation for offshore wind turbines is presented. The idea of making such a procedure came from an offshore wind turbine park near the Belgian coast, the project at Thorntonbank, in which a GBF was used as a foundation for the wind turbines. The design procedure is made by reproducing this project, because it's the only project in which such a GBF is used. When the design of the GBF is made, the amount of material that is necessary to build it can be determined and the costs can be compared to the costs of other foundation types in the same circumstances. For making a design the following steps have to be taken: • Study reference projects. • Investigate what soil and weather conditions are present in the site location. • Determine the maximum and minimum water depths and the height of the waves. • Make assumptions and simplifications to make the design easier. • Estimate the dimensions of the GBF. • Determine all the loads that could act on the GBF. • Decide the failure modes and the loads that are governing in the failure mode. • Make analyses of the structure and decide if the GBF can resist all the loads. • If not, determine the new dimensions and start again from that point on. • If the GBF is strong enough, calculate the amount of material that is needed. • Determine the costs of the materials of the GBF. In the report the check of the check that need to be done are described. The checks are applied and all the loads can be calculated. The amount of material and the costs follow. Contents Chapter 1 – Assignment Chapter 2 – GBF Thorntonbank Chapter 3 – Variables Chapter 4 – Loads Chapter 5 – Analysis GBF Chapter 6 – Costs Chapter 7 – Conclusions Chapter 8 – Recommendations

Ref:	Title:	Author:	Date:
5.23	Lateral Behavior of Large Diameter Offshore Monopile Foundations for Wind Turbines	L. Bekken	10-2009

Summary:

Relevance to thesis
soil interactions, monopile design considerations, wind and wave loads, monopile aspect ratio

Summary

To make economic use of offshore wind energy possible, foundation structures with minimum costs, but sufficient stiffness have to be designed. One foundation concept that has often been realized recently is the monopile concept. The traditional monopile is an open ended large diameter steel cylindrical pile driven into the soil.

The loads from wind, waves and currents must be in equilibrium with the reaction of the soil. The soil reaction is mobilized when the foundation pile starts to deflect mainly laterally due to the lateral forces. In the offshore industry the soil in horizontal pile-soil interaction problems is modeled by means of multi linear depth dependent elastic-plastic soil springs, so called ‘p-y-curves’. It is not known whether these curves can be used for relatively short and large diameter monopiles.

The objective of the study in this report is to determine if the 3D FE-model gives better and more reliable results than the ‘p-y’ method for the design of offshore foundation piles, and to determine if the ‘p-y’ method is suitable for the design of large diameter monopile foundations.

A study is performed on the effects of increasing the pile diameter:

- The effect of the normal effective stresses, the horizontal shear stresses and the vertical shear stresses around and along the pile shaft.
- The effect of the shearing resistance in the pile tip due to the pile tip displacement.
- The effect of the interaction between the soil springs.

Contents

Chapter 1 – Introduction
Chapter 2 – State of the Art
Chapter 3 – Input for Calculations
Chapter 4 – Pile Design with ‘p-y’ method
Chapter 5 – Finite Element Model
Chapter 6 – Validation of the FE Model
Chapter 7 – Finite Element Results of Large Diameter Monopile

Ref:	Title:	Author:	Date:
5.24	Load Reduction of Support Structures of Offshore Wind Turbines	U. V. Anderson	08-2008

Summary:

Relevance to thesis
cost effective design, fatigue loads, soft support structures, dynamic analysis

Summary
A significant proportion of the cost of offshore wind turbines consists of the support structure. One important design parameter for support structures of offshore wind turbines is the fatigue loads. In this project the fatigue loads of the 5MW UpWind baseline turbine examined, with the aim to reduce the fatigue loads. For this purpose wind and wave data from the Dutch North Sea is used. The focus is spilt into two topics, the prospects and challenges of using softer designs in support structures and the effect of wind-wave misalignment.

A wind turbine with a soft support structure is designed with an eigen frequency of 0.202 Hz. This corresponds to the 1P frequency of 12.1 rpm, which is the rated rotational speed of the baseline turbine and causes thereby resonance. This design is made simply on the base of the baseline turbine by decreasing the Youngs module of the steel. The findings show that the soft design leads to higher fatigue loads under the same load conditions than the baseline turbine. Furthermore it is shown that the fatigue loads can be reduced by increase the damping of the structure, and finally it is shown that resonance can be avoided by decreasing or increasing the rotational speed using new controllers.

