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Ice engineering challenges for offshore wind development in the Baltic Sea

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Baltic Sea offshore wind development has seen a rapid growth in the past decade with major projects developed and constructed in the Southern Baltic Sea and attention now slowly turning to the more challenging Northern Baltic Sea areas. With respect to sea ice engineering, the focus the past years has been on determination of global loads on the support structures, in particular development of ice-induced vibrations has received much attention. In this paper specific sea ice engineering questions encountered in discussions with designers of offshore wind support structures between 2018 and 2023 are presented. The focus is on questions which do not seem to have a straightforward answer yet. These relate to the completeness of the load case table, interpretation of the ice strength coefficient C_R, jamming and sheltering effects for multi-legged structures, design of appurtenances for ice loading, ridge loads, and sea ice dynamics in the presence of wind farms.

Keywords: Ice induced vibrations; ice ridges; monopile; jacket; substation; appurtenances

1. Introduction

Baltic Sea offshore wind development has seen a rapid growth in the past decade with major projects recently developed and constructed in the Danish and German waters of the Southern Baltic Sea, developments in Polish waters in an advanced stage, and attention now slowly turning to the more challenging Northern Baltic Sea areas with, for example, the announced development of the Korsnås offshore wind farm. In this region, as well as for example the Bohai Sea and regional lakes, ice, both sea ice and formation of ice on the structure (icing), form specific engineering challenges to overcome (Figure 1).

Figure 1. Left: Fast ice in the vicinity of the Tahkluoto wind farm (picture courtesy of Cody Owen). Center: Icing on a boat landing and ladder. Right: broken ice near turbine foundations in the Bohai Sea (picture courtesy of prof. Qu Yan).

If the projected installation of thousands of structures (~90 GW) in the Baltic Sea materializes the coming decades, it will provide a unique learning opportunity for those studying sea ice in interaction with structures. Certainly, the potential for data gathering is immense (Yu et al., 2020), and combined with the development of data analysis tools and AI we are bound to learn a lot. However, we don't have the data yet, and the structures have to be built soon. In that respect there is a bit of a parallel with historical sea ice engineering developments, with the main difference that the field has matured since the 1960s and we can rely on existing standards, academic research, and historical lessons learned.

Assur (1975) provides a short summary of sea ice engineering in the context of the developments in the late 1960s and early 1970s sparked by discovery of petroleum deposits on the north coast of Alaska and in the Canadian Arctic (Croasdale, 1977) and in relation to deployment of lighthouses and aids-for-navigation (Reinius et al., 1971). Now, fifty years later, the uncertainty with respect to loads on structures has certainly reduced, consensus of opinion has been reached on some topics, but ice loads on structures still remain in the realm of highly uncertain (Timco and Croasdale, 2006; Timco et al., 2013), when compared to wind- and wave loads, for example. The presentation by Croasdale at IAHR 2022 provides an overview of how load methods for vertical structures, the main topic of this paper, developed since the 1970s (Croasdale, 2022).

Stories of past experiences are important reminders that unforeseen ice loading scenarios can be quite catastrophic. Such as that of the Nygrän lighthouse collapse in Sweden (Reinius et al., 1971) where the center of attack of the ice was higher than assumed possible due to thick ice sliding upward on the conical surface of the caisson. And the Kemi I lighthouse which collapsed in the first winter after installation and experienced 'lantern equipment failures' already at the beginning of the first ice season and for which 'already the crushing of a relatively thin ice sheet had caused severe vibrations." (Määttänen, 1975). What can be considered the starting point of Bohai Sea ice engineering in the Spring of 1969 was the moment the Bohai No.2 jacket platform completely collapsed due to not accounting for sea ice in the design sufficiently, and a very severe winter (Liu, 1996).

