APPROACH CHANNELS

Risk- and simulation-based design

APPROACH CHANNELS
Risk- and simulation-based design

TOEGANGSKANALEN

Risico- en simulatie-gebaseerd ontwerp

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof.dr.ir. J.T. Fokkema,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op dinsdag 17 Juni 2008 om 15:00 uur

door

NGUYEN Minh Quy
Master of Engineering
Hanoi University of Civil Engineering
geboren te Hanoi Vietnam

Dit manuscript is goedgekeurd door de promotor:
Prof.drs.ir. J.K. Vrijling

Toegevoegd promotor:
Dr.ir. P.H.A.J.M. van Gelder

Samenstelling promotiecommissie:

Rector Magnificus	voorzitter
Prof.drs.ir. J.K. Vrijling	Technische Universiteit Delft, promotor
Dr.ir. P.H.A.J.M. van Gelder	Technische Universiteit Delft, toegevoegd promotor
Prof.ir H. Ligteringen	Technische Universiteit Delft
Prof.dr.ir. C. van Rhee	Technische Universiteit Delft
Prof.dr. Lucjan Gucma	Maritime University of Szczecin, Poland
Prof.dr. Zou Zaojian	Shanghai Jiao Tong University, China
Dr. Shinya Nakamura	Japan Marine Science Inc., Japan

Printed by PrintPartners Ipskamp BV, the Netherlands
Cover picture: a ship simulator room
Front cover: designed by Nguyen Van Tuan

ISBN: 978-90-9023201-0

To my family

Abstract

Although continuous efforts are being made to prevent the occurrence of ship collisions and grounding accidents numerous such accidents are being continuously reported every year, worldwide, and will certainly continue to occur. Most of these accidents are observed in the approach channel or entrance channel where the open sea is connected to a harbor or port. These areas constitute complex systems because they include environmentally dynamic actions, shallow waters, surrounding structures and high traffic density. All these aspects combined amount to various degrees of threat to navigational safety while relating strongly to the dimensions of the designed channel. With the increasing demands being placed on safety and economic growth for port operation and management, it is very interesting to be able to determine and predict the probability and outcome of accidents under the navigational conditions provided.

Recently, risk probability assessment techniques have been widely applied to safety level estimations of the ship navigation on shallow or restricted waterways. The objective of this thesis is to develop new interpretation methods and models for the overall risk assessment of navigation aspects in combination with waterway designs. These methods, which are based on the results achieved from ship maneuvering simulation and numerical models, address the two ship accident scenarios of grounding or collision with fixed objects in terms of the occurrence probability of such accidents. The final results of risk assessment can be straightforwardly used in the optimal design of waterway dimensions.

Several issues are addressed in this thesis. Regarding the risk assessment for channel width designs, real time simulations are used to establish the probability density functions of ship positions during passage along a simulated waterway together with the distributions of ship speeds and courses. Worldwide data on ship maneuvering results has been gathered for the purposes of this study. The probabilities of ship excursion (off track sailing) from the safe navigational zone in each section of waterway can be defined using the above-established density functions. These results are still however crude and insufficient for the long-term optimization of waterway projects because: (1) they are merely based on a limited number of real time simulations. The calculated risk does not therefore equal the overall risk, which is defined over the lifetime of the project and (2) the results only give separate estimates of the accident risk for particular sections of the waterway. However for the risk-based design of waterway width, the integrated risk of the entire waterway is needed.

For the first problem a new method is proposed requiring the development of two models: the first model uses ARMAX techniques to estimate the system outputs (course, position, etc.) from the inputs (rudder, engine, etc.) of the ship steering dynamics. The stochastic sequences of the inputs for the

first model used are generated according to a semi-Markov model. One implementation of the semi-Markov model for rudder actions has been studied. In essence, these models use a set of data observed in present time to predict future system behavior by generating a random sequence that contains patterns of data characteristics. The method allows the results obtained from real time simulations to be extended to predict future ship response conditions. On the basis of the predicted results and using the probabilistic approach, the possible margins of ship maneuvering areas can be identified and the long-term assessment of the navigational risk can be implemented involving straightforward use of the optimal design of the channel widths. Good results were obtained even where there were only limited ship handling results.

A spectral analysis technique is applied to deal with the second problem. Assuming that trajectories of the ship tracks or swept paths obtained from ship handling simulators are considered to be the response ensemble of either a stationary or a non-stationary random process, the study then concentrates on estimating the response spectral density and its characteristics using a probabilistic modeling technique. The extreme statistics of a ship exceeding the waterway limits are determined on the basis of this information. Numerical examples have been given and the proposed approach has been quantitatively evaluated.

Regarding the risk-based design of channel depths a new simulation model is developed for the lifetime of the channel project in which the risk of ship grounding due to wave impacts can be assessed for every ship transit. This new model includes four main components: (1) an exponential probability law for the number of ship departures; (2) a parametric model of the wave-induced ship motions; (3) the modeling effects of tidal variations on channel performance; and (4) a Poisson probability law for the grounding model in a single random ship departure. One key procedure in the simulation process is the defining of minimum underkeel clearance allowance for ship entrance while simultaneously determining the downtime that corresponds to an acceptable grounding risk for a specified ship and a generated environmental condition. The final results derived from the simulation model can be seen as the key parameters in the analysis and selection of an optimal depth. The model has been applied to the entrance channel of Cam Pha Coal Port, Vietnam as a case study.

The developed simulation model is characterized by the inclusion of a model of the wave-induced ship motions and its effect on the risk of ship grounding. The key element of the risk model, which is based on a probabilistic method, is a determination of the probability of touching the bottom during a transit. This therefore requires reliable modeling of the ship vertical motion response due to the wave effects. For this purpose an advanced model of the ship motion response has thus been successfully developed in this study.

Contents

List of Figures

List of Tables

List of Symbols

Roman Symbols

B	ship beam [m]
b	half channel width [m]
d	water depth [m]
f	density function
H	transfer function [m]
H_s	significant wave height [m]
kc	average underkeel clearance [m]
L	channel length [m]
L_P	overall ship length [m]
m_{ox}	zero moment of $\{x(t)\}$
m_{oz}	zero moment of $z(t)$
m_{2x}	second moment of $\{x(t)\}$
m_{2z}	second moment of $z(t)$
n	number of ship arrivals
n_s	number of simulation trials
P	probability distribution function
r	rudder angle [degree]
S_η	wave spectrum [m s^2]
S_{max}	maximum sinkage due to squat [m]
S_r	response spectrum of $z(t)$ [m s^2]
S_{xx}	response spectrum of $\{x(t)\}$ [m s^2]
T	ship draft [m]
T_h	ship passage time period [s]
T_z	mean zero-crossing wave period [s]
t	time [s]
V	forward ship speed [m/s or knots]
W	bottom width of one way channel [m]
$x(t)$	ship position in plane [m]
$\{x(t)\}$	an ensemble of $x(t)$
$z(t)$	wave-induced vertical ship motion [m]

Greek symbols

α	acceptable probability risk of ship accident
β	certain level of wave-induced ship motion
β_s	significant wave-induced ship motion
δ	wave angle relative to ship speed vector
ν	mean rate for a certain crossing level
ω	frequency
ω_e	encounter frequency
$\bar{\eta}$	extreme value of wave-induced ship motion
ϵ	specified normalized random mean square error
ε	error function

Chapter 1

Introduction

1.1 Why this study

Waterborne transport has proven its value in worldwide economic development and it is a fundamental tool in the creation of global trading activities. In the aim to reduce transportation costs and, over the years, to quickly meet the growing demand for overseas transport, the ability of the worldwide shipping industry to construct larger ships seems to be never-ending. Accommodating these larger ships to existing ports is an emerging problem. At the same time, marine infrastructure has not always been improved to keep abreast with such development due to natural conditions and financial restrictions. This has created more potential risks in waterborne traffic. Safer and more efficient shipping operations and the protection of the environment have therefore been of great interest in waterborne transport research. Finding more efficient and accurate waterway design tools will always be a priority solution. This, in turn, has encouraged new and improved techniques to offset the traditional approach to waterway design, an approach that can result in the establishment of waterways of questionable safety and excessive cost, or both because of uncertainty, conservatism, and reliance on rules of thumb (Webster, 1992). Trade-off between costs and benefits should always be done.

The aim of this study is to develop new interpretation methods and overall risk assessment models for navigation aspects in association with waterway design. The methods, which are based on the results achieved from ship maneuvering simulation and numerical models, address two ship accident scenarios (i.e. grounding or collision with fixed objects) in terms of the occurrence probability of such accidents. The final results derived from risk assessment are straightforwardly used in the optimal design of waterway dimensions. Several important procedures pertaining to the application of design tools and techniques for such purposes have also been discussed.

Collision and grounding accidents continue to occur in spite of continued efforts to prevent them (Wang et al., 2002). The accident of Exxon Valdez oil tanker in 1989 caused one of the worst environmental disasters ever. The Exxon Valdez ran aground, spilling 250,000 barrels, an amount equal to more than 10 million gallons, of oil into Alaska's Prince William Sound. Another unforgettable disaster was the grounding of the crude oil tanker known as the Sea Empress in February of 1996. The accident resulted in the discharge of approximately 72,000 tonnes of oil into the seas around the coast of South-West Wales. Figure 1.1 shows a picture of the most recent grounding accident of a bulk carrier of 40485 GT and overall length of 225 m. The carrier, named "CORONIS", grounded in the southern part

Figure 1.1: CORONIS on ground (pictured by DMA on 26 February 2007)

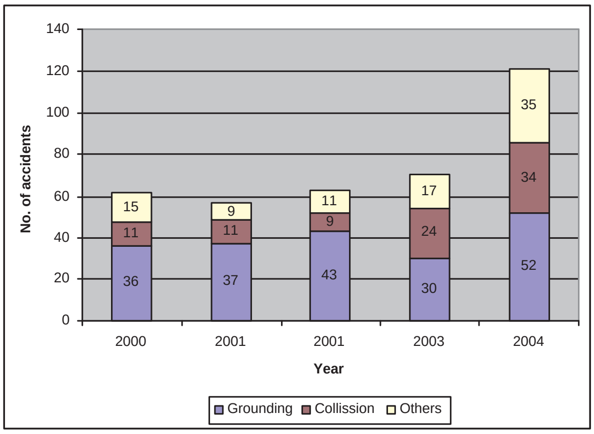

Figure 1.2: The number of ship accidents in the Baltic Sea during the 2000-2004 period

of the Sound, at the northern entrance to the Drogden Channel, on 26 February 2007. One of the main reasons for this accident which was later investigated by the Danish Maritime Authority (DMA, 2007) was CORONIS pilotage error. The speed of CORONIS was maintained at about 13 knots until it grounded while the pilot should never have exceeded a speed of 10 knots in the Drogden Channel. This investigation has provided valuable data for this PhD research.

The ship accidents observed in the Baltic Sea in recent years have increased public awareness of these risks. According to the report implemented by the Baltic Coastal States (HELCOM, 2006) there were 374 ship accidents in the Baltic Sea in 2000 - 2004 (see Figure 1.2). The total number of accidents has been slowly increasing since 2001 and increased significantly in 2004.

Grounding and collision have been investigated as the major types of ship accidents and accounted for over 50% of all types (HELCOM, 2006; Fowler & Sorgard, 2000). The causes that led to the accidents were mainly related to human factors. Depending on the different authors and reports, the human error has been reported accounting for 40 to 90 per cent of all accidents (Baker & McCafferty, 2005; Gucma, 2005; ECO, 2005; and Liu et al., 2005). In this PhD study attention has therefore been placed on the introduction of human behavior into the risk assessment. Figure 1.3 shows the types of accidents and the percentage of accidents in the Baltic Sea according to HELCOM (2006) investigations. The causes of the accidents were investigated in this report as pointed out in Figure 1.4, in which human factors accounted for 39% of all accidents during 2004.

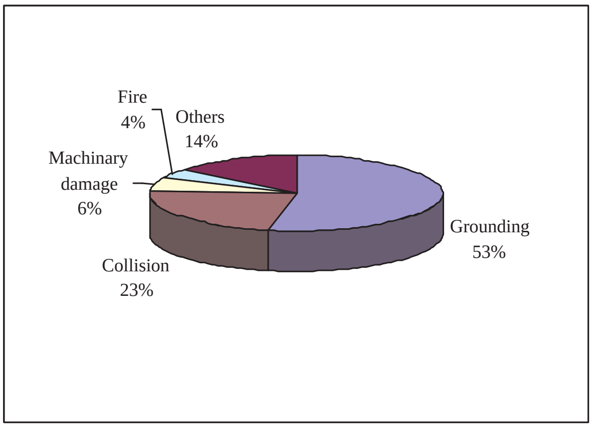

Figure 1.3: The types of the accidents in the Baltic Sea during the 2000-2004 period

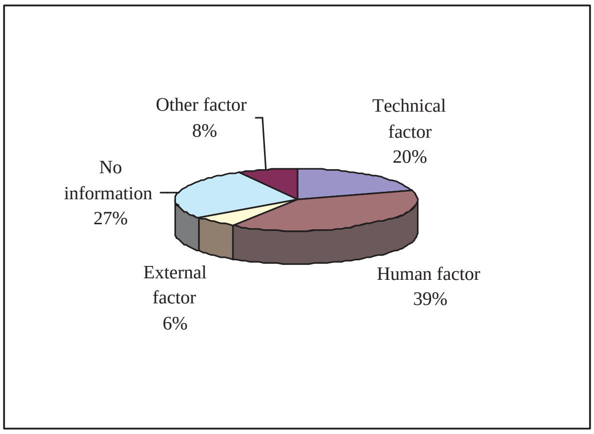

Figure 1.4: The causes of the accidents in the Baltic Sea during 2004

Hence, with the increasing demand for waterway transport safety and for the protection of the environment, it is vital to be able to predict and determine an accident, assess its consequences and ultimately minimize the damage caused by accidents to ships and the environment. This research field is broad and concerns itself with the complex nature of the events leading up to any ship accident.