The fatigue loads on the support structure, caused by wind-wave-misalignment, have been analyzed. Here it have been found that for the given load conditions wind-wave misalignment increases the fatigue loads on the support structure with a maximum at 90° (or 270°) wind-wave-misalignment. It have been analyzed how much the fatigue loads at the support structure can be reduced by introducing yawing strategies together with other effects of such strategies. This has shown that the fatigue loads at the support structure can
be reduced and that this also leads to a reduction in power production as well as an increase in the loads on the blades.

Contents

Ref:	Title:	Author:	Date:
5.25	Selection- design and construction of offshore wind turbine foundations	S. Malhotra	[-]

Summary:

Relevance to thesis
foundation design considerations, support structure concepts, cost effects

Summary
The European Wind Energy Association estimates that between 20 GW and 40 GW of offshore wind energy capacity will be operating in the European Union by 2020. The US Department of Energy predicts that 50 GW of installed offshore wind energy will be developed in the next 20 years. This means at least US$100 billion of capital investment with about US$50 billion going to offshore design and construction contracts.

Along the northeast coast of the United States, offshore development is an attractive alternative because electricity costs are high and transmission line construction from the mid-west faces many obstacles. Higher quality wind resources, proximity to coastal population centers, potential for reducing land use, aesthetic concerns, and ease of transportation and installation are a few of the compelling reasons why power companies are turning their attention to offshore development. Offshore turbines are being made larger to economize in the foundation and power collection costs. As the technology for wind turbines improves, the industry has developed wind turbines with rotor diameters as large as 150 m and power ratings of over 7.5 MW to 10 MW. As increasing number of wind farms are being planned 15 to 50 km from shore in water depths of over 50 m, the combination of water depth, the increasing wind tower heights and rotor blade diameters create loads that complicate the foundation design. Moreover, offshore foundations are exposed to additional loads such as ocean currents, storm wave loading, ice loads and potential ship impact loads.

This report summarizes current practices in selecting and designing such foundations.

Contents

Ref:	Title:	Author:	Date:
5.26	Transport and Installation of Offshore Wind Farms	S. A. Herman	02-2002

Summary:
<u>Relevance to thesis</u> *transport and installation costs, cost model, transportation and installation concepts* <u>Summary</u> A computer model that calculates the transport and installation costs of a wind farm has been composed and implemented in the OWECOP II model. The latter quantifies all costs of implementation of a wind farm, at a determined location on the Dutch Exclusive Economical Zone. Transport and installation are a part of it. The computer model is an Excel workbook that includes an input part, a database part and a calculation part. Transport and installation costs have been derived based on known offshore techniques and they are structured according to possible wind turbine assembly procedures. Besides the cost of offshore equipment, also an estimation of delays due to bad weather and the use of several vessels simultaneously have been included. Other costs included are: Scour protection costs, costs of soil research, costs of electric cable installation and costs of removal of wind turbine and wind turbine components after their operational lifetime. The possible transport and installation techniques are analyzed based on state-of-the-art offshore equipment. These techniques are then reviewed with respect to the governing costs. A cost model is compiled, which describes both the costs, and implementation of all transport and installation aspects. The calculation of costs for transport and installation of offshore wind turbines as implemented in the OWECOP model, could be detailed by a deeper analysis of workable conditions (probability of work), and implementation of wind turbine sizes and dimensions related to the transport and installation vessels. <u>Contents</u> Chapter 1 – Introduction Chapter 2 – Offshore Turbine Configuration Chapter 3 – Offshore Turbine Types, Impact on Design Chapter 4 – Offshore Wind Turbine Dimensions and Mass Chapter 5 – Analysis of Transportation Costs Chapter 6 – Analysis of Installation Costs Chapter 7 – Integration of Transport and Installation Costs into the Cost Model Chapter 8 – Evaluation of Results Chapter 9 – Conclusions and Recommendations