Many of these early problems are now accounted for in design standards, but it is important to acknowledge that offshore wind turbines are new to sea ice. Some caution is warranted given that almost all 'new' types of structures ever built in icy waters encountered a loading scenario or load effects that were not completely foreseen in the design. Typical foundation concepts considered for offshore wind turbines have their historical counterparts in aids-for-navigation (lighthouses) and oil-and-gas facilities (Bohai Sea and Cook Inlet). During the development of those concepts a lot of knowledge has been gathered which can be utilized for design of offshore wind support structures.

When discussing the current sea ice challenges for the Baltic Sea it is important to acknowledge regional differences. We can speak of a 'Northern' and 'Southern' Baltic Sea (Figure 2), with a boundary around the latitude of the Gulf of Finland and Archipelago Bay. The Southern region is characterized by ice occurring only in extreme winters, vertical support structures being the preferred choice given that wave loading dominates most of the time, monopiles and jackets being considered due to reasonable soil conditions, and the developments are ongoing as we speak. The Northern region is characterized by ice occurring annually, consideration of structures with cones for dealing with the heavy ice, gravity-based foundations in areas with challenging soil conditions for pile driving, and development just starting to be considered.

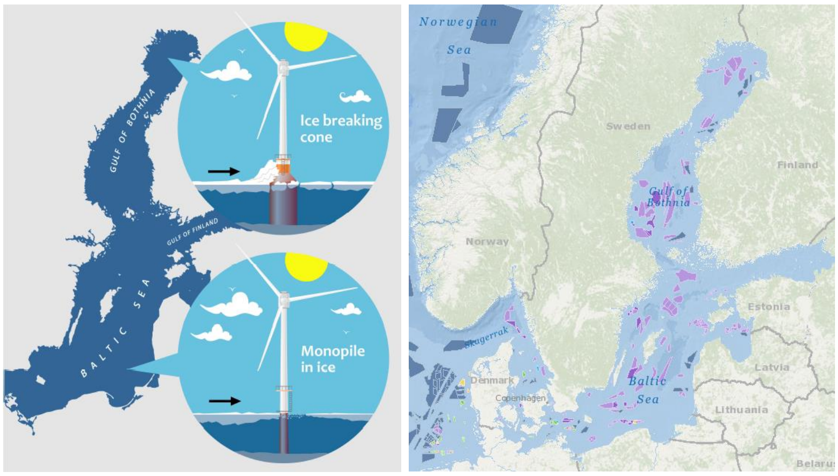

Figure 2. Left: The Northern and Southern Baltic Sea are characterized differently when it comes to the severity of sea ice (illustration courtesy of VTT). Right: Possible locations for offshore wind development in the Baltic Sea (source: 4COffshore).

There have been previous papers about sea ice challenges in relation to offshore wind, mostly related to the Bay of Bothnia. Fransson and Bergdahl (2009) present their work on recommendations for design of foundations around the Swedish coastline. They highlight the important differentiation between fast ice and moving ice and refer to some interesting conclusions from Haapanen et al. (1997) that 'wind power plants should only be built in areas known to have land fast ice'. Määttänen (1999) presents the wind energy potential in the Gulf of Bothnia and relevant environmental and ice conditions, making a case that "with increasing size of wind turbines (only 0.6 kW at the time of writing) the relative increase in the foundation cost for ice action will diminish, making subarctic offshore wind energy a promising opportunity in the near future”. That near future seems to have arrived for the Bay of Bothnia now almost 25 years later. A final noteworthy study which does not seem to have been disseminated broadly in the public domain is the installation and monitoring of a 3 MW turbine foundation in the land-fast ice zone in the northernmost part of the Gulf of Bothnia, Figure 3 (Määttänen, 2010).

Figure 3. 3 MW OWEC test foundation in land-fast ice in 2010 (Picture source: Määttänen, 2010).