1.2 Background to the risk- and simulation-based design approach

Approach channels, which connect open sea to the water basins of a port or connect channels, are seen as the weakest link in waterborne chains. This part is a complex system because it includes environmentally dynamic actions, shallow water, surrounding structures and high traffic density. All of these factors combined threaten navigation safety to various degrees and relate strongly to the dimensions of the channel in question. All of the above considerations rationally lead to requirements for economic- and risk-based design processes which subsequently allow the determination of the horizontal and vertical dimensions of the approach channel to be optimized.

Risk-based design is a formalized design methodology that systematically integrates risk analysis into the design process by embedding prevention/reduction of risk (to life, property and the environment) in the design objective, alongside all the standard primary design objectives (such as speed, cargo capacity, and turnaround times).

The risk-based design of approach channels encompasses a number of disciplines including ship handling and maritime engineering and links these factors to probabilistic analysis tools in order to raise waterway design to a desired level of navigability and safety. This requires the assessment of a number of key elements in this system, including ship size and behavior, the human factor in ship handling and the effects of the physical environment (PIANC, 1997).

Risk- and simulation-based models with the aid of a probabilistic analysis method are a powerful tool and most frequently used for the design as well as the operation of navigation in approach channels. This approach usually consists of a two-step process: first, the application of modeling methods for generating data of ship maneuvering characteristics; and secondly, the assessment of navigation risk based on this data. The sections below have outlined the state of the practice applying this approach.

1.2.1 Overview of the use of modeling methods in waterway designs

Modeling methods in which a computer-based simulation is the core model are considered by many design engineers to be a potentially important and effective tools for waterway design. There is growing interest in using modeling methods to increase confidence in waterway designs and reduce the costs of construction and maintenance (Webster, 1992).

There are a number of modeling methods for waterway designs. Some of the selected models have been discussed hereunder.

The distinction between the methods is presented in Figure 1.5. The application of each method is dependent on the given purpose and project costs. The main distinction is between physical models and mathematical models. The major application of the physical models is to determine various coefficients used in the mathematical models. The physical models are not often used in isolation but can sometimes be combined with hydraulic models in harbor design thus making it possible to study the environmental and ship system in three dimensions. One successful application of such approach is in assessing the probability of a ship accident in the entrance channel of Barbers Point Harbor, Oahu (Briggs et al., 2003).

The mathematical models can be classified into the four main groups, including computer simulation, analytical model, empirical model and numerical model. Nowadays the mathematical models are quite commonly used in ship maneuvering simulation techniques in which a computer-based simulation is the core element. The computer-based simulation in waterway designs is developed from macro-level to micro-level. In the macro-level model overall traffic behavior is studied. Depending on the research purpose, this type of simulation can either be a traffic capacity model to assess channel capacity or can

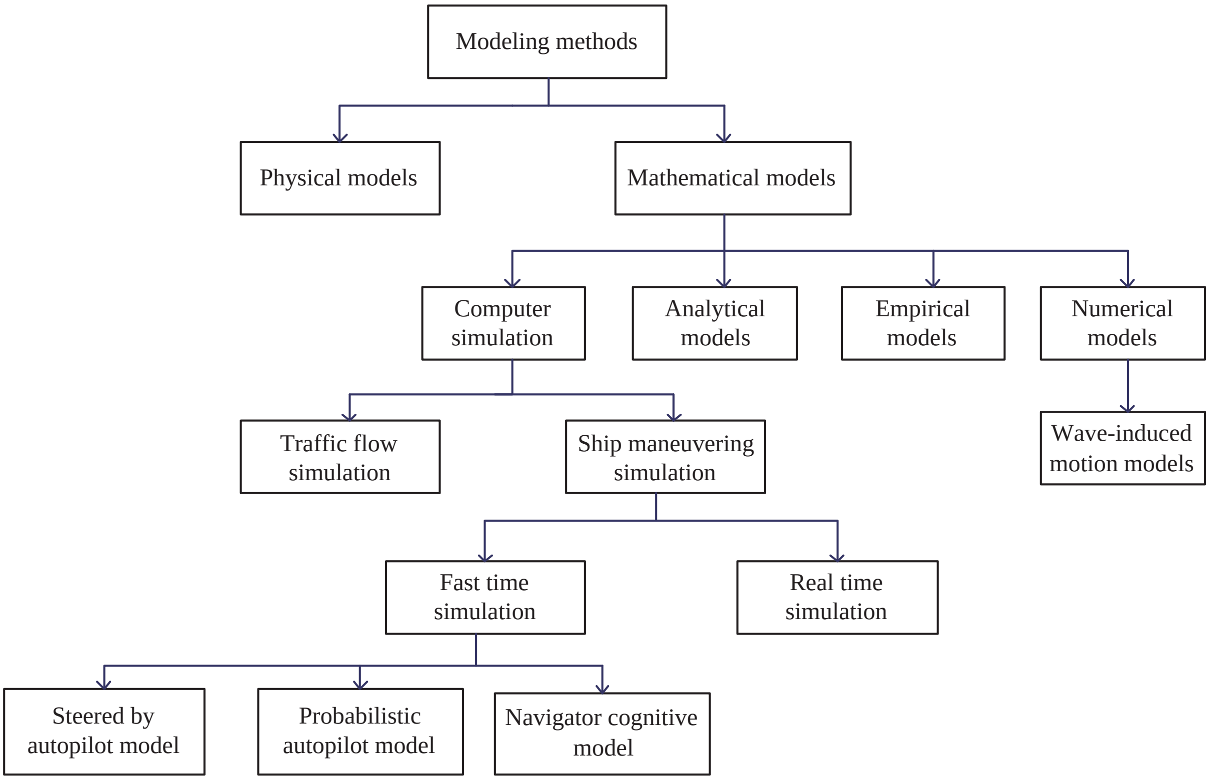

Figure 1.5: Various modeling methods used in waterway design

be the overall estimation of the risk of an accident in a complex system of transport routes. Normally, human aspects are not taken into account in these models. In the micro-level system, by contrast, the maneuvering behavior of individual ships for given simulated waterway in conjunction with human action is considered (PIANC, 1997). In this thesis, the micro-level model approach is particularly focused. However, the state of the practice of the macro-level model has been briefly reviewed and presented in Chapter 2.

The simulation methods in the micro-level system can roughly be divided into two groups known as non-interactive simulation and interactive simulation. (i) Non-interactive simulation, which is often named "fast time simulation", is a technology used for generating the track of a ship in a waterway by means of a pilot model. The pilot model, the so-called "autopilot", is a computer-based model designed to conduct a ship through a given route using a set of programmed commands to react properly within a fixed time interval. Although autopilot models are a valuable tool in judging certain maneuvers during the feasibility design stage, it is never similar to a real pilot. To make fast time simulation results more realistic, some probabilistic variables were applied to pilot model design (Lan, 2003) or were introduced to environmental conditions (Vrijling, 1995; Huchison, 2003), leading to a so-called "probabilistic fast time model". Another type of much more complicated pilot model is a navigator model. This model may include a complete mathematical description of the human behavior of the pilot or helmsman. However, it is still under development and can only be applicable to a simple navigation task (Itoh et al., 2001).

(ii) Interactive simulation is commonly known as "real time simulation". In this case operation of a ship simulator is taken by a real pilot. The most important elements of this model are human control, which is considered to be the central element, mathematical modeling of ship dynamics under the influence of external conditions and the visualization facilities of the environment. The visual models can produce the changing scene in enough detail to allow the pilot to determine his location and the rate of motion. The simulator is equipped with all necessary instruments and control systems as are available onboard of a real ship so that the pilot can feel similar to the way he does in real life. The real time simulation method is assumed to be the most accurate way of providing data for waterway design as well as navigation risk assessment. This model has been emphasized in this study and has been described in more detail in Chapter 2.

The movement of a ship can be described in six degrees of freedom. Because the vertical motions interact little with the steering and maneuvering characteristics of the ship, these motions (pitch, heave and roll) are often not considered in most simulation models. To determine the vertical motions for the design of channel depths, the three degrees of freedom in the vertical plane must therefore be considered. Because of the dependence of wave actions only (other factors, including pilot control effort, have little effect so they can be ignored) the vertical motions can be numerically calculated from wave parameters and ship specifications (sizes and speed). A range of theories are available for this problem. In this study, a numerical model of the wave-induced vertical motions developed by Journee (2001) has been used.

1.2.2 Risk determination methods

The purpose of the above mentioned models in waterway designs is to generate the data of ship trajectories when subjected to the action of environmental conditions. The analysis of the swept paths and vertical motion profiles of the ships that form the shape of a waterway is an essential design step.

The way of analyzing such data is developed from deterministic approach to probabilistic approach. The deterministic approach is mostly applied to autopilot models and is often only used in the concept design stage because of the lack of insight into the likelihood of risk. The starting point for the probabilistic approach needs to be the detailed design process. The framework of the detailed design process reported in many documents involves applying the techniques of risk assessment and cost-benefit analysis to the decision-making process. There are several steps in the detailed design process, as explained in Chapter 2, but the determination of risk is the core element. This subject is discussed throughout and remains the central issue in this particular thesis.

One of the most important aspects of the risk determination is the probability of ship accidents. Assessing factors contributed to the risk and measuring consequences of the accident are the other aspects. In ports and approach channels the consequence of an accident may not be casualties but it may be serious damage to the environment and/or loss of revenue for the port. On the basis of the results of ship maneuvering characteristics and the database obtained from real accidents, a variety of techniques and models for determining risk have been developed, some of which include fault tree and event tree models, analytical models, and probabilistic models. The use of these models depends on many factors, including the research objective, the required accuracy and the project budget. An overview of these models is given in the following chapter.

The results of risk determination will indicate the relative passage risks and will provide insight into the various navigation factors (principally turning characteristics, channel width, and depth). These factors are selected in an attempt to optimize the balance between the risks and costs inherent in the design (Webster, 1992).

1.3 Problem definition

Although meaningful data for channel designs can be obtained by modern tools as described, it still needs a further treatment for the use in the optimal design as well as in the risk assessment process. One of the most important aspects is the information on the accident probability during the lifetime of the channel project. The existing methods for such purposes are not yet comprehensive so the application of the risk assessment process to optimizing channel dimensions is less practical. To assist the designer, various groups and researchers have developed guidelines for design dimensions (PIANC, 1997; USACE, 2006). Although these guidelines are often helpful for visualizing a new waterway in initial studies, they are too general to guarantee optimum design for a given condition. There were available examples of workable waterways in reality that did not meet the guidelines by wide margins (Webster, 1992).

The current practical application of modeling methods to waterway design is to focus on ships and extreme conditions that may strain safety in specified waterway zones. Other safer places and navigation conditions are omitted. Such practice can lead to underestimating the risk level and to missing information about the process of a ship passage through the waterway (Gucma, 2000). As a result, the current practice is limited to the subjective judgment that waterway design is not satisfactorily based on limited simulation results. Finding ways to extend real time simulation experimental results and to apply these to lifetime channel risk analysis is still something that challenges researchers.

In other contexts, risk estimates should be made for channel projects by summing up the products of the probabilities of each possible accident in the project lifetime and the cost of the consequences of a particular accident. These estimates also indicate the safety level of the channel during its lifetime. Performing such computation from the results of ship handling simulation remains problematic (PIANC, 1997).

The overall risk of the long-term channel project is strongly depending on the short-term ship “entrance policy” for each particular passage. Many studies have been done on the establishment of this policy, but there is a significant gap in terms of current practice.

There are certain limits beyond which operations become unsafe and it is important that the designer is able to estimate these limits at the design stage (PIANC, 1997). In addition, the designer may need to make allowances for any existing operational limits. If the operational limits are particularly restrictive, they could have a significant commercial impact on port operations, and it may be decided to modify the design to allow greater freedom. The determination of such limits is still being researched.

1.4 Objectives and research questions

It is beyond the scope of this study to examine all the above-mentioned problems in detail. The focus of this research is related to the method of a simulation-based probabilistic risk assessment to quantitatively estimate the probability of a ship accident in conjunction with approach channel design. However, the method is restricted to the two failure mechanisms, collision and grounding. The specific objectives of this thesis are:

1. To generalize the results achieved from simulation and apply them to long-term navigation risk predictions;
2. To identify ship manoeuvrability when determining overall risk and navigation limits;
3. To integrate the navigation risks in relation to entire channels; and
4. To model ship motion responses used in the long-term optimization of channel depths.