Ref:	Title:	Author:	Date:
5.27	Design of Support Structures for Offshore Wind Turbines	J. van der Tempel	04-2006

Summary:

<u>*Relevance to thesis*</u>
support structure design, fatigue design considerations, foundation concepts

<u>Summary</u>
To meet growing energy demands, the Kyoto protocol and the much desired diversification of supply, wind energy has become a mainstream source of energy in the EU. Cost wise it is already competing with gas fired electricity. In the last decade wind moved offshore to accommodate even more wind power. The offshore wind resource is more abundant and of a better quality, resulting in higher electricity output. On the other hand, the cost of installing turbines offshore is higher than onshore. To improve the cost-effectiveness of offshore wind, the risks involved must be known and mitigated and the critical design parameters must be optimized. From an engineering point of view, these requirements can be met through the following steps; understand the basics of offshore wind turbines; apply lessons learned from previous projects; improve design tools.

The study in this report focuses on the design of the support structure. An overview is given of four actual offshore wind farm designs and their details. The design methods were compared mutually and with a design of a typical offshore oil platform. For most of the design steps, the methodology is consistent.

Fatigue assessment in offshore engineering is done in the frequency domain. This method can be applied because the wave loads can be effectively linearized. The advantages of the frequency domain method are the clarity of presentation of intermediate results and the final outcome as well as the speed of calculation. The offshore wind industry standard uses time domain simulations, which enables taking all non-linearity's of the turbine operation into account.

A key issue in the accuracy of the method is the effect of the aerodynamic damping of the operating turbine on support structure dynamics. Several calculation methods for this damping have been tested and have shown to give reasonable results. The frequency domain method is currently being implemented in the software of an offshore contractor while other companies have already shown interest.

<u>Contents</u>

APPENDIX F – SUMMARY OF DESIGN STANDARDS

Ref:	Standard:	Representative:	Date:
6.01	Barents 2020: Phase 1 - Norwegian Baseline on HSE, Ice and Metocean	Det Norske Veritas	2008
Summary:			

<u>*Relevance to thesis*</u>
environmental standards, sea ice, meteorology, oceanography, safety factors, arctic environment

<u>Introduction</u>
Focus will be on industry standards and harmonization of HSE industry standards for the petroleum industry between Norway and Russia in the Barents Sea. The baselines developed in Phase 1 of the project constitute a basis for evaluating and harmonizing of industry standards in Phase 2 and 3 of the project, where standards are evaluated and harmonized. This document contains the ice and metocean input to the Norwegian position paper on HSE-standards in Phase1 of the Barents 2020 project. Phase 1 of the Barents 2020 aims at:
1) Presenting the current set of HSE standards under which offshore and maritime operations take place in Norway and Russia
2) Identifying main areas of changed risk when moving operations to the arctic parts of the Barents Sea.
The following codes have been identified as the most relevant to apply for metocean and ice input to design for the Norwegian shelf:

- NORSOK N-002 - Metocean data and NORSOK N-003 Action and Action Effects
- ISO 19901-1 Part 1 - Metocean design and operating considerations
- DNV-RP-C205 - Environmental conditions and environmental loads

ISO 1990-01 is the most extensive but NORSOK N-003 has some more strengths (more specific; combinations of loads).

Ref:	Title:	Author:	Date:
6.02	Design Standards for Offshore Wind Farms	American Bureau of Shipping	06-2011
Summary:			

<u>*Relevance to thesis*</u>
standard to wind farm design, wind induced loads, wave induced loads, case studies

<u>Introduction</u>
The main objectives of this document, as outlined in the BOEMRE Contract M10PC00105, are to:

- Study the governing load cases and load effects of bottom-founded offshore wind turbines subjected to the hurricanes on the US Outer Continental Shelf (OCS)
- Review and evaluate the existing methods of calculating the breaking wave slamming load exerted on an offshore wind turbine support structure
- Provide recommendations to support the future enhancement to the relevant design criteria for offshore wind turbines

This report presents the results of the state-of-the-art review, the case study results for the characteristic responses of bottom-founded offshore wind turbines assumed as being installed in hurricane-prone regions on the US OCS, the research findings of modeling breaking wave slamming loads, and the recommended design methods.

Section 1 is considered as an introduction into the research project and present design standards.