Most recently, at the last POAC conference, the high-level challenges with sea ice action on structures for offshore wind were presented by Høyland et al. (2023) as part of a session dedicated to sea ice actions on offshore wind support structures. This paper builds on that work and serves as an introduction to the special session at IAHR 2024 on offshore wind development in the Baltic Sea. The topic of this paper is sea ice engineering challenges. More specifically: the problem of the calculation of ice forces on structures. There are many more aspects of sea ice engineering which are relevant, but given that this paper draws mainly from experience of the author (and I have a passion for ice-induced vibrations) one may recognize some items to receive more attention than others. A clear example is the essential activity of sea ice assessment (Tikanmäki et al., 2019; Tikanmäki and Heinonen, 2021; Wang et al., 2021), concerned with providing ice properties as input to design calculations, which is not specifically addressed, but often has the largest impact on the ice loads one ends up designing for. There are several papers in the special session addressing this topic in more detail.

This paper introduces sea ice related challenges and questions encountered during design of support structures for eight offshore wind farms between 2018 and 2023. I had the opportunity to be involved in the definition of- and discussions about ice loads for design related to all currently considered relevant load cases. These discussions often sparked questions which do not yet seem to have answers, or to which I could not straightforwardly give an answer based on public literature. The next section starts with some open questions related to the design load cases as currently defined in IEC61400-3-1 (2019). The following two sections focus on monopiles and associated ice-induced vibrations, and jackets and the questions related to sheltering and jamming. Appurtenances are briefly touched upon, as there is virtually no guidance available for those in standards. Finally, the consideration of wind turbines as part of wind farms when looking at ice-structure interaction is introduced.

2. Sea ice design load cases for offshore wind

The sea ice engineering focus the past years has been on determination of global loads on the support structures and in particular development of ice-induced vibrations. This has been fueled by the developments in the Southern Baltic Sea, for which Tuomo Kärnä first demonstrated the possibility to design structures without ice cones (personal communication, Helge Gravesen). It is also in part the consequence of the definition of the design load cases for sea ice in the IEC61400-3-1 (2019) standard (Table 1). As ice ridges are not to be considered during power production, and the overturning moments from a turbine producing power are significantly higher than from an idling one, the combination of level ice with a producing turbine often becomes driving for design at mudline. This does bring us to the first relevant question for Baltic Sea offshore wind development, which is: Are we considering all relevant load cases? In a way the answer to this question is already given, and is clearly no.

Table 1. Design load cases for lake- and sea ice from IEC61400-3-1 (black) and DNV-ST-0437 (additional info in blue). D1, D2 and D5 are not included in DNV-ST-0437 (2021).

Design situation	DLC	Wind condition	Marine condition				Other conditions / Ice condition	Type of analysis	Partial safety factor
			Waves	Wind and wave directionality	Sea currents	Water level			
Drifting sea ice (Power production)	D1	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out} Wind speed resulting in maximum thrust				NWLR	Horizontal load from temperature fluctuations	U	N
	D2	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out} Wind speed resulting in maximum thrust				NWLR	Horizontal load from water level fluctuations or arch effects	U	N
	D3 / 9.1	NTM $V_{in} < V_{hub} < V_{out}$	No Waves	n/a	NCM	NWLR	Horizontal load from moving ice at relevant velocities $h = h_{50}$ or largest value of moving ice Dynamic effects from ice loading – frequency lock-in effects	U	N
	D4 / 9.2	NTM $V_{in} < V_{hub} < V_{out}$	No waves	n/a	NCM	NWLR	Horizontal load from moving ice at relevant velocities *Use values of h corresponding to expected history of moving ice occurring.* Dynamic effects from ice loading – frequency lock-in effects	F/U	F/N
	D5	No wind load applied				NWLR	Vertical force from fast ice covers due to water level fluctuations	U	N
Drifting sea ice (Parked, standing still, or Idling)	D6 / 9.3	EWM Turbulent wind model $V_{hub} = V_1$	No waves	n/a	NCM	NWLR	Pressure from hummocked ice and ridges	U	N
	D7 / 9.4	NTM $V_{hub} < 0.7\,V_{ref}$ $V_{hub} < 0.7\,V_{50}$	No waves	n/a	NCM	NWLR	Horizontal load from moving ice at relevant velocities *Use values of h corresponding to expected history of moving ice occurring.* Dynamic effects from ice loading – frequency lock-in effects	F/U	F/N
	D8 / 9.5	EWM Turbulent wind model $V_{hub} = V_1$	No waves	n/a	NCM	NWLR	Horizontal load from moving ice at relevant velocities $h = h_{50}$ or largest value of moving ice Dynamic effects from ice loading – frequency lock-in effects	U	N