The above objectives are closely related to the following research questions:

1. How can a ship entrance policy be established that will allow ships to leave and enter ports within a certain level of navigation safety?
2. Is the channel width and depth large enough for ships to maneuver adequately in the channel provided that the accident risk of its passage is acceptable?

1.5 Structure of the thesis

The research outline is visualized in Figure 1.6. It consists of three parts. The first part gives an overview of the waterway design approaches and tools; the second part is concerned with channel width design; while the third part deals with some aspects of channel depth designs and operations.

Part one - Chapter 2 - Design approaches and tools

This part gives an overview of the approach to channel design methodology. The problems underlying the application of the well-known existing guidelines used in the initial design stage are revealed. The procedures of the detailed design process applying risk- and simulator-based methods are given. A short literature review of the risk assessment models and the new achievements in the development of the techniques used in simulators are also presented in this chapter.

Part two - The channel width design

Part two consists of Chapters 3 and 4. In this part, the three first research objectives are addressed. In Chapter 3, based on (Quy et al., 2007a; Quy et al., 2007b; Quy et al., 2008), it is started with a brief description and the application of real time simulation results to waterway designs. The real time simulation method, which is assumed to be the most advanced and accurate method, is not sufficient in several aspects of risk analysis, especially as regards long-term period study and the optimal design of the channel project. To deal with this problem, two models are developed: the first model uses the

ARMAX technique to estimate the system outputs (course, position, etc.) from the inputs (rudder, engine, etc.) of the ship steering dynamics. The stochastic sequences of the inputs for the first model used are generated using a semi-Markov model. One implementation of the semi-Markov model for rudder actions has been described. The study used input/output measurements from a ship-handling simulator to estimate the model parameters. The human factor has therefore been included in the models. The method allows the results obtained from the simulator to be extended to predict the future conditions of system outputs. On the basis of the predicted results and using probabilistic approach, possible margins of ship maneuvering area can be identified and the long-term assessment of the navigational risk can be implemented. Another important topic included in this chapter is the identification and estimation of ship navigation limits, which involves the straightforward use of the optimal design of channel widths.

In Chapter 4, based on (Quy et al., 2006b; Quy et al., 2006a), a new method of the integrated risk assessment for the entire waterway regarding a ship exceeding the waterway limits is presented. Conventionally, the risk is considered for critical points of the waterway only. Such a practice can result in a waterway of questionable safety because of the missing information on the process of ship passage through the waterway (Gucma, 2006). The total risk of the entire waterway is not known. It is assumed that the trajectories of ship tracks or swept paths can be considered as the response ensemble of either stationary or non-stationary random processes. The study then concentrates on estimating the response characteristics by analyzing their power spectrum density. Finally, the extreme statistics of a ship exceeding the channel limits for the entire channel are determined on the basis of all this information. In that way, it subsequently becomes possible to study channel width and channel depth in an integrated manner. An accurate probabilistic model of ship grounding risk for the entire channel has therefore been established. Numerical examples have been given and the proposed approach has been quantitatively evaluated.

Part three - The channel depth design

Part three embraces Chapters 5 and 6 for addressing the fourth objective and involves both the research questions that are concerned with channel depth design. In Chapter 5, based on (Quy et al., 2006; Quy et al., 2007d; Quy et al., 2007c), the parametric modeling method of ship motion responses for risk-based optimization and operation of channel depths is presented. The study focuses on computing response motion spectra as a function of the sea states (described by significant wave height H_s and wave period T_z) and transit conditions (ship speed V and ship draft T) using a parametric modeling technique in combination with a numerical ship motion model; and then using these spectra applying a probabilistic model to determine the ship grounding risk. This makes it possible to establish an entrance policy in which the guidance information for safe transit will be provided. On the basis of the developed entrance policy a long-term optimization of channel depths can therefore be implemented. Chapter 6, based on (Quy et al., 2007e; Quy et al., 2008), presents an application of the aforementioned approach for a real case study in Vietnam.

Finally, Chapter 7 provides the research conclusions and discusses some open issues to potential future research.

1.6 Basic definitions

There are different definitions in the relevant literature for some of the phrases and words related to this research field. To prevent confusion, some of the more important terminology are explained as they are applied in this thesis.

Approach channel and waterway

An approach channel or channel is defined as any part of a waterway linking the berth of a port to the open sea or connecting channels. In this thesis, "approach channel" or "channel" and "waterway" are alternatively used in the same context.

Powered grounding

An event type that occurs when a ship collides with the shoreline or hits the bottom while underway due to navigational error or lack of pilot vigilance. For simplification we use "grounding" instead of "powered grounding". Other types of grounding are not considered in this study.

Hard collision

An event that occurs when a ship collides with a fixed object. Collision between two ships underway is not considered in this thesis.

Probabilistic admittance policy or accessibility (entrance) policy

Probabilistic admittance policy is a set of conditions, including navigational condition (ship speed and draft), water level and environmental conditions. On the basis of this policy a ship is allowed to enter the channel with an acceptable probability level of an accident.

Overall risk

An overall risk is defined as the probability that a particular accident may occur combined with some measure of its consequence. The overall risk is determined for the lifetime of the channel project.

Entire risk

An entire risk is defined as the probability of ship exceeding the channel borders or touching the bottom combined with some measure of its consequence. The entire risk is determined for the channel as a whole by integrating the risk along the channel.

Total risk

A total risk is equal to the entire risk when the risk is defined for the lifetime of the project.

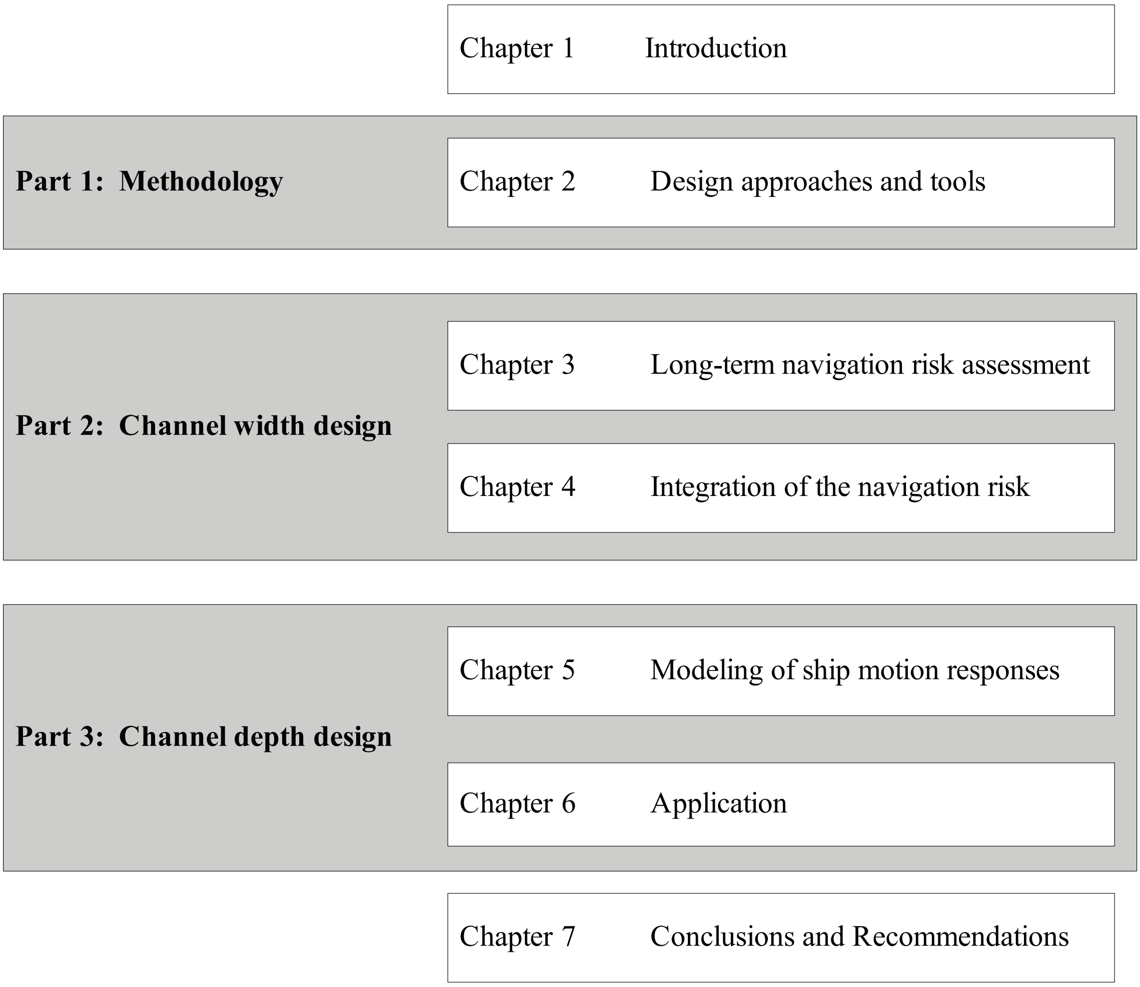

Figure 1.6: Thesis outline

Chapter 2

Design approaches and tools

2.1 Introduction

The design of an approach channel requires the assessment of a number of key elements, including vessel size and behavior, human factors in ship handling and the effects of the physical environment in order to determine the waterway dimensions and allowances with acceptable environmental conditions to a desired level of navigability and safety. To assist the channel designer and planner in the initial design stage, various groups and authors have developed guidelines defining of these allowances as well as design of channel dimensions.

This chapter, mainly based on the PIANC guideline (PIANC, 1997) and Vietnamese practice, describes the state of practical design of the waterway to establish the context in which computer-based simulations are applied. The discussion provides a basis for understanding the advantages and limitations of simulation methods and the potential for advances in the underlying technology. The latest achievements in the development of risk-based models used in the design process are given. Section 2.2 provides brief information about well known guidelines that have been frequently used in practice. In Section 2.3, problems of application of these guidelines by exploring two study cases are presented. Section 2.4 outlines the detailed design process in which methods of risk assessment are reviewed. Brief description together with some of the applications of the simulator-based method used for waterway design is given in Section 2.5. Finally, Section 2.6 draws some conclusions for this chapter.

2.2 Existing guidelines for approach channel designs

As reported in many guidelines, the design process for the approach channel can be divided into two stages: the conceptual and the detailed design stages. These guidelines outline an initial design method for the channel based on a design ship while determining the initial estimates of the overall physical parameters of the proposed channel as a multiple of the ship dimensions. This design stage aims at forming the channel shape which is represented by the following three issues: alignment, channel depth, and width. In essence the required dimensions of the channel are obtained by adding up the separately quantified conditions of all the relevant factors derived from the experience of helmsmen and pilots,

Table 2.1: Main factors of conceptual design

Design factors	Channel width	Channel depth	Remarks
Vessel speed	x	x	
Wind	x		little effect for depth, can be neglected
Water currents	x		little effect for depth, can be neglected
Waves	x	x	
Aids to navigation	x		
Bottom surface material	x	x	
Depth of water	x	x	
Cargo hazard level	x	x	
Bank clearance	x		
Others		x	siltation, water density, air pressure

experiment tests or historical accident records. The main factors which contribute to dimensioning of channel shape are presented in Table 2.1.

This section outlines two different approaches that are very often used in practice. One that is well known is the PIANC guideline, the other is the current technical practice applied in Vietnam both for the conceptual and detailed design stages. However, a short overview of the other research and recommendations is also presented.

2.2.1 Channel widths

The PIANC guideline method

The Permanent International Association of Navigation Congresses (PIANC) has its headquarters in Brussels, Belgium. It is an organization that is concerned with the technical aspects of navigation and port infrastructure, and with the associated safety, economic and environmental matters. PIANC was founded in 1885 and is sponsored by 40 national governments, including the United States.

In line with the PIANC method, channel width is defined as the sum of a basic width and a number of additions, the total width depends on many factors as mentioned in Table 2.1. For a one-way channel the bottom width, W, is defined as:

$$W = W_{BM} + \sum_{i=1}^{n} W_i + W_{Br} + W_{Bg} \tag{2.1}$$

where W_{BM} is the basic maneuvering lane, which the design ship requires to sail in a very favorable environment and operational conditions; W_i is the additional width allowing for the effect of vessel speed, cross winds, currents, waves, aids to navigation, bottom surface, the channel depth and the hazard level of cargo. W_{Br} and W_{Bg} are the bank clearances on the ‘red’ and ‘green’ sides of the channel, in other words, on the port and starboard sides of the ship.

The parameters W_{BM}, W_i, W_{Br} and W_{Bg} can be empirically estimated as a function of the beam of the design ship for specified conditions. In the case of a straight channel PIANC provides recommendations for the determination of these parameters, which are tabulated in the tables given in Appendix A.