Section 2 presents the research findings on the design load cases for offshore wind turbines to be deployed in hurricane-prone regions. The section starts with the discussion of the outcome of the state-of-the-art review of subjects relevant to the hurricane design load cases. The results of comparative study of two representative turbulent wind models and the study of the effect of failure of turbine’s yaw and pitch control systems are then reported. Extensive case studies using three typical configurations of offshore wind turbine support structures are carried out to explore characteristic responses of offshore wind turbines subjected to hurricane environmental conditions. The correlations of the support structure responses with various design parameters, including the environmental conditions, support structure configurations, site conditions and turbine operating conditions are evaluated in the study and reported in this section. This section concludes with the recommended strength design criteria for bottom-founded offshore wind turbines to be installed in hurricane-prone regions.

Section 3 is dedicated to the review and evaluation of existing breaking wave slamming load models. The outcome of the state-of-the-art review, which covers various analytical and numerical wave slamming force calculation methods as well as the slamming experiments, are first reported in this section. An evaluation is performed to identify the relative importance of various parameters affecting the calculation of wave slamming forces. This is followed by parametric analyses of four representative analytical slamming load models as well as the resultant dynamic responses of a monopile support structure. The combined effect of soil conditions and structural damping ratios is evaluated. Based on the results of the literature review and numerical analyses, recommendations are made for the design of an offshore wind turbine for which the breaking wave slamming is a matter of concern.

Section 4 contains the main conclusion and recommendations.

Ref:	Title:	Author:	Date:
6.03	Offshore Standard - DNV-OS-J101 Design of Offshore Wind Turbine Structures	Det Norske Veritas	09-2011

Summary:

<u>Relevance to thesis</u>
design standard for offshore wind turbines, foundations, load cases, environmental effects

<u>Introduction</u>
DNV-OS-J101 is the DNV standard for design of offshore wind turbine structures. The standard covers design, construction, installation and inspection of offshore wind turbine structures, support structures and foundations. The design principles and overall requirements are defined in this standard. The standard can be used as a stand-alone document. The standard does not cover design of support structures and foundations for substations for wind farms. For design of support structures and foundations for substations, such as converter stations and transformer stations DNV-OS-J201 applies. The standard also does not cover design of wind turbine components such as nacelle, rotor, generator and gear box. For structural design of rotor blades DNV-DS-J102 applies. The standard has been written for general world-wide application. National and governmental regulations may include requirements in excess of the provisions given by this standard depending on the size, type, location and intended service of the wind turbine structure.

The standard specifies general principles and guidelines for the structural design of offshore wind turbine structures. The objectives of this standard are to:

- Provide an internationally acceptable level of safety by defining minimum requirements for structures and structural components.
- Serve as a contractual reference document between suppliers and purchasers related to design, construction, installation and in-service inspection.
- Serve as a guideline for designers, suppliers, purchasers and regulators.
- Specify procedures and requirements for offshore structures subject to DNV certification.
- Serve as a basis for verification of offshore wind turbine structures for which DNV is contracted to perform the verification.

This standard gives requirements for the following subjects: design principles, selection of material and extent of inspection, design loads, load effect analyses, load combinations, structural design, foundation design and corrosion protection.

Section 1 – Introduction
Section 2 – Design Principles
Section 3 – Site Conditions
Section 4 – Loads and Load Effects
Section 5 – Load and Resistance Factors
Section 6 – Materials
Section 7 – Design of Steel Structures
Section 8 – Detailed Design of Offshore Concrete Structures
Section 9 – Design and Construction of Grouted Connections
Section 10 – Foundation Design
Section 11 – Corrosion Protection
Section 12 – Transport and Installation
Section 13 – In-Service Inspection, Maintenance and Monitoring

Ref:	Title:	Author:	Date:
6.04	Guide for Building and Classing Offshore Wind Turbine Installations	American Bureau of Shipping	12-2010

Summary:

Relevance to thesis
offshore wind turbine regulations, environmental loads, design criteria

Introduction
This Guide provides criteria for the design, construction, installation and survey of permanently sited support structures for offshore wind turbines. The requirements in this Guide are applicable to the Support Structure of an Offshore Wind Turbines. Previously developed guidelines to date have been primarily based on experience from European coastal waters. However, ABS' Guide is the first to specifically consider the conditions these structures may encounter in tropical storm prone waters. The Guide takes into account the well-established International Electrotechnical Commission (IEC) 61400 series of standards for wind turbines, the American Petroleum Institute's Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms (API RP 2A), ABS' offshore Rules and Guides and the unique environmental conditions on the US OCS.