Whether or not this is cause for alarm depends on one’s perspective. Ridge load models which can be used for design of structures have not seen the same level of development as those for level ice over the past years. It may very well be that with the development of probabilistic models (Samardžija, 2024) and more detailed modelling of ridge-structure interaction (Croasdale, 2018; Høyland, 2014), design loads from ridges turn out to be less of a ‘problem’ than currently anticipated based on the design equations provided in ISO19906 (2019). Nevertheless, if we were to combine ridges with power production (a not unlikely scenario) as an additional load case this case would often dominate the loads on structures given the current design approaches. At the time of writing including such load case is proposed for the update of DNV-ST-0437. As a consequence, an increase in studies on ice ridges and the loads these exert on structures is therefore expected the coming years, and also welcomed.

There are other considerations when looking at the developments for the Northern Baltic Sea which may require some attention. The presence of sea ice for longer periods of time during the year may impact the dynamic behavior of the structures, especially in the fast ice zone. The ‘frozen-in’ condition could affect the natural periods and fatigue accumulation on structures. A first study on this topic is presented in the special session at this conference. Abnormal events are not typically considered for wind turbine design, but a discussion of the implications of an abnormal winter for multiple wind farms in a region may be relevant. For this purpose, an approach similar to the robustness criteria in IEC 61400-3-1 (2019) can be followed for sea ice, in which a very severe ice event is to be survived. An important aspect is also the consideration of wind farms instead of individual structures, which is starting to get some attention and is treated in more detail in the last section of this paper.

3. Monopiles, level ice loads, and ice-induced vibrations

Given the dominance of design load case D3 (Table 1) in terms of overturning moment at mudline, and the attractiveness of vertical foundations for the Southern Baltic Sea, level ice loads and the potential development of ice-induced vibrations were hot topics the past years. Offshore wind turbines on monopile foundation are flexible structures with little damping (especially when idling). When compared to structures which have experienced ice-induced vibrations in the past these are to be expected to experience significant vibrations in the relatively mild ice conditions they are designed for (Figure 4).

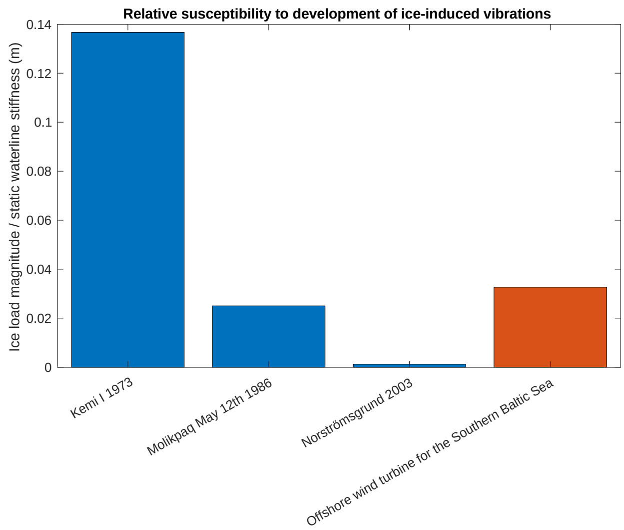

Figure 4. Relative susceptibility to ice-induced vibrations of different offshore structures. The typical wind turbine on monopile foundation designed for Southern Baltic Sea conditions ranks between the Kemi I lighthouse which experienced significant damage due to ice-induced vibrations in 1973 (Määttänen, 1975) and the Molikpaq which experienced high synchronized loading on May 12th 1986 (Gagnon, 2012).