Vietnamese practice

Table 2.2: The drift angle by current α_1 (degree)

Ratio of current velocity	α_1 when the incident angle is						
to ship speed	10	30	60	90	120	150	170
0.50	10	23	30	27	19	10	3
0.40	6	17	23	22	16	8	3
0.30	4	12	17	17	13	7	2
0.20	2	7	11	11	9	5	2
0.10	1	3	6	6	5	3	1
0.07	1	2	4	4	3	2	1
0.05	0.5	2	3	3	2	1	0.5
0.03	0	1	2	2	2	1	0

The Vietnamese standard practice amounts to a guideline for waterway design. The practice was established mainly on the basis of the Russian standard known as $BCH-19-70/MMQ$ and $BCH-24-71/MMQ$. The practice has been applied since 1998 to both the conceptual and detailed design stages and endorsed by the Vietnamese Ministry of Transport.

Vietnamese practice dictates rather detailed calculations of the channel width when compared with the PIANC. The navigational width of the channel is expressed as:

$$W = B_{hd} + 2C_1 + \Delta B \tag{2.2}$$

where B_{hd} is the width of the ship maneuvering lane; C_1 is the additional width for bank slope; ΔB is the additional width for maintenance dredging (due to sliding of the slope).

The B_{hd} for a certain design ship is calculated as:

$$B_{hd} = L_P \sin(\alpha_1 + \alpha_2) + B \cos(\alpha_1 + \alpha_2) + tV_{\max} \sin \alpha_o \tag{2.3}$$

where L_P and B are the overall length and beam of the design ship, respectively; t is the maximum allowable time that the ship goes away from a desired track; α_o is the drift angle; V_{max} is the maximum allowable ship speed and the value of the product ($tV_{\max} \sin \alpha_o$) is defined as a maximum drift distance which is often taken as 3.0 m; α_1 and α_2 are the drift angles affected by current and wind, respectively. The values of these angles can be determined in Table 2.2 and Table 2.3, depending on V_{max} in combination with current velocity and wind speed.

2.2.2 Channel depths

The channel depth is estimated by including ship draft allowances to provide safe underkeel clearance, as illustrated in Figure 2.1. The safe clearance is defined as the clearance needed between the bottom of a channel and the keel of a ship to prevent accidents due to grounding. It includes ship draft, squat, tide, wave-induced motion, over-dredging, advanced maintenance, bottom-type, water density

Table 2.3: The drift angle by wind α_2 (degree)

Ratio of wind speed to ship speed	α_2 when the incident angle is						
	10	30	60	90	120	150	170
10	10	19	24	26	10	7	3
9	9	17	22	24	9	6	2.5
8	8	15	20	21	7	5	2
7	6	12	17	18	6	4	1.5
6	5	10	14	16	5	3	1
5	4	8	12	13	4	2	0
4	3	6	9	10	2	1	0
3	1	4	6	7	1	0	0
2	0	2	3	4	0	0	0
1	0	0	0	0	0	0	0

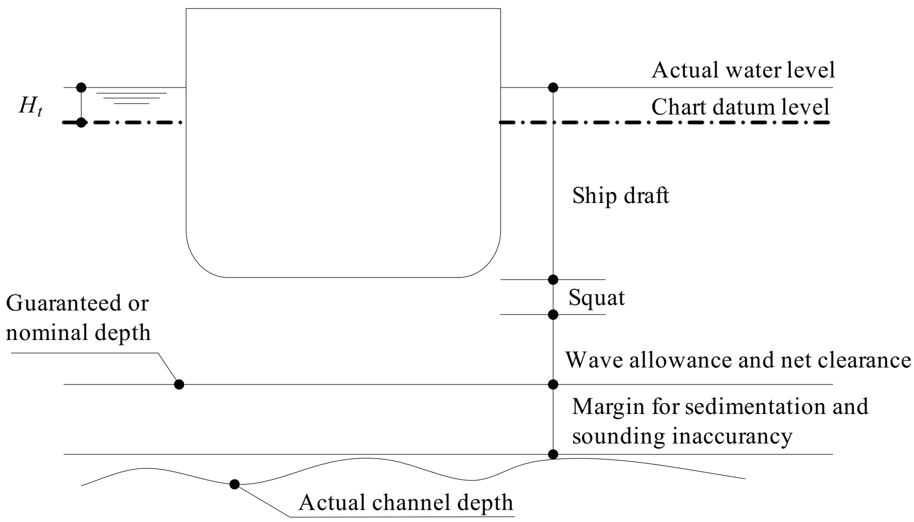

Figure 2.1: Channel depth allowances and components

and bottom location uncertainty.

The method of PIANC guideline

As recommended by PIANC (1997), a water depth can be estimated from draft of ship design, tidal height, squat, wave-induced motion, a margin depending on type of bottom and the effect of water density on ship draft, which can be expressed by the following equation (Literingen, 2000):

$$d = T - H_t + S_{\max} + \beta + m_s \tag{2.4}$$

where d is the water depth; H_t is the tidal elevation above reference level; T is the ship draft; $S_{\max}$ is the maximum squat; β is the wave-induced motion; and m_s is the remaining safety margin.

It is also recommended in the absence of the above mentioned information that all these factors may be lumped together into one depth/draft taken as 1.3 in waves up to one meter in height and 1.5 in the case of higher waves with unfavorable periods and directions. For sheltered channels, this ratio should be at least 1.1.

Vietnamese practice

The Vietnamese practice gives a detailed expression for determining a required water depth in the approach channel as follow:

$$d = T + \sum_{i=1}^{4} Z_i \tag{2.5}$$

where T is the maximum loaded draft of the design ship; $Z_i, i = 1 - 4$ are the allowances due to unbalanced loading of the ship, the allowance due to squat, the allowance for waves, and the reservation for possible sediment or siltation, including errors in dredging and measuring. For the specified sailing conditions of the design ship with a certain environmental condition the value of these parameters can be defined as given in the tables of Appendix A.

2.2.3 Other guidelines

Beside the PIANC guidelines there are some publications dealing with the determination of dimensions of the approach channel. Two of them should be mentioned, the design guideline of U.S. Army Corps of Engineers (USACE, 2006) and the Port Designer's Handbook written by Thoresen (2005). Generally speaking, the design procedures of these guidelines are similar to those given by PIANC. The recommendations on ways of calculating the channel dimensions are more or less detailed.

The following section presents calculation results for two real case studies based on the four above-mentioned guidelines. Comparisons are made to reveal the problems that arise when applying these guidelines to approach channel designs.

2.2.4 Real case examples

Initial study of the channel depths at Mombasa Port, Kenya

The first real case example is the study project of the approach channel depth of Mombasa Port in Kenya. The project was carried out by Royal Haskoning Consultants (Haskoning, 2004). The determination of the channel depth, based on a Panamax-type container vessel of 4,500 TEUs, was divided into two sections: the inner and outer channels. Table 2.4 summarizes the vessel specifications for the design.

PIANC, 1997

The significant wave height was reported up to 1.5 m in the entrance channel. For the design ship the combined RAO for heave, picth and roll was estimated at 1.2 (Haskoning, 2004). The squat was

Table 2.4: Vessel specifications

Items	Unit	Dimensions	Remarks
Length, Loa	m	294	
Beam	m	32.2	
Draft	m	13.5	
Capacity	TEUs	4,500	
Vessel speed	Knots	4-6	Inner channel
		8	Outer channel

calculated to be at 0.3 m for a speed of 8 knots. The remaining safety margin is calculated depending on the type of soil along the channel, 0.3 m for soft mud, 0.5 m for a sandy bottom and 1.0 m for hard soil or rock (Literingen, 2000) and it was taken as 0.5 m for this case. Adding the above gives an underkeel clearance of 3.1 m and required depth of 16.6 m.

The inner channel is protected from wave impact, the significant wave height can therefore approximate to zero. The squat was calculated at 0.1 m for a speed of 5 knots. And adding up all allowances gives recommended underkeel clearance of 0.6 m and required depth of 14.1 m.

USACE, 1998

The USACE calculates the underkeel clearance of a vessel by summing up the allowances for waves and squat. The net depth allowance for waves is normally 1.2 H_s (significant wave height) for deep draft vessels. For the outer channel this resulted in an allowance of 1.8 m. The allowances for the other factors, including dredging, sounding errors and tidal correction, provided a total clearance of 0.8 m (Haskoning, 2004). Adding up the estimates gives an underkeel clearance of 2.9 m and required depth of 16.4 m, implying that there is a depth draft ratio of 1.21 for the outer channel.

Without wave effect, the total required inner depth includes the allowances for dredging and sounding accuracy, leading to a value of 14.4 m; i.e. a depth to draft ratio of 1.07.

Thoresen, 2005

Thoresen mentions that “vessel motions can be as much as 2/3 of the significant wave height, larger vessels will scarcely respond to waves with periods less than 10 seconds”. He further gives the following recommendations for the design of channels:

- For exposed channels the clearance should be approximately 25% of the maximum draft;
- For protected channels and berthing area the clearance should be approximately 15% of the maximum draft.

The above information indicates that for the outer channel the depth draft ratio should be 1.25; and for the inner channel with the clearance is 15% of the maximum draft, the required depth would be 15.5 m.

Table 2.5: Recommended depths of the entrance channel from various sources

Methods	Outer channel		Inner channel	
	Required depth (m)	Depth-draft ratio	Required depth (m)	Depth-draft ratio
PIANC	16.60	1.22	14.10	1.05
USACE	16.40	1.21	14.40	1.07
Thoresen	16.88	1.25	15.50	1.15
Vietnam	18.23	1.35	15.50	1.15

Vietnamese Practice, 1998

Based on Vietnamese Practice the depth and draft ratios of 1.35 and 1.15 could be applied to the outer and inner channel, respectively. Table 2.5 summaries the above and presents the recommended channel depths.

The study of the channel widths at Barbers Point Harbor, USA

With regard to the channel width, Table 2.6 presents the results of the total width requirements according to different guidelines for a one-way straight channel of Barbers Point Harbor (Briggs et al., 2003). The results are based on the C9 container ship with an overall length (L_p) of 262 m, a beam (B) of 32.2 m, and a draft of 10.7 m. As can be seen from this table, PIANC gives detailed outlines of width allowances taking all design factors into account, with a required width of 4.2$\times B$. The others, by contrast, provide rather rough estimates. USACE recommends a value from 3.5 to 5.0 times of the ship beam for a one-way channel width subjected to three design factors including type of channel, cross current and navigation aid conditions. The result estimated by USACE at 4$\times B$ is quite close to the PIANC result. According to Thoreson the total channel width should be 3.1-4.5 times the ship beam depending on the sea and wind conditions. The result estimated at 3.75$\times B$ which is derived from Vietnamese practice seems to be reasonable in comparison with other findings.

Table 2.6: Recommended widths of the one-way channel from various sources

Description	PIANC	USACE	Thoresen	VN practice
Basic maneuvering lane	1.3 B		1.6-2.0 B	
Vessel speed: slow, 5 knots	0.0 B			
Cross wind: Beaufort 4 to 7	0.5 B			
Cross current: 0.65 knots	1.0 B	x	0.5 B	
Waves: 1-3 m height	0.5 B			
Aids to navigation: good	0.1 B	x		
Bottom surface: sloping and hard coral	0.1 B			
Channel depth/draft: d/T=1.25-1.5	0.1 B			
Cargo hazard: low	0.0 B			
Bank clearance: sloping sides	0.6 B	x	1.0-2.0 B	
Total	4.2 B	4.0 B	3.1-4.5 B	3.75 B

2.3 The problems of the application

Based on the previous results and comparisons we may reveal some remaining factors concerning the application of the existing guidelines, such as theses:

1. The drawback of these methods, which are based on a deterministic approach, is that the level of navigation safety is undefined.
2. For the same situation these guidelines provide differences in the dimensioning of the channel size, both in the definition of the channel depth and width. These differences are mainly due to the fact that the parameters and recommendations derived are based on "average" navigation situations and conditions for different ship types, so they are probably not approximate to a given condition of a given channel project and a specified ship.
3. In practice, it is common to use the results from one or more design guidelines for determining the shape of a navigational channel. This, however, is almost impossible to define which results should be more reasonably accepted.
4. Regarding the channel width, actual practice has indicated that widths of channel dimensions differ from those recommended by traditional guidelines, in which some channels are operated successfully for the larger ships than those recommended in the design stipulations (Webster, 1992).
5. Unfortunately, for a variety of reasons, the above guidelines have been generally accepted for the detailed design stage in Vietnam.

2.4 Methodology of detailed design process

Even with useful guidelines available for the designers of waterways, many important aspects fail to be considered, such as navigation safety, risk assessment and channel optimization. In this section, such aspects have been discussed and reviewed as an important part of the detailed design process. The design methodology, mainly based on PIANC, can be broadly divided into several procedures as shown generally in Figure 2.2.

Risk- and simulation-based optimization is an advanced approach that has very often been applied to waterway detailed design in recent years. It involves using the techniques of risk and cost-benefit assessment to assist in the decision making process.