The Guide incorporates refinements to the design environmental conditions and design load cases required by IEC 61400-3 to account for the effects of tropical hurricane conditions. Site-specific design is more directly addressed in the definition of the design load cases. The Guide also specifies a unique set of strength design criteria for the steel support structure of an offshore wind turbine based on the commonly accepted working stress design (WSD) approach. ABS offers a class notation for those turbine support structures complying with the requirements and conditions of the Guide. The notation A1 Offshore Wind Turbine Installation will be listed in the ABS Record. Other optional class notations are S (years) for the return period of maximum design environmental conditions and FL (years) for the design fatigue life.

Contents

Chapter 1 – Classification and Surveys
Chapter 2 – Materials and Welding
Chapter 3 – Environmental Conditions
Chapter 4 – Loads
Chapter 5 – Structure and Foundation Design
Chapter 6 – Marine Operations

Ref:	Title:	Author:	Date:
6.05	ISO/FDIS 19906: Petroleum and natural gas industries — Arctic offshore structures	International Organization of Standardization	2010

Summary:

Relevance to thesis
arctic offshore eningeering, structural design criteria, ice load design parameters, FEM modelling

Introduction
The series of International Standards ISO 19900 to ISO 19906 addresses design requirements and assessments for all offshore structures used by the petroleum and natural gas industries worldwide. Through their application, the intention is to achieve reliability levels appropriate for manned and unmanned offshore structures, regardless of the type of structure and the nature or combination of the materials used. It is important to recognize that structural integrity is an overall concept comprising models for describing actions, structural analyses, design rules, safety elements, workmanship, quality control procedures and national requirements, all of which are mutually dependent. The modification of one aspect of design in isolation can disturb the balance of reliability inherent in the overall concept or structural system. The implications involved in modifications, therefore, need to be considered in relation to the overall reliability of all offshore structural systems.

This International Standard was developed in response to the offshore industry's demand for a coherent and consistent definition of methodologies to design, analyze and assess arctic and cold region offshore structures.

Structures capable of resisting ice have been in use in temperate regions for well over a century. These include bridge piers and navigation aids in ice-covered rivers and estuaries. In fact, bridge codes in cold countries have included methods for ice loads dating back many decades. In more severe arctic and cold regions, ice resistant structures are more recent. But much experience has been gained commencing in the 1960s, and this knowledge is incorporated into this International Standard. Where uncertainties still exist, conservative approaches and methods have been recommended. This International Standard also addresses issues such as topsides winterization, and escape, evacuation and rescue that go beyond what is strictly necessary for the design, construction, transportation, installation and decommissioning of the structure. These issues are essential for offshore operations in arctic and cold region conditions and they are not covered in other International Standards.

Contents

Sections 1 to 4 – Scope, References, Definitions and Symbols
Section 5 – General Requirements and Conditions
Section 6 – Physical Environmental Conditions
Section 7 – Reliability and Limit States design
Section 8 – Actions and Action Effects
Section 9 – Foundation Design
Section 10 t0 15 – Design of various construction types / materials
Section 16 – Ice Engineering topics
Section 17 – Ice Management
Section 18 – Escape, Evaluation and Rescue

Ref:	Title:	Author:	Date:
6.06	IEC 61400-3: Wind turbines Part 3: Design requirements for offshore wind turbines	International Electrotechnical Commission	2009
Summary:			

<u>*Relevance to thesis*</u>
offshore wind turbine regulations, environmental loads, design criteria, structural design

<u>Introduction</u>
This part of IEC 61400 specifies additional requirements for assessment of the external conditions at an offshore wind turbine site and it specifies essential design requirements to ensure the engineering integrity of offshore wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime.