Design standards do not provide sufficient guidance to determine which type of interaction regime (intermittent crushing, frequency lock-in, continuous brittle crushing) is to develop under certain defined ice conditions. This leads to uneconomical support structures given the predicted levels of fatigue damage from direct application of the standards. Also, the combination of significant, and sometimes misaligned, ice- and wind loading has raised questions on how the interaction between wind and the structure may influence the ice-structure interaction. A question which is perhaps less relevant for different types of offshore structures where sea ice is often the main source of environmental loading.

Questions related to the development of ice-induced vibrations have been addressed the past five years in the SHIVER research project led by the author. A model-scale dataset for offshore wind turbines on monopile foundations has been generated (Hendrikse et al., 2022) and allows for validation of numerical models which aim to predict ice-induced vibrations of offshore wind turbines. A notable finding from the experiments is a multi-modal interaction regime which can be explained to occur due to the specific modal properties of an offshore wind turbine (Figure 5, Hammer et al., 2023). To ascertain confidence in the model-scale test results the campaign focused on also testing structures for which full-scale data is available. This resulted in a new scaling method that qualitatively captures ice-induced vibrations in model-scale (Hammer et al., 2024). The results of the campaigns give confidence in the qualitative value of the specific data gathered for offshore wind turbines as a relevant benchmark dataset. Of course, it has to be acknowledged, that we will only learn the true accuracy of our predictions when full-scale data becomes available in the future.

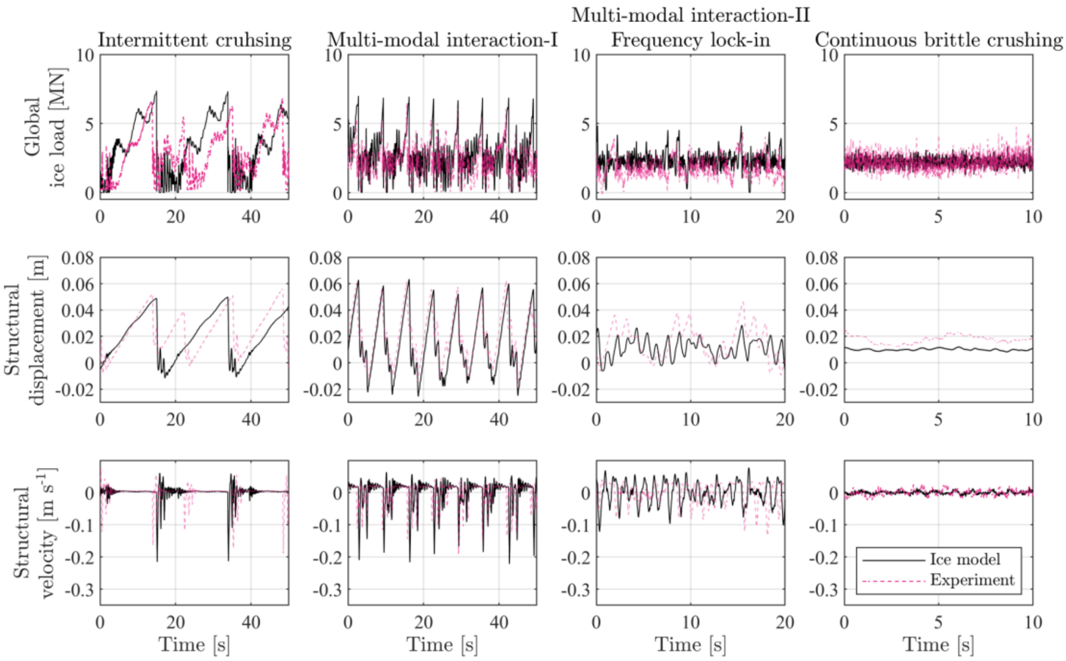

Figure 5. Example of different types of ice-induced vibrations encountered in model tests for offshore wind turbines and validation of the 'VANILLA' model capabilities to simulate those (Hendrikse and Nord, 2019). Figure courtesy of Tim Hammer.