There is a tendency for the designers and operators to give more flexibility to using a variety of methods to deal with their design. In risk-based optimization, one or more objectives are usually involved. Typical objectives might include safety and cost. In this approach, risk and cost are modeled in terms of failure likelihood, consequence, and operation rules. The most important elements, which involve the use of risk- and simulation-based models in relation to safety aspects, have thus been reviewed and discussed in the following sections.

The assessment of risk is the core element and it plays a significant role in the risk-based design process, among which the application of an appropriate risk model for the design is an essential step.

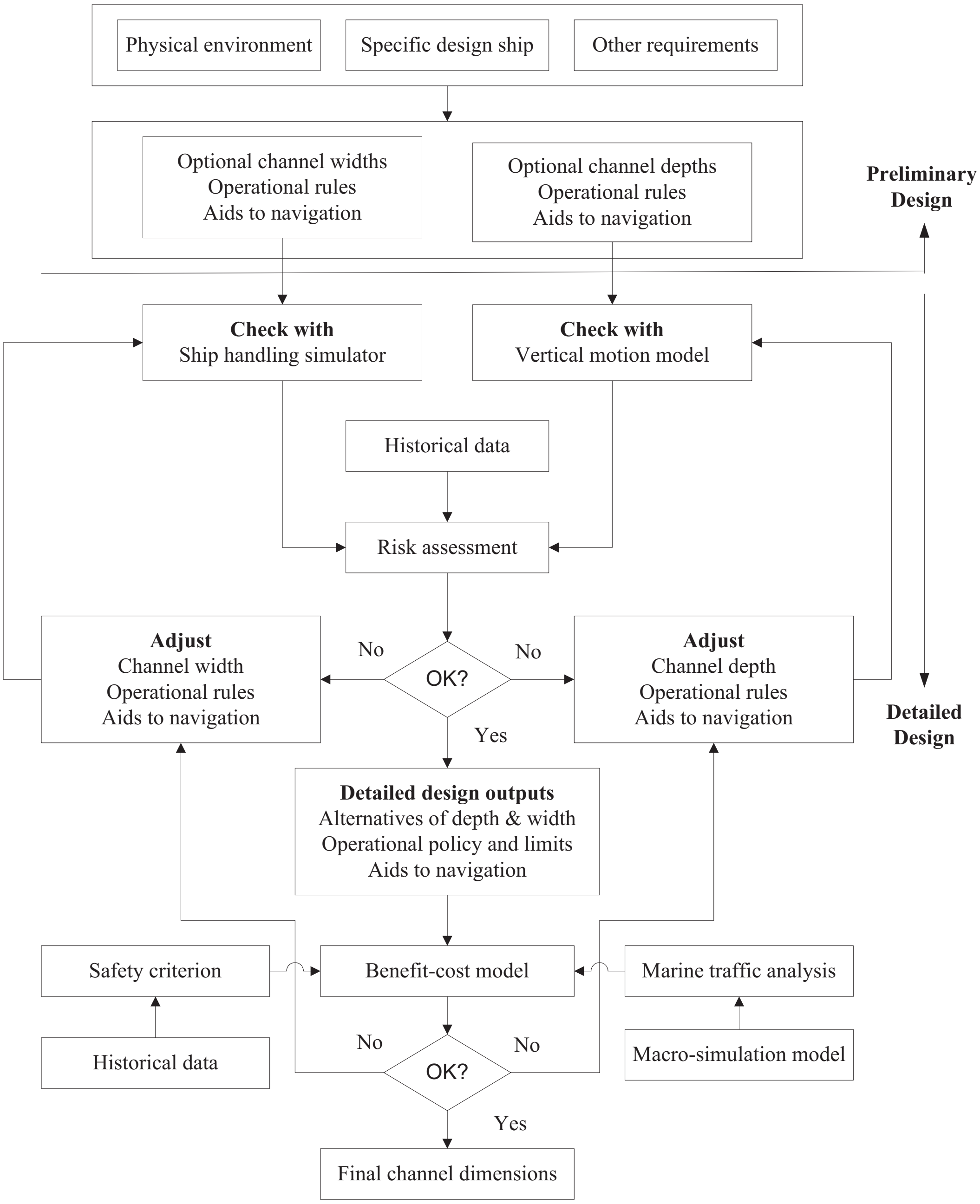

Figure 2.2: Overall procedures of the detailed design process (created by the author based on the PIANC)

2.4.1 Risk assessment models

The following sections review the state of the art of the risk models used in the risk-based optimization of approach channels. We aim at providing the latest achievements that have been made in modeling and estimating the risk of ship accident during navigation.

Over the years the risk model associated with the various mechanisms has been studied by many authors using different approaches. Within the scope of this thesis only brief reference will be made to the aspect of grounding risk assessment.

This step aims at estimating risk and assessing the factors that influence the level of safety during navigation for a particular channel dimension. The risk is determined from the probability of occurrence of a particular accident combined with a certain measure of its consequence. The occurrence probability can be determined on the basis of the following three approaches:

- from historical data;
- from risk models with expert judgments and calibration based on historical data; and
- from the results of simulation experiments and numerical models.

The approach based on historical data

The overall quantification of the probability of ship accidents existing in a certain waterway can be estimated on the basis of studies of accident statistics. The statistical results of the probability of accidents would provide an overall view of the levels of navigation safety provided by the waterway.

The probability of accident occurrence can be computed from past accidents. The statistical and probabilistic analysis techniques are commonly used to perform such computation. Furthermore, two important aspects can be distinguished in the analysis of historical records, namely the definition of accident scenarios, in the form of grounding and collision; and the potential and physical factors contributing to such accidents (Kite-Powell et al., 1999; Lin et al., 1998). As far as this thesis is concerned, some databases such as the Lloyds List Casualty Reports (Fowler & Sorgard, 2000) and maritime accident reports (ECO, 2005; HELCOM, 2006 and Meyer, 2005) constitute useful sources.

Although historical accident data provide useful information for determining the characteristics of local potential risk under specified navigation conditions, it cannot be solely used for dimensioning the shapes of waterways. Further processing is needed to make this information meaningful in relation to engineering design applications.

The risk modeling approach

Recently, the risk modeling approach has emerged as a very powerful tool for maritime risk assessment. There are a variety of risk models which apply different analysis techniques. Within the concept of maritime engineering design they can be divided into the following two major categories.

Risk models of hard collisions and grounding on banks in relation to navigational widths

The first hard collision model with a fixed object that relates to waterway lane width was presented by McDuff (1974). In this model the probability distribution of ship collision with a fixed structure was determined by multiplying two probability distributions which are represented by (i) random variables of the ship track on the collision course and (ii) navigator operation error. More advanced models similar to McDuff's concept have been developed and presented in recent studies (Fowler & Sorgard, 2000; Otto et al., 2002; Gucma, 2005) in which some other probability distributions such as the probability of given technical equipment failure and the probability of objects located on the ship route are furthermore considered. Usually the possible parameters of these probability distributions are considered and defined on the basis of engineering judgment and seafaring experience. Finally, the choice of these parameters for model use will be verified by comparison with the data of ship tracks achieved either from real time measurements or from computer simulations.

The other risk models with a different focus that are currently used in the Formal Safety Assessment process (FSA) are of great interest. The FSA was proposed by the International Maritime Organization as a structured and systematic methodology aiming at enhancing maritime safety by using risk and cost-benefit assessment tools (Sii et al., 2001). The FSA process has placed emphasis on the application of Probability Safety Assessment to shipping and on the offshore industry as reported in several publications by Wang and others (Wang, 2001; Sii et al., 2001; Wang, 2004; Wang, 2006; Rosqvist & Tuominen, 2004). However, it can be broadly applied to any maritime engineering problem.

Over the years, various studies in maritime risk modeling have taken place within the framework of the FSA. As far as waterway design is concerned, the following research achievements have been reported.

Kite-Powell et al. (1999) formulated a Bayesian model to estimate the probability of running aground during transit into and out of any port as a function of potential risk factors. Essentially, the Bayesian method is a technique involving the combining prior knowledge such as expert judgment, which is then described in terms of prior distribution to obtain posterior distribution. Such posterior distribution can then be used to estimate the overall accident probability using the probabilistic analysis method. This approach has the advantage of permitting a range of potentially contributing factors to be included. A more comprehensive Bayesian network model in combination with fault tree analysis has been developed for collision risk assessment of high speed craft on the open sea (Trucco et al., 2007). The model makes it possible to integrate the analysis of human factors into the FSA process. The research conducted by Amrozowicz et al. (1997) and Magnus et al. (2007) on the probabilistic analysis of tanker grounding is applied to oil spill risk assessment in marine traffic systems. The former has outlined three levels of risk assessment applying fault trees and event trees to quantify individual errors and to provide a more detailed view of how grounding has actually occurred. The latter proposed a dynamic risk model by utilizing "near" real time information on ship surroundings and the dynamic environment to predict the risk of drift grounding accidents during the ship passage.

A generic model can be introduced to the FSA process that considers ship behavior and the engineering system as the center of the model (Trucco et al., 2007). In essence, this model considers the frequency and severity of different accident types before going on to formulate a risk matrix (Wang, 2001). The risk matrix can be calculated by applying historical data about ship parameters and the navigation conditions that lead to such accidents. The application of this model to the assessment of pollution risk in relation to crude oil tankers was successfully implemented by Eide et al. (2006). The model utilizes information about the vessel's age, size and hull type to estimate the expected risk level with regard to several accident types. More advanced models following this approach have been presented in recent research (Sii et al., 2001; Gucma & Pietrzykowski, 2006; Hu et al., 2007). The model, based on fuzzy set functions, takes much more detailed information into account on accident characteristics than previous studies. The potential applicability of fuzzy set theory lies in assessing uncertainties and including them in the risk model.

Considerable effort has been made by European countries to make FSA process more practical for the improvement of maritime transport safety. The Commission of the European Communities developed a methodology for the risk-based analysis of the safety of shipping in coastal waters named SAFECO (Safety of Shipping in Coastal Waters). The SAFECO project has further developed a quantitative risk model known as MARCS (the Marine Accident Risk Calculation System) enabling the assessment of each set of risk control options within a single framework (Fowler & Sorgard, 2000). However, this project demonstrated rather the use of the risk assessment framework in maritime industry than an accurate modeling of the present risk level.

To conclude, the FSA is generally viewed as a promise of efficient assessment, management and control of risk. However, in order to be able to demonstrate the practical application of this process to the risk-based design of waterways, it should be said that there are certainly some challenges to be faced when it comes to the implementation of the method. The most difficult ones are:

- the modeling of characteristics of navigational conditions, including dynamically changing environments, the dimensions of waterways and ship behavior;
- the defining, among other things, of the effect of waterway parameters on the risks being estimated. The lack of statistical data due to limited experience makes it more difficult to perform a quantitative analysis; and
- the rules and policies of waterway operation, which are the key issues of waterway design, are not easily included in the risk models.

The risk models of grounding regarding navigational depths

With regard to the risk models created for the design of navigational depths, the determination of the probability of a ship touching the bottom is the key issue, this can possibly result in grounding accidents. Strating et al. (1982) demonstrated a probabilistic method for the optimization of navigational depths, taking into account the effects of tidal variations and waves in the assessment of the grounding risk. The environmental and transit conditions are divided into a number of limited regimes with their occurrence frequencies respectively. The probability of the ship grounding (i.e. touching the bottom) is determined using the Poisson model.

One of the most important aspects of the grounding risk model is to determine the allowable minimum underkeel clearance (UKC) under certain wave conditions. To do that, the stochastic modeling of major factors affecting the UKC such as water level, ship speed, and draft should be described. Using either the probabilistic approach or the Monte Carlo method (Gucma, 2005; Thoresen, 2005), a minimum UKC associated with the probability of a ship grounding under selected navigation conditions can then be found. A significant contribution was made to the development of a probabilistic admittance policy in the Flemish Harbors (Vantorre & Laforce, 2002) and Rotterdam Ports (Savenije, 1995), in which the relationship between UKC and wave conditions in the associated probability of ship grounding risk was given. However, the study was mainly based on physical models, so only very limited conditions could be investigated.

Andrew and John (1998) presented another risk-based methodology to determine optimum navigational depth. The study presented a predicting system for underkeel clearance and the corresponding risk of grounding, especially in the case of deep draft vessels transiting shallow entrance channels. However, this model is used more for the admittance of a particular ship in transit than for waterway design. Risk models can be used in combination with a physical model to make it possible to study the environmental and ship system in three visual dimensions. One successful application of this approach has been the assessing of the probability of ship accidents in the entrance channel of Barber Point Harbor, Oahu (Briggs et al., 2003). The point of criticism resides in the fact that the modeling accuracy of this large scale and complex system is not always satisfactory and the work required is extremely expensive.

The definition of various grounding scenarios and the assessment of the damage to a ship are the other concerns, as presented in several publications by Simonsen and others (Simonsen, 1997; Simonsen & Hansen, 2000; Simonsen & Hansen, 2002). The authors concentrate on descriptions of different models of the grounding scenarios based on worldwide recorded grounding accidents and developed analysis tools to define the grounding impact and damage levels. This research approach is more appropriate for ship structure design than for marine engineering. However, it is helpful in the later analysis of the accident consequences that have to be considered when determining the optimal design of waterway dimensions.