This standard focuses on the engineering integrity of the structural components of an offshore wind turbine but is also concerned with subsystems such as control and protection mechanisms, internal electrical systems and mechanical systems. A wind turbine shall be considered as an offshore wind turbine if the support structure is subject to hydrodynamic loading. The design requirements specified in this standard are not necessarily sufficient to ensure the engineering integrity of floating offshore wind turbines. It should be used together with the appropriate IEC and ISO standards, in particular with IEC 61400-1.

<u>Contents</u>

Sections 1 to 4 – Scope, References, Definitions and Symbols
Section 5 – Principal Elements
Section 6 – External Conditions
Section 7 – Structural Design
Section 8 – Control and Protection System
Section 9 – Mechanical Systems
Section 10 – Electrical System
Section 11 – Foundation Design
Section 12 – Assessment of the External Conditions at OWT site
Section 13 – Assembly, Installation and Erection
Section 14 – Commissioning, Operation and Maintenance

APPENDIX G – SUMMARY OF BOOKS

Ref:	Title:	Author:	Date:
7.01	Dynamics of Offshore Structures ISBN: 0-471-26467-9	James F. Wilson	1993

Summary:

Relevance to thesis
Design of offshore structures against extreme environmental loading and dynamic effects such as waves, wind, current, earthquake, ice and soil loading.

Chapter 1
This chapter describes various offshore structures, environmental forces, structural materials, modeling and analysis.
Chapter 2
This chapter describes structure-environment force interactions, ice impact, wave slamming, structural (added) mass and (added) damping.
Chapter 3
This chapter describes various offshore wave conditions, deterministic and stochastic wave modeling.
Chapters 4 to 10
These chapters describe modeling and analysis of wave forces on various offshore structures
Chapter 11
This chapter describes the behavior of foundation piles, jacket legs and monopiles against dynamic, axial and lateral loading. Also computer aided modeling of piles is described.

Ref:	Title:	Author:	Date:
7.02	Frontiers in Offshore Geotechnics II ISBN: 978-0-203-83007-9	Susan Gourvenec David White	2011
Summary:			

Relevance to thesis
soil properties, soil capacity and modeling, piled foundations, monopile-soil interaction.

This book is a compilation of the "*International Symposia on Frontiers in Offshore Geotechnics* ". The symposium provide a platform for academics and practitioners to discuss the emerging challenges in offshore geotechnical engineering and present recent practice and research. Key themes include geohazards, site investigation techniques and foundations for renewable energy, as well as anchoring solutions for deep water and pipeline geotechnics. Greater emphasis has been placed on in situ soil testing techniques and pore pressure measurement, and the characteristics of unusual seabed deposits found in frontier regions.

The keynote papers reflect the key stages of an offshore project. The first three keynotes cover the assessment and interpretation of offshore geohazards, in situ site characterization and pore pressure measurement, and the behavior of West African clays – West Africa being a critical frontier region with particular challenges. Two following keynotes describe state-of-the-art design considerations for piled foundations and pipelines, The third keynote describes recent advances in centrifuge modeling and the final keynote examines risk and reliability in offshore geotechnics. The keynotes alone contain many man-years of accumulated experience.

The papers collected in these proceedings include 7 keynotes and a further 117 peer-reviewed general papers that represent the current state-of-the-art in offshore geotechnics. These provide an invaluable resource to all those working in offshore construction, design and research.

Relevant Keynotes or Papers:

- Axial and lateral pile design in carbonate soils.
- Strength measurement in very soft upper seabed sediments.
- Repeated loading and unloading of the seabed.
- Centrifuge modeling of offshore monopile foundation.
- Observations of shallow skirted foundations under transient and sustained uplift.
- Behavior of piles under combined lateral and axial loading.
- Investigations on the behavior of large diameter piles under cyclic lateral loading.
- Installation of suction caissons for offshore renewable energy structures.
- Design of monopile foundations in sand for offshore wind farms.
- Experimental evaluation of backfill in scour holes around offshore monopiles.
- Study on soil-structure interaction of suction caisson by large-scale model tests.