There are some remaining questions, such as: what is the worst misalignment angle between the wind- and ice drift direction for the development of ice-induced vibrations? In terms of potential impact on design though, the interpretation of the ice strength coefficient C_R is the most urgent discussion point to address at this moment. The ice strength coefficient for high-speed crushing for the Kattegat and Baltic Proper regions, with relatively similar winter conditions, typically varied between 0.66 MPa and 1.1 MPa in sea ice assessments for offshore wind projects the past decade (Figure 7). The need to account for the velocity effect (ice loads being higher at low speed) resulted in final effective design values for the ice strength coefficient between 1.3 MPa and 2.2 MPa. These are estimates assuming either the PSSII model (Kärnä, 1992), VANILLA model (Hendrikse and Nord, 2019) or accounting for the 'compliance effect' based on Gravesen and Kärnä (2009) were applied in the projects. Also indicated in Figure 6 is the recommended ice strength coefficient of 1.8 MPa for the Bay of

Bothnia (ISO 19906, 2019). For a detailed explanation of velocity effect and the interpretation of C_R the reader is referred to Hendrikse and Owen (2023).

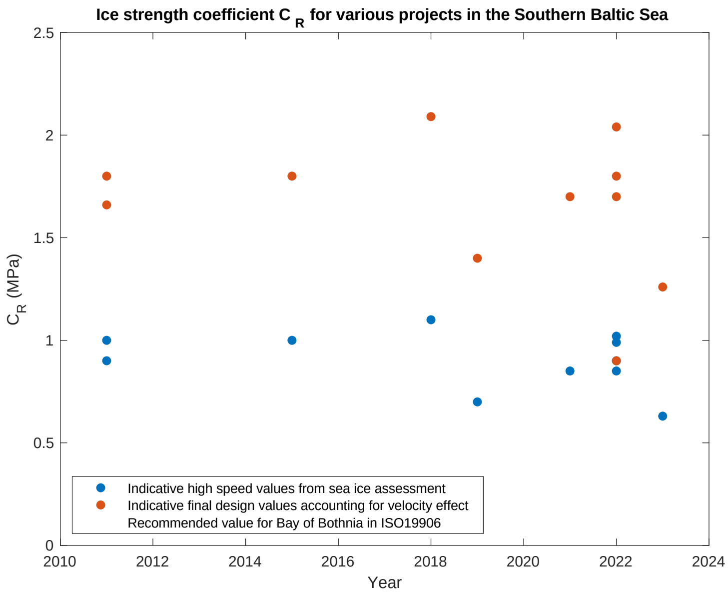

Figure 6. C_R values for offshore wind projects in the Southern Baltic Sea and Kattegat area over the last decade. Note that IEC61400-3-1 did not require the use of the iso crushing equation up to the edition of 2019. Also, the estimates given here may differ from what was used in the final design.

While there does not really seem to be a trend over the years, there are some interesting outliers which adopted an approach yielding significantly lower loads than others. Also interesting is that after accounting for the 'compliance' of the structure many turbine support structures were designed for an effective C_R that exceeds requirements for the Bay of Bothnia in ISO 19906. It is noteworthy that the difference between a C_R of 2.1 MPa for design, and one of 1.4 MPa for design, yields a reduction in the overturning moment for a typical 8.5 m monopile in 30 m water depth and 0.4 m ice thickness of 65 MNm (characteristic value). This is around 8 to 10% of the total moment due to wind and ice combined for DLC D3. Given that this load case can be defining the pile penetration depth, such difference is significant and a more aligned interpretation of C_R for the region may yield significant savings or add the right amount of conservatism in the designs.