The approach based on simulation experimentation models

Ship maneuvering results derived from real time simulation experimentation by means of ship handing simulator are effectively used by design engineers and channel planners because they contain very important and valuable information for waterway design. There are the following main reasons for this application (Gucma, 2000):

- Accident statistical data concerning grounding are not available when, for example, the waterway is being projected, or is in the design stage;
- Nonexistence or inadequacy of historical accident data if the period of waterway service is still short;
- Unknown causes of accidents that can be recognized by replication in computer simulations; and
- Simulation method might be potentially possible when a scaled physical model is impractical due to the high level of cost.

Depending on the goal and the research problem, the simulation experiment models can be distinguished into two main groups as explained in Figure 2.3 and Figure 2.4.

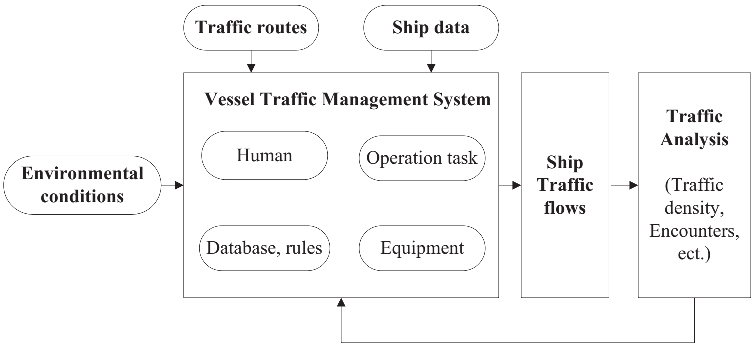

Figure 2.3: Simplified macro-simulation model

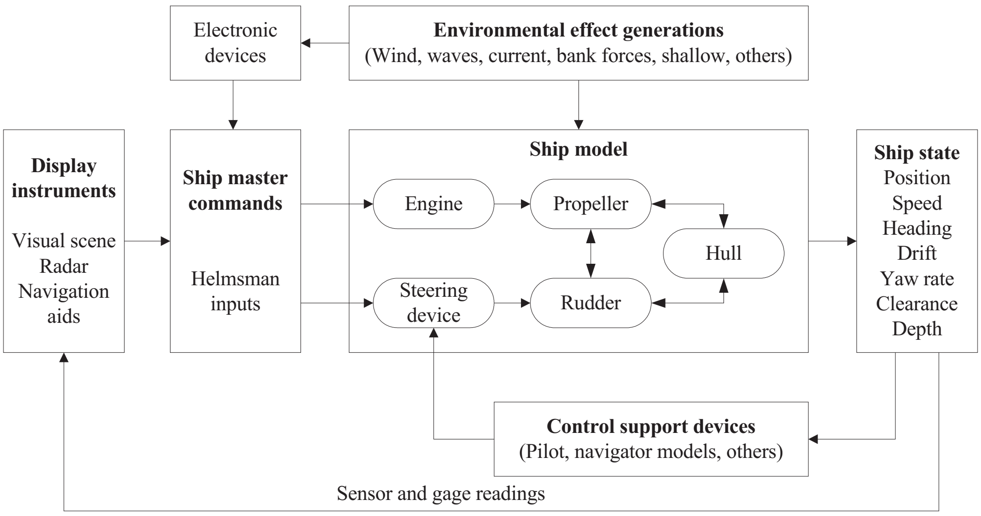

Figure 2.4: Simplified micro-simulation model

The emphasis of the macro-simulation model is on the behavior of traffic flows within a port or/and on the prediction of the accident risk where traffic density is high, especially in port development study. In essence, this simulation model is a time-compressed-stepping model in which a number of vessels in the play area move along prescribed routes and maneuver according to a set of rules. The data relating to vessel movements, paths and types of the past, present and future therefore needs to be collected and identified in the interests of traffic development studies. This data can generally be described by means of probability distributions and then read from the simulation. The established rules for simulated ship navigation will determine when and how the ship will respond (i.e. in terms of course, speed) before, during and after an encounter with other ships. Such actions are triggered by computing the Closest Point of Approach (CPA) with the use of an automatically controlled model of ship steering dynamics, which is monitored continuously for all simulated ships (Dand & Colwill, 2003);

The results of the simulation will reveal whether the proposed channel design is safe enough and whether, with its traffic rules and environmental conditions, it can handle the traffic demand with acceptable amount of ship waiting time. Alternatively, starting from the maximum acceptable waiting time, the simulation model can estimate the port's maximum channel capacity with the level of navigation safety requirements, commonly expressed by the number or the frequency of the encounters (PIANC, 1997). Although the traffic models can, for instance, provide estimates of the encounter frequency considerable effort still has to be made before this information can be directly used for risk assessment. Because this involves (Da-Qing et al., 2003):

- The estimated risk as based on the correlation factor between the estimated frequency of simulated encounters and real accident data. Such procedure relies heavily on the inadequate data of accidents and expert opinion, so a satisfactory correlation factor is generally not achieved;
- A realistic model of ship behavior which does not exist.

The advanced macro-simulation model is very often used in the so-called Vessel Traffic Management System (VTM), where the Vessel Traffic Service (VTS) station is the core element (Hanekamp & Vries, 1998). The VTM system consists of human management and hardware, all of which contribute to the safe and efficient flow of traffic in a certain area. As mentioned previously, during the SAFECO project, the VTM system was adopted and developed to assess the risk of ship accidents, specifically the risks of collision and grounding (Eide et al., 2006). A fault tree model was designed to link the VTS-related errors to the initiating events in the overall SAFECO risk model. The outcome of the fault tree analysis is the probability of the occurrence of a "VTS information failure", which was estimated at once in every ten ship movements a VTS-related error takes place (Hanekamp & Vries, 1998). Other applications of this model to navigation safety assessment can be found in various recent studies (Bruzzone et al., 2000; Merrick et al., 2001; Merrick et al., 2003). However, the macro-simulation model is not considered in this thesis.

On other occasions when the port has little traffic or for the design of a channel/basin, micro-simulation models are used to assess the safety and the behavior of individual vessels associated with certain navigation conditions. A micro-simulation model, which is often named "simulator", is incorporated with human pilot known as "real time simulation". The simulator has now become a reliable and indispensable tool in the assessment of navigational safety of a ship in harbors and fairways. The results are usually used for navigation risk level assessment and tend to concern the following waterway design process procedures:

- Determination of the probability of the ship exceeding the channel margins so that a level of the channel width can be decided for acceptable navigation conditions;
- Assessment of navigator competence for a given channel configuration; and
- Evaluation of the ship handling difficulty so that the rule of operation as well as the operation limits can be defined.

There are some difficulties in such a process; this thesis relates to and discusses most of the problems listed above, as presented in Chapters 3 and 4.

2.4.2 Safety criterion and risk acceptance

The safety criterion places restrictions on the engineering designs and channel operations so as to maintain the safety of navigation transport, including shipping and related facilities, at a certain level. The restrictions amount to a loss of benefit (downtime) both to the port and to the related partners (e.g. ship owners).

Risk acceptance involves a subjective balancing of the benefits and possible costs due to risks and it depends on the accident rate and the consequences of accidents. A level of acceptable risk can be established by analyzing the cost-benefit model in which the consequence of accident should be weighted to money. A safety criterion is commonly defined for a particular transit; whereas a risk acceptance level is often assigned to the lifetime of a channel project.

Although the safety criterion and risk acceptance are different aspects in the study of the failure process, there is a significant relationship between them. This relationship can be expressed by a function of various parameters such as the human factor, the management factor and the engineering factors, all of which relate to the rule of operation. The risk, in this context, can be expressed by the degree or possibility of colliding with the seabed or another object and the consequences of such an accident. Safety criteria are therefore indirectly and partially subject to the occurrence frequency of such accidents. On the other hand, an acceptable risk of accident will be strictly limited by the safety criteria. It is apparent from this philosophy that the more accurate the calculated probability of a ship accident is, the more practical the safety criteria will be. The following example explains the use of safety criteria when designing approach channels and applying Dutch and other channel regulations.

For Dutch channels the safety criterion is defined thus: "During a 25 year period the chance of touching the channel bottom with maximum minor damage must not be more than 10%" (Savenije, 1998).

A widely accepted assumption is that the number of ship accidents (e.g. touching the bottom) for an expected accident rate during a given time period t (years) can be described by the Poisson law as:

$$P(x = k) = \frac{\lambda^k}{k!} e^{-\lambda} \tag{2.6}$$

where k is the number of accidents; λ is the intensity, the rate of accidents.

Refer to the safety criterion of 10% in 25 years, the accident rate is therefore estimated at 0.105, if the expected number of ship arrivals is 250 per year. So the safety criterion for a particular transit in 25 years will be $0.105/(25{\times}250){=}1.68 \times 10^{-5}$. This means that the time between accidents (touching the bottom) is 25/1.05=237 years. Table 2.7 gives a summary of the different results applying this methodology.

The explanation for these cases as given by Savenije (1998) is as follows:

1. The first case is the same as the safety criterion as used for the Euro-Maas channel in the past;
2. The British formulation of the safety criterion is "a ten per cent of the chance of bottom touches in 100 years" as presented in case two;
3. This is the formulation following case two as applied to the criterion of the Euro-Maas channel;

Table 2.7: Different results of safety criteria application

Case	Probability, P	k accident	Period (year)	Intensity	Safety criterion
1	10%	> 1	25	0.532	8.510×10^{-5}
2	10%	> 1	100	0.112	0.448×10^{-5}
3	10%	> 0	100	0.105	0.042×10^{-5}
4	10%	> 0	25	0.105	1.680×10^{-5}
5	2.8%	> 0	25	0.028	0.448×10^{-5}
6	10%	> 0	25	0.105	1.200×10^{-5}

Table 2.8: Safety criteria in Netherlands, (Savenije, 1998)

Items	Outcome	Safety criteria
Occupational Hazards	Death	0.1×10^{-4}/year
Car driving	Death	1.0×10^{-4}/year
North sea channel	Collision	0.6×10^{-4}/year
Dutch dikes	Inundation	1.0×10^{-4}/year

4. This is the above calculation, which is at present being used for Euro-Maas channel;
5. This case is the British criterion as given in case two, but the definition has been adapted to the Rotterdam Port.
6. This criterion was calculated on the basis of 350 ship arrivals every year.

The above criteria can be compared with the other generally accepted safety criteria used in the Netherlands, as shown in Table 2.8. It can be seen that these criteria seem much higher than others. It was also recommended by Savenije (1998) that these results could be multiplied by a factor of ten for two reasons: (i) in reality, the problem of ship touching of the bottom does not always result in an accident. So the probability of actual accidents will be smaller than the chance of bottom touches; (ii) the estimated probability of ship accidents based on historical data is less than that reflected this calculation.

It may be remarked that the overall safety of a harbor will depend on the combined safety of individuals. To increase the safety we have to either decrease the frequency of accidents or mitigate the consequence of accidents from each individual.

2.4.3 Operation rules

Allowing a ship to be able to navigate in all conditions of tides and heavy weather is not always possible and would indeed make the channel construction very costly. There are certain navigation restrictions beyond which operations become unsafe and it is important that designers are able to estimate these limits at the design stage (PIANC, 1997).

The rules of operation should be established on the basis of these restrictions to guarantee that a required safety of the navigation channel is maintained. If navigation safety is not guaranteed, then the rules of operation should be adjusted to improve matters before alterations to the channel design need to be addressed. The margin of navigation restrictions at one hand, and the operational design conditions for the channel project at the other hand can be identified using ship handling simulator. Weather extremes and rare tidal conditions are normally part of the design conditions. This matter will be discussed in detail in Chapter 3.

2.4.4 Cost-benefit analysis

Any optimal design process leads to the use of a cost-benefit analysis. In the maritime transport, the cost-benefit analysis process is aimed at determining an optimal design to provide a balance between the benefit of transport increment, downtime reduction and increased costs of initial/maintenance investments for a long-term project.