Ref:	Title:	Author:	Date:
7.03	Structural Integrity of Offshore Wind Turbines ISBN: 978-0-309-16082-7	U.S. Transportation Research Board	2011

Summary:

<u>*Relevance to thesis*</u>
design of offshore wind farms, support structures, risk assessment, design standards

This book is a report of a research committee established by the U.S. government. The committee was tasked with a study with the following scope and objectives:

> The study will provide findings regarding:
>
> **Task I.** *Standards and Practices*: The applicability and adequacy of existing standards and practices for the design, fabrication, and installation of offshore wind turbines.
>
> **Task II.** *Role of Certified Verification Agents (CVAs)*: The expected role of the CVA in identifying standards to be used (including determining the compatibility—the acceptability of mixing and matching—of standards from different sources), and the expected role of the CVA in conducting monitoring and onsite inspections to verify compliance with the standards.
>
> **Task III.** *CVA Qualifications*: The expected experience level, technical skills and capabilities, and support equipment and computer hardware/software needed to be considered a qualified CVA.
>
> The focus of the study will be limited to the safety of structural and operational characteristics of offshore wind turbines, including turbine design, fabrication, and installation.

Chapter 1
This is an introduction into the research committee, study, scope and objectives of the research.

Chapter 2
This chapter provides a brief overview of the motivation for the United States in developing offshore wind energy. It then reviews offshore wind energy production worldwide and describes the technologies involved in current offshore turbine generators.

Chapter 3
This chapter reviews existing standards, the differences among them, and the work under way to identify deficiencies and develop new standards.

Chapter 4
This chapter sets out the regulatory philosophies underlying various oversight regimes and how they might be incorporated into standards and guidance for application in the United States.

Chapter 5
This chapter targets the second part of the committee's charge by reviewing the role of third-party oversight and CVAs.

Chapter6
This chapter assesses the qualifications needed by CVAs.

Chapter 7
This final chapter summarizes the committee's key findings and recommendations for structural and operating safety of offshore wind energy turbine generators.

Ref:	Title:	Author:	Date:
7.04	Wind Energy: Fundamentals, Resource Analysis and Economics ISBN: 978-3-540-30905-5	Sathajith Mathew	2006

Summary:

Relevance to thesis
design of offshore wind farms, support structure concepts, risk assessment, economics

Introduction
In view of the rapid growth of wind industry, wind energy technology has emphasis in many fields of engineering. Fundamentals of wind energy conversion, which is discussed in the preliminary chapters of this book, are aimed at students and engineers active in this field. Advanced resource analysis tools are derived and applied. The Wind Energy Resource Analysis (WERA) software, provided with the book, is an effective tool for wind energy practitioners for assessing the energy potential and simulating turbine performance at prospective sites.

Chapter 1
The introductory chapter narrates the historic development of wind energy technology along with its present status and future prospects.

Chapter 2
This chapter presents the basic principles of wind energy conversion. Descriptions on different types of wind machines and their performances are briefed here. Basics of wind rotor aerodynamics and its application in the turbine design are also presented in this chapter.

Chapter 3
This chapter is devoted to the methods of measurement and analysis of wind spectra for energy use. Statistical methods for wind energy analysis are introduced here. These are further extended for developing models for estimating the wind energy potential of a prospective site.

Chapter 4
This chapter describes the constructional features of various systems and sub-systems of a Wind Energy Conversion System. Along with wind electric generators, wind powered water pumping systems are also considered. Features of wind farms are also discussed in this chapter.

Chapter 5
This chapter deals with performance models of WECS. Tools to simulate the field performance of wind powered generators and water pumps are presented in this section.

Chapter 6
This chapter describes the environmental aspects of wind energy conversion. While highlighting the environment related merits of wind energy, the recent concerns are reviewed, and a life cycle based approach is adopted for these discussions.

Chapter 7
This chapter deals with the economics of wind energy conversion, following the present worth method. Factors affecting the costs and benefits of wind generated electricity are discussed and indices for economic appraisal are evolved.

Ref:	Title:	Author:	Date:
7.05	Wind Energy Handbook ISBN: 0-471-48997-2	Tony Burton David Sharpe	2001

Summary:

<u>Relevance to thesis</u>
wind turbine design, operation, maintenance, wind farm economics, wind turbine loading

<u>Introduction</u>
As environmental concerns have focused attention on the generation of electricity from clean and renewable sources wind energy has become the world's fastest growing energy source. The *Wind Energy Handbook* draws on the authors' collective industrial and academic experience to highlight the interdisciplinary nature of wind energy research and provide a comprehensive treatment of wind energy for electricity generation.

<u>Contents</u>

- An authoritative overview of wind turbine technology and wind farm design and development
- In-depth examination of the aerodynamics and performance of land-based horizontal axis wind turbines
- A survey of alternative machine architectures and an introduction to the design of the key components
- Description of the wind resource in terms of wind speed frequency distribution and the structure of turbulence
- Coverage of site wind speed prediction techniques
- Discussions of wind farm site constraints and the assessment of environmental impact
- The integration of wind farms into the electrical power system, including power quality and system stability
- Functions of wind turbine controllers and design and analysis techniques

Ref:	Title:	Author:	Date:
7.06	Actions from Ice on Arctic Offshore and Coastal Structures ISBN: S-8114-0703-3	Sveinung Løset Karl N. Shkhinek Knut V. Høyland	2006
Summary:			

Relevance to thesis
Ice actions against structures, ice mechanics, arctic environment, arctic concepts

Introduction
Low winter temperatures, the presence of ice and some offshore permafrost and the darkness make offshore petroleum production and transport from Arctic regions more challenging than in most other locations where hydrocarbons are extracted. Ice may impose large actions on platforms and may create gouges in the sea floor, which can affect pipeline and sub-sea equipment integrity. Ice can also impede access by supply ships and tankers, and create difficulties for personnel evacuation. The influence of ice will usually require customized solutions to the engineering and operations of offshore petroleum production and transport facilities, regardless of whether these are sub-sea or surface based.

The book "Actions from Ice on Arctic Offshore and Coastal Structures" is written to help engineers meet the growing demand for construction of structures in Arctic and other cold waters. It is meant to increase the knowledge of Arctic / cold climate technology for safe and sound petroleum production and transport from the Arctic region. In particular it aims towards sustainable development and exploitation of petroleum resources in Arctic waters.

Contents

Chapter 1 – Introduction
Chapter 2 – Actions and Action Effects
Chapter 3 – Ice Physics and Mechanics
Chapter 4 – Ice Features
Chapter 5 – Ice Actions
Chapter 6 – Icing in the Ocean
Chapter 7 – Ice Management
Chapter 8 – Design for Ice Gouges
Chapter 9 – Actions caused by Earthquakes

Ref:	Title:	Author:	Date:
7.07	Engineering Aspects Related to Arctic Offshore Deleopments ISBN: 978-5-8114-0723-1	Sveinung Løset Karl N. Shkhinek Knut V. Høyland	2006

Summary:

Relevance to thesis
arctic offshore developments, arctic structures, structural design, arctic environment

Introduction
As many geologists estimate that 25% of the remaining non-detected oil and gas resources may be found in Arctic areas, the interests for exploration of Arctic oil and gas resources have increased considerably over the last years. Oil and gas deposits recently discovered have lead to a demand for engineering knowledge tailored to the prevailing conditions in Arctic waters. This means development of offshore solutions for waters just as deep as in the North and Norwegian Seas, but with the potential for sea ice and icebergs intruding the area most of the year. Further to the East, ice conditions are considerably heavier. The influence of ice will usually require customized solutions to the engineering and not at least the operations of offshore oil and gas systems.

This book considers some of the key engineering aspects related to the Arctic offshore developments. As the risk involved in developing the Arctic is the product of the probability for an accidents and the consequences of a potential accident, both the technology needed for safe and environmentally friendly developments and operations and mitigation measures have to be considered. For successful execution of projects, good project management is required, and this aspect is also discussed.

Contents

Chapter 1 – Introduction
Chapter 2 – Arctic Offshore Developments
Chapter 3 – Main Building Blocks used in Hydrocarbon Field Developments
Chapter 4 – Project Development Principles
Chapter 5 – Arctic Offshore Structures
Chapter 6 – Arctic Innovative Projects
Chapter 7 – Offshore Loading and Transport of Hydrocarbons
Chapter 8 – Pipeline Design
Chapter 9 – Terminal and Breakwaters
Chapter 10 – Environmental Issues