Agreeing on a single value for design for specific regions of the Baltic Sea would close this topic of discussion, and in a way ISO19906 already provides 1.8 MPa as a recommendation for the Bay of Bothnia to start from. Accounting in detail for exposure and other effects is, in my opinion, mostly a distraction. We sometimes find ourselves arguing if the ice strength coefficient C_R shall be 0.66 MPa or 0.85 MPa for a certain location, only to later multiply it by a factor two inside a 'black-box' simulation model to account for velocity effects. When discussing global pressures with two significant digits of accuracy it is also important to not lose sight of the uncertainty associated with ice loads and their measurement in the field. Spending a day with the original Norströmsgrund lighthouse data makes one wonder if we should not just round C_R to the nearest integer to account for everything that was not measured. Nevertheless, to move forward on this topic, it is recommended to treat the data obtained from the Norströmsgrund lighthouse in a theoretical framework that can explain the velocity effect on ice loads and as such give the correct meaning to the high-speed load data often used to substantiate choices for C_R (Gravesen and Kärnä, 2009). A first attempt in doing so is presented as part of the special session at this conference.

4. Jackets, sheltering, shielding and jamming

Offshore substations considered for the Southern Baltic Sea are mostly of the jacket type, though monopile alternatives are also considered. These are not typical three- or four-legged jackets for which some experience with sheltering and jamming has been obtained in the past (Evers and Wessels, 1986; Timco, 1986; Kato, 1990; Spenser and Masterson, 2002; Politko and Kantardgi, 2017), but can contain ten members or more crossing the waterline (Figure 7, left). Asides from substations, jackets with- and without ice cones are also considered as support structures for wind turbines (Figure 7, center).

Full-scale experience with jacket structures in ice is available from the Bohai Sea oil developments. As already mentioned, one of the early jackets collapsed in the Spring of 1969 due to not accounting for sea ice in the design sufficiently (Liu, 1996). Later platforms were designed much more conservatively, with often uneconomical designs as a result. This seems a challenge substation jackets for the Southern Baltic Sea suffer from as well, in the sense that sea ice may affect economic feasibility significantly. A common solution adopted in the Bohai Sea has been to equip the structures with ice cones, though these do not necessarily mitigate the development of ice-induced vibrations (Yue and Li, 2003).

A somewhat urgent topic of study is to define guidelines in terms of sheltering and interference for more than four-legged platforms. Perhaps dedicated model testing to determine associated factors for structures with more than three- or four members crossing the waterline can be conducted. Asides from this the potential of jamming developing between the jacket members is very uncertain. Experience with jamming between closely spaced conductor arrangements can be taken as starting point for, for example, j-tubes and boat landings on a substation (Figure 7, right). What is often questioned though, is the necessity to assume ice to be jammed between jacket legs when loaded by incoming competent level ice and ridges as one of the design scenarios. Certainly, it is impossible to associate any particular annual probability of exceedance with this type of event. The inclusion of this scenario in design is nevertheless important, as it may result in the largest global loads on the support structure. As such, the topic of jamming is a relevant topic of study.

Figure 7. Left: An example concept of a substation jacket with nine members of different size penetrating the waterline (illustration courtesy of Kasiphon Kurojjanawong). Center: Jacket support structures in ice at the Nissum Bredning wind farm in Denmark. Right: Ice plug inside casing pipes in 2021 in the Bohai Sea (picture from Wang and Zhang, 2023, CC BY 4.0 DEED).

5. Appurtenances and sea ice

For appurtenances similar questions as for jackets remain in terms of sheltering, interference and jamming effects. It is noted that the design load cases in Table 1 may have to be amended for the design of appurtenances. There is very little guidance in standards on this topic, most likely as appurtenances are typically protected from direct sea ice action when possible. ISO 19906 (2019) recommends to consider vertical forces due to adfreeze on light members and further states that: “Bracing and appendages should not be exposed to ice actions unless designed specifically to resist them.”. With respect to cathodic protection systems the experience is also clearly included in the standard: “For a structure exposed to sea ice interactions, sacrificial anode systems should be designed and placed to prevent damage by ice and ensure functionality. The design of cathodic protection systems shall be based on established methods. The cathodic protection design shall take into account that it is generally not feasible to locate anodes in zones subject to ice action”. Calculation methods for those cases where external routing is preferred, or necessary, are lacking.