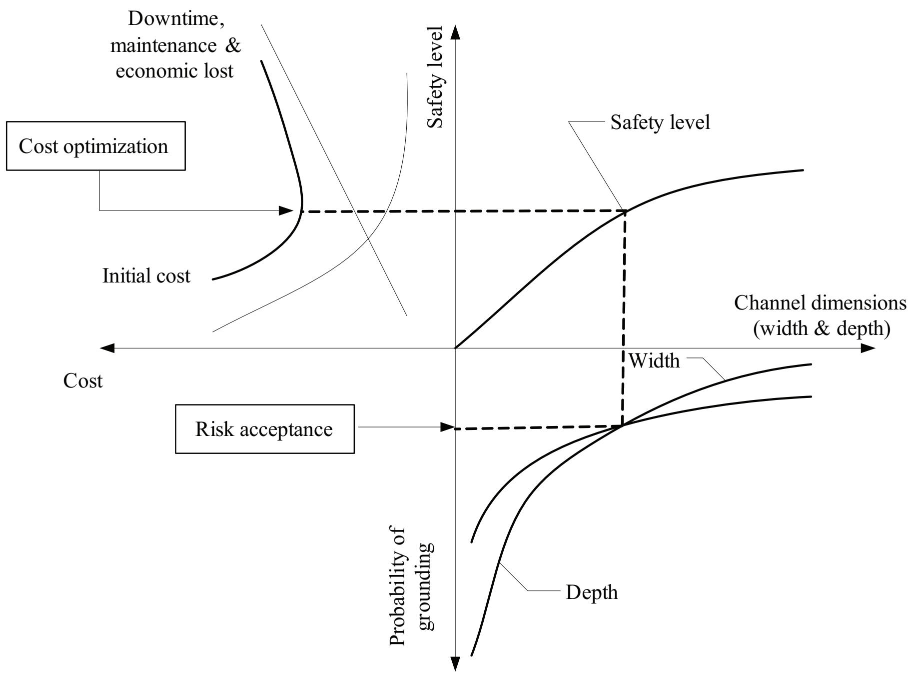

Figure 2.5: Risk-based chart for selecting an optimal design of waterway dimensions

With the optimization of waterway dimensions operation rule, which can be weighted in terms of downtime, the safety criterion or risk acceptance will be interdependently introduced to the cost-benefit analysis process. It can be basically explained that the benefits of downtime reduction and increase in transport capacity should be plotted against whether the ship is allowed to navigate in adverse environmental conditions accepting, consequently, a higher probability of ship accident (and higher risk) or increases in channel dimensions, ultimately resulting in the increment of dredging costs. As long as most costs (enlarging channel, downtime and the consequence of possible bottom touches) and total benefits for all possible operation rules (or alternatives) can be qualified in terms of monetary values, an optimal design can be selected in such a way that the net present value (NPV) of the total benefits and costs for the lifetime of the project is maximized with an acceptable risk or safety criterion. The following well known equation can be used to calculate the NPV:

$$NPV = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1 + r_d)^t} \tag{2.7}$$

where B_t is the sum of benefits, including downtime reduction, the increment in transport capacity and risk reduction in a period t, and C_t is the sum of costs in a period t; r_d is the discount rate per period.

The benefit of the risk reduction, B_{rr}, can be expressed in terms of a probabilistic equation as:

$$B_{rr} = Co.P_a \tag{2.8}$$

where Co is the consequence of the accident (ship grounding) expressed in terms of monetary value, and P_a is the acceptable occurrence probability of the accident.

Though these equations look simple they are a very important tool in relation to the optimal design process. Figure 2.5 interactively illustrates the relationship between the aspects in the optimization of channel dimensions.

2.5 Simulator-based navigation study

2.5.1 Introduction

Over the decades, ship handling simulators have become popular worldwide. As users are becoming familiar with the relevant technology, they are also starting to explore the creative applications of simulators for maritime engineering design, research and training purposes. Productive and credible simulator usage requires a good understanding of its model bases, algorithms, assumptions, and limitations.

Generally, the basis of a mathematical model of a simulator and its structural components is not always furnished with adequate detail. Due to the complex nature of the simulation mathematical model and its implementation in a simulator system, many channel designers and users treat this heart of the simulator as a black box (Hwang, 2004). The responsibility for understanding and validating the mathematical model before conducting simulation runs tends to fall with the designers of the simulator and its mathematical model, who are not channel project staff. Consequently, the understanding of how a simulator works and how a simulation experiment can be set up remains the terrain of engineering design staffs.

This section, based on the information and data gathered from the worldwide simulator center which we have experienced in operation, has focused on new achievements in the ship maneuvering modeling used in simulators. Certain selected elements which involve the procedures prepared by channel designers before initial real time simulation runs are further discussed in this section. Some elements have been included in later chapters while other elements which are less related to channel design are only tested out. The specific objectives are therefore:

- to establish good preparation and data collection for a simulator-based channel design project;
- to use the simulator within its boundaries while avoiding the risk of going beyond its valid application range;
- to extend the currently available implementation methods of real time simulation results used for approach channel designs.

2.5.2 Specific components of a ship-handling simulator

A number of ship simulators exist worldwide and have different applications with various levels of capacity. Essentially, a ship handling simulator is a computer-generated system that simulates the actual operation parameters of the ship in various maneuvering conditions in real time and displays the scenery from the navigation bridge visually and audibly on the screen. Simulators comprise a wide range of facilities and man-machine interfaces as schematically represented in Figure 2.6. An advanced ship simulator includes models of ship motions, the simulated navigation channel, the environmental impacts, the visual scene, the radar image, tugs and thrusters, the ship bridge controls, and typical bridge instruments (USACE, 1998).

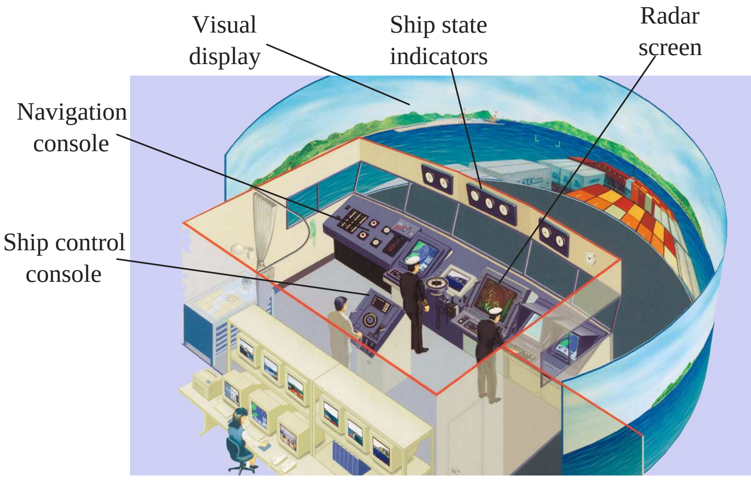

Figure 2.6: Main features of a ship simulator room

Mathematical model

The core of the ship dynamic model is the set of equations of ship motion that refer to a coordinate system commonly fixed in the ship. The equations should be complete and realistic reflecting the ship hull dynamics, engine thrust, control surface hydrodynamics, bank and shallow water effects, currents, wind and wave impacts, and the tug supporting forces.

Equation of motion

The basic mathematical model used to present a maneuvering ship in the present environmental conditions consists of a set of coupled non-linear deferential equations in six degrees of freedom (DOF); a translation motion (position) in three directions: surge, sway, and heave; and a rotation motion (orientation) in about three axes: roll, pitch and yaw. To determine the equations of motion, two

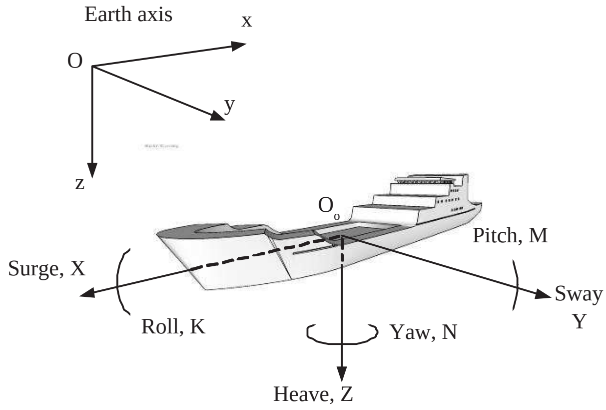

Figure 2.7: Earth-fixed and ship-fixed coordinate systems

reference frames are considered: the inertial or fixed to earth frame O that may be taken to coincide with the ship-fixed coordinates in some initial conditions and the body-fixed frame O_0 (see Figure 2.7). For surface ships, the most commonly adopted position for the body-fixed frame is such that it gives hull symmetry about the $x_0 z_0$-plane, while the origin of the z_0 axis is defined by the calm water surface (Price & Bishop, 1974). The magnitudes describing the position and orientation of the ship are usually expressed in the fixed frame. Whilst the forces $[\ X \quad Y \quad Z\ ]^T$, moments $[\ K \quad M \quad N\ ]^T$, linear velocities $[\ u \quad v \quad \theta\ ]^T$, and angular velocities $[\ p \quad q \quad s\ ]^T$ are usually expressed in the body-fixed frame as shown in Figure 2.7. The force and moment vector is defined as:

$$\tau = [\ X \quad Y \quad Z \quad K \quad M \quad N\ ]^T \tag{2.9}$$

and these magnitudes are generated by different phenomena and can be separated into components according to their originating effects:

$$\tau = \ \tau_h \quad \tau_r \quad \tau_p \quad \tau_e\ , \tag{2.10}$$

where:

- τ_h: the forces and moments arise from the movement of the hull in the water;
- τ_p: the forces and moments come from the propulsion system, e.g., propellers and thrusters.;
- τ_r: the forces and moments arise due to the Control Surfaces like rudder, fins, etc. movement;
- τ_e: these are the forces and moments acting on the hull due to the environmental disturbances, e.g., winds, currents and waves.

Motions in pitch and heave can generally be neglected in comparison with the other motions for many simulators; thus, ship motion modeling can be considered to be only 4-DOF: surge, sway, yaw and roll can be written as (Fossen, 1994):

$$\begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m & -mz_G & mz_G \\ 0 & -mz_G & I_{xx} & 0 \\ 0 & mx_G & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} u' \\ v' \\ p' \\ s' \end{bmatrix} = \begin{bmatrix} X \\ Y \\ K \\ N \end{bmatrix} + \begin{bmatrix} m\left(vs + x_G r^2 - z_G ps\right) \\ -mus \\ mz_G us \\ -mx_G us \end{bmatrix} \tag{2.11}$$

where m is the mass of the ship, I_{xx} and I_{zz} are the inertias about the x_0 and z_0 axes, and x_G and z_G are the coordinates of the center of ship gravity with respect to the body-fixed frame.

The formal mathematical model of ship motions used in simulators was initially developed using Taylor-series equations of hydraulic forces. The advanced model currently used in almost all simulators is based on the concept of the modular maneuvering model (Ankudinov V., 1993). This means that the ship hull, propeller and rudder are viewed as interacting modules and the mathematical models are based on an examination of the established hydrodynamic principles. Each module, whether it relates to hydrodynamic or control forces or external effects, is self-contained. The modules are designed by reference to the detailed physical analysis of the process being modeled. The system as a whole is then modeled by combining the individual elements and expressing their interaction by means of other physical expressions (Sarioz & Narli, 2003). All the different force and moment components acting on the hull and their models will be described in the following sections.

Hull module

The hull module contains all the hydrodynamic data which is specific to the underwater part of the hull. The hydrodynamic forces and moments acting on a maneuvering ship hull are generally considered to originate from independent components: inertial hydrodynamic forces or added masses, viscous dissipative forces or hull lifting and cross flow effects, and hydrostatic forces. Essentially, the inertial forces are a function of the underwater hull geometry and are expressed in terms of added mass values. A strip method is employed in the simulation program in which the total added masses are calculated by integrating the sectional added mass values along the ship length and a semi-empirical 3D correction technique is applied (Sarioz & Narli, 2003).

Considerable effort has been put into the predicting of hydrodynamic derivatives in order to estimate these forces for the purpose of predicting a ship maneuvering performance. The most notable studies and the ones which might be useful when addressing needs in the development of modern ship maneuvering simulators are:

- Pawlowski (1996) who presented "An analysis of the properties required of hydrodynamic models for ship maneuvering simulation";
- A study of the cost-effective prediction of hydrodynamic forces has been made by British Maritime Technology in combination with the European Union Research Project (Burnay & Ankudinov, 2003);
- Mathematical modeling methods and series experimental testing for the prediction of ship maneuverability have also been carried out (Eloot, 2006b).

The estimation of hydrodynamic forces as well as the prediction of ship maneuverability are strongly related to the accuracy of determining ways in which the mathematical models of simulators can be specified. Different methods for the identification of hydrodynamic coefficients, comparing their merits and shortcomings, have been extensively presented by Michele et al. (2003).

Propeller module

The propellers are the means of transmitting the power generated by the ship engines to propel the ship through the water. Ships may have one or two propellers which may be fixed or controllable pitch type. Realistic modeling of the propeller force is important for maneuvres involving thrust, torque and speed reversal, and indirectly for rudder force modeling. The propeller force is represented by a quadratic equation in terms of ship resistance, length, relative speed, propeller diameter, the propeller advance coefficient and efficiency.

Propeller efficiency is the ratio of thrust power output to engine power input. When the ship approaches a harbor the maximum propeller capacity is restricted to Harbor Full. To leave some power reserves for unexpected events and emergencies, Half Ahead is considered to be the maximum power use.

Rudder module

The rudders only generate a force on the ship when the ship is moving (when water is flowing past them). Ships can have one or two rudders. Rudder modeling techniques are derived from aerodynamic theories relating to wing profiles in an air flow. The interaction between the rudder with the propeller slipstream should be carefully considered and in the case of large turning angles some empirical corrections are provided. The analysis of rudder use during ship maneuvering simulation provides vital information on ship and human performance. The following equation can be used (Nakamura, 2005):

$$R_{index} = \frac{1}{m-n}\sum_{t=m}^{n} |r\left(t\right)| dt \tag{2.12}$$

where R_{index} is the index of the rudder use; m and n are the start and end times of the simulation, respectively; r is the recorded rudder angle at a predetermined time interval.

The larger value of the rudder index reflects the poorer maneuverability of the ship or the less experienced human operates. In many ships, the maximum rudder angle is less than or equal to 35^o. However, sailing with a rudder angle of more than 20^o for a long period of time is considered undesirable in combination with half propeller use.

The effectiveness of the rudder is strongly related to propeller use. The rudder force can be expressed as a function of the rudder angle and the square of the propeller revolutions. A safety parameter with regard to propeller and rudder use is defined as follows (Lan, 2003):

$$S_{PR} = \frac{\overline{r}}{20}\left(\frac{p}{p_{half}}\right)^2 \tag{2.13}$$

where S_{PR} is the safety parameter; $\overline{r}$ is the average rudder angle use; p is the propeller use; and p_{half} is the propeller revolution of a half engine setting.

Engine module

The ship engines, working through the propellers, generate force primarily along the axis of the ship. The water offers resistance to the ship motion that is proportional to the square of the ship speed. Because the resistance of the water to the ship motion increase so steeply with increases in speed, a ship using half of its power can reach about 80 per cent of its maximum speed. The engine of the ship is modeled using standard models for diesel engines and steam power plants. Characteristics of the engines can be represented by the propeller revolution, rpm.

Wind and current force models

Generally, wind load is calculated on the basis of the wind load coefficients obtained from the most accurate calculation method for a specific vessel. There are many alternative ways to calculate these forces. The applicable methods are the experimentally and statistically determined algorithm as presented by Blendermann (1994), OCIMF (1977) and Isherwood (1972). One such algorithm published by the Oil Companies International Marine Forum (OCIMF) is commonly used for the calculation of these terms. The OCIMF model is considered to be one of the more suitable algorithms for tanker studies as this algorithm focuses on very large crude carriers (VLCC), tankers, floating production, storage, and offloading shapes. The OCIMF model expresses the wind and current forces as follows:

- Wind forces:

$$X_{wind}(N) = \frac{1}{2} C_x \beta_R \rho_w V_R^2 A_T \tag{2.14}$$

$$Y_{wind}(N) = \frac{1}{2} C_y \beta_R \rho_w V_R^2 A_L \tag{2.15}$$

$$N_{wind}(N.m) = \frac{1}{2} C_N \beta_R \rho_w V_R^2 A_L L_P \tag{2.16}$$

where X_{wind} and Y_{wind} are the transverse and longitudinal wind forces, respectively; N_{wind} is the moment force; C_x, C_y are the force coefficients and C_N is the moment coefficient, which are derived from the OCIMF recommendations using the towing tank test; ρ_w is the density of air (kg/m^3); β_R is the wind angle which is formed between the wind and sailing directions (degree); V_R is the average wind speed (knots); A_T and A_L are the transverse and longitudinal projected area of the ship (m^2); L_P is the overall length of the ship (m).

- Current forces:

$$X_{current}(N) = \frac{1}{7600} C_{xc} \rho_c V_c^2 T L_P \tag{2.17}$$

$$Y_{current}(N) = \frac{1}{7600} C_{yc} \rho_c V_c^2 T L_P \tag{2.18}$$

$$N_{current}(N.m) = \frac{1}{2} C_{nc} \rho_c V_c^2 T L_P^2 \tag{2.19}$$

where $X_{current}$ and $Y_{current}$ are the transverse and longitudinal current forces, respectively; $N_{current}$ is the moment force; C_{xc}, C_{yc} are the drag current force coefficients and C_{nc} is the drag moment coefficient, which are derived from the OCIMF recommendations according to the towing tank test and depending upon the current angle of incidence; ρ_c is the density of water (kg/m^3); V_c is the average current speed (m/s); T is the ship draft (m).

Wave force models

Waves affect a maneuvring ship in two distinct ways: (1) through the first order oscillatory forces centered on the dominant wave encounter frequency, and (2) by means of the second order drift forces which consist of a steady component and a low frequency component. Usually, the second order drift forces are not introduced to the simulators. The first order forces are of a much larger magnitude compared than the second order forces. A strip theory based approach is used to compute the first order hydrodynamic coefficients. The assumption is that the ship is small compared to the wavelength and the water surface across the hull can be approximated as a plane surface (Fossen, 1994). The first order oscillatory forces can be determined as:

$$X_{wave}(N) = C_{xw} H_s^2 \delta \quad (2.20)$$
$$Y_{wave}(N) = C_{yw} H_s^2 \delta \quad (2.21)$$
$$N_{wave}(N.m) = C_{nw} H_s^2 \delta \quad (2.22)$$

where X_{wave} and Y_{wave} are the transverse and longitudinal wave forces, respectively; N_{wave} is the moment force; C_{xw}, C_{yw} are the wave force coefficients and C_{nw} is the wave moment coefficient, which are derived from the towing tank test; δ is the wave angle of incident (degree); H_s is the significant wave height (m).

2.5.3 Limitations of the simulator-based study in shallow water areas

The prediction of ship maneuverability based on real time simulation methods for maritime engineering research started in 1960. However, the understanding of the physical processes occurring around a maneuvering ship still remains insufficient for many environmental and operational conditions throughout the lifetime of a ship when approaching and entering harbors, such as:

- maneuvering with a small underkeel clearance;
- maneuvering in harbors and at low speeds;
- passing near banks, approaching banks; and
- passing and approaching other ships.

Shallow water effect

In (PIANC, 1992) the following rather arbitrary distinction is made between water depth d and ship draft T:

- deep water d/T >3.0;
- medium deep water 1.5< d/T <3.0;
- shallow water 1.2< d/T <1.5; and
- very shallow water d/T <1.2.

In general, hydrodynamic forces increase with decreasing water depth as the flow around the hull is hindered by the restricted clearance between the keel and the bottom. Many studies show that shallow water distinctly affects ship behavior so it is an aspect that cannot be neglected when modeling the environmental effects.

One of the aspects which must be considered while a ship is moving in areas with restricted underkeel clearances is the sinkage of the ship. The scale of sinkage increases considerably in shallow water due to the proximity of the sea bed (PIANC, 1997). This phenomenon, known as squat, will not be examined in detail in this research; but since it affects the channel design its certain effects will be discussed in the following chapters.

Recent researches on this phenomenon include:

- A study (Yasukawa & Kobayashi, 1995) based on free-running model tests for four different ship models;
- Eloot (2006b) and Simonsen et al. (2006) conducted series of experimental tests to determinate and evaluate of a mathematical model on ship maneuvering in shallow water;
- A validation of ship motion models in restricted and shallow waters based on the measurements of ship motions in the Houston Channel (Daggett et al., 2003);
- Jiang and Henn (2003) developed a numerical method for prediction of ship squat; and
- Lee et al. (2006) investigated ship maneuvering characteristics as a function of ship form in shallow water.

Ship maneuvering performance at low speed

Ships usually sail at two types of speed, a service speed in deep water and a cruising (or low) speed in shallow water (Wang et al., 2002). A mathematical model of hydrodynamic forces acting on the ship hull has accurately been developed for the service speed. A ship can be observed to maneuver satisfactorily at its service speed according to the International Maritime Organization criteria (IMO, 2007). The model is, however, no longer valid when a ship is navigated below a certain level of ship speed because of *memory effect*. The concept of *memory effect* or *time history effects* has been defined and investigated by Eloot and Vantorre (2004) with the introduction of Planar Motion Mechanisms to determine and measure fluid forces. These forces and moments acting on a manoeuvring ship model can be greatly influenced by the previous motions so that the memory effect is the hydrodynamic effect on the local flow at some part of the ship due to the earlier flow at another part of the ship. The following issues have furthermore been researched:

- Dand (2003) argues low speed maneuvering in the IMO Guidelines for merchant ships and makes some suggestions as to the form the criteria might take;
- An extensive study is described in (Wei-Yuan et al., 2003), which was performed by the Technical and Research Program of the Society of Naval Architects and Marine Engineers (SNAME) through Panel H-10 (Ship Controllability). The objective of the project was to identify and develop slow speed maneuvers in line with the philosophy of the IMO standard maneuvers for deep water, which are considered to be simple, relevant, comprehensive, measurable and practicable;
- Eloot and Vantorre (2004) demonstrated an approach for the prediction of low speed maneuvering based on captive model tests. This study focused on the results of model tests with the

fourth generation containership with a draught of 15.0 m at an under keel clearance of 20%.

- Yeon et al. (2006) established an optimal input design for the identification of a low speed maneuvering mathematical model.

Bank effects and ship channel interaction

The basic effect of a channel bank on a ship is that it exerts an asymmetrical lateral force and moment acting on the ship even when the ship is laterally symmetric with no yaw or rudder deflection. Generally the lateral force on the ship is directed toward the bank and the lateral moment tends to turn the bow away from the bank. In order to simulate the bank effects the force and moment on the sides of the ship are calculated independently and the resulting forces and moments are added up to provide the total bank effect. The bank forces and moments are calculated for the vertical bank case and then corrected for effects of bank slope and partial depth banks. The modeling of bank effects is still something that is challenging to researchers and has not been considered in most simulators worldwide.

The research concerning these effects has been published in series of MARSIM conferences (Da-Qing et al., 2003; Chun & Kijima, 2003; Vantorre et al., 2003; Ankudinov & Filippov, 2006).

Ship-ship interaction

For the design of double lane approach channels, the effect of passing ships on the width design is significant. The interaction between two ships involves a complex hydrodynamic phenomenon that is difficult to predict in a form used in real time simulations. The problem is further complicated by the presence of channel boundaries and depth effects. The ship-ship interaction model employed in the simulation software is based on a theoretical approach including empirical corrections based on model test results. Much effort was put into this phenomenon but little achievement has so far been gained (Yasukawa, 2003; Chun & Kijima, 2003). Those studies mainly focused on particular situations relating to the interaction forces between specified ships; but no general hydrodynamic model of this effect has been produced.

2.6 Conclusions

The bulk of this chapter has described the techniques and guidelines at present available for the design of approach channels and waterways. The problems surrounding these guideline applications have also been discussed to make clear that risk and simulation-based approaches are meaningful tools allowing the dimensions of a waterway to be checked while also providing for the optimization and rules of operation. The emphasis has been on the analysis of various risk models and methods used in navigation risk assessment. To this end, an important part of the chapter has been devoted to aspects involved in the optimization of waterway dimensions which include safety criteria or risk acceptance, operation rules and cost-benefit analysis models. The balance leading to an optimal design has also been addressed.

The risk models based on fault or event tree analysis and the generic data of ship accidents are widely used in maritime risk assessment to provide a more detailed view of how ship accidents are caused; but the shortcoming is that they require more historical data than that is actually available. Still, significant effort is required to build up a database of ship accidents, especially concerning aspects of collision and grounding scenarios. In view of these concerns, combining limited historical data with probabilistic approaches and expert judgment would be a better way to solve this problem (Wang et al., 2002). An understanding of the physical factors leading to the accidents emanating from this database is also very important as they are directly used in the development of the risk model.

A procedure for the risk-based design of channels aims at preventing accidents should ideally include the probabilities and consequences of all possible accidents. Obviously, such a risk-based procedure requires insight into very complex phenomena, such as human behavior; and although much research is at present being conducted in this field, it will take several years to develop practically applicable design tools.

It should again be pointed out that ship handling simulators play an important part in the assessment and evaluation of ship-human behavior and in providing meaningful data used for waterway dimension design to reduce the risk of shipping accidents. Furthermore, because of the dynamic nature of navigation conditions and traffic patterns, the use of a simulation technique makes it possible to accurately model the effect of these changes during the design stage, such as when introducing all kinds of possible operation rules, performing with different levels of safety criteria and considering the various skill levels of mariners, which is beyond the capacity of the other mentioned models.

In the near future, a larger-scale model of navigation risk assessment is expected to incorporate the results of port analysis and to investigate more local factors, such as the specifics of channel design, navigational aid configuration and currents. Meanwhile, an advanced model of economic risk providing estimates of economic loss associated with the probability of grounding for a given region continues to be an important topic warranting further study (Lin et al., 1998).

Chapter 3

Long-term navigation risk assessment

[1]

3.1 Introduction

Risk-based approach applied to waterway detailed design, as reviewed in Chapter 2, is a complicated process. Some elements of the risk-based design process create demand for the application of computer-aided design techniques, including ship handling simulator. The purpose of the simulator experiments for waterway design is to predict the track of a ship piloted by a mariner who is experienced in pilotage of the existing waterway or getting familiar with the projected waterway after several tests. Carefully designed simulator experiments are conducted to obtain the ship maneuvering results that are then considered to draw conclusions about optimum or required minimum waterway horizontal dimensions. There is difficulty to deal with such process. That is, only a limited number of navigation conditions and trials in each condition can be tested in a short time period, which do not give enough confidence in several aspects of risk analysis, especially in extending the research for longer time period (Gucma, 2005). The overall risk of ship navigation should therefore be