6. Wind farm effects on sea ice drift, growth, deformation and ice-structure interaction

One aspect that differentiates structures for offshore wind from other structures in ice is the fact that multiple structures are built in a relatively small area as part of a wind farm. Though the spacing between the structures is in the order of kilometers and as such makes the loading on the structures independent, the fact that there are multiple structures present should have an effect on ice drift and growth. This aspect has received little attention so far, with the first larger studies only now having started in Finland. A typical example of where this may be important is in the definition of the joint-probability of occurrence of certain ice- and wind conditions, relevant for the fatigue design load cases D4 and D7 (Table 1). Currently the assumption in projects is that the ice drift speed can be correlated to the wind speed at 10 m height by a specific factor, effectively assuming unobstructed ice drift. That assumption is incorrect in the presence of wind farm(s), which would promote lower ice drift speeds and more conditions of stationary ice due to the resistance the structures provide to ice motion. This is relevant for vertical structures, as the most severe interaction types and largest ice loads often develop at low drift speeds.

Asides from these considerations the wind farms may ‘lock the ice in place’ in severe winters, causing ridge building from drift ice around the edges (Figure 8). It is unclear to what extent this may protect the wind farm from high ice loads, or may even increase the ice loads on outer turbines compared to when these are assumed to be individual structures. The ridge building may also have further adverse effects for access to and shipping in the vicinity of the locations with wind farms. In general, it is unclear at the moment if inner wind farm structures can be designed for lower ice loads, being protected by the outer structures. Studies on this topic may provide opportunities in terms of strategic placement of substations inside wind farms and wind farm layout optimization.

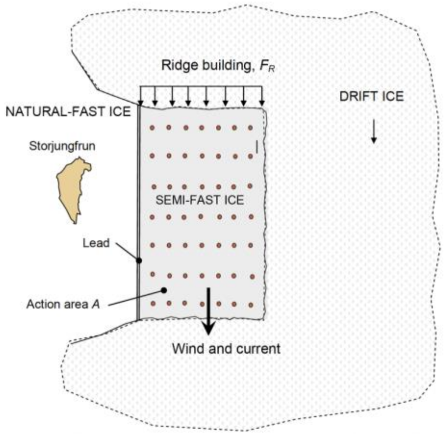

Figure 8. Example scenario where ice is 'stuck' inside a wind farm and ridge building is to be expected at the edges of the wind farm (figure after Kärnä 2011)

Conclusion

It is exciting when thinking of thousands of structures for offshore wind in the Baltic Sea exposed to ice providing data over the coming decades to an extent we have not seen before. It is my hope that this will lead to many special sessions on this topic to follow at future conferences such as IAHR and POAC. While looking forward with excitement it is also important to appreciate what was learned in the past, often the hard way, and to not forget that ice loads are still uncertain even though plots of full-scale data in public literature don't always indicate this as such.

In the short-term, relevant topics of study for the offshore wind developments are ridge load models, models for shielding and sheltering for multi-legged structures, and definition of all-inclusive C_R coefficients for design. With the wind farms in the Northern Baltic Sea now starting to gain attention it is important to investigate those scenarios which are not covered in detail in standards yet, such as for example the frozen-in condition, and to develop an understanding of wind farm effects on ice drift and growth, complementary to studies of loads on individual structures.

By posing some of the current relevant questions in this paper I hope some readers will become excited to start working on these difficult challenges, and some interested to participate in the discussions between industry and academia. It is also encouraged as part of the special session at IAHR 2024 to bring answers to the questions posed which are already in the public domain, but which I failed to find.

Acknowledgments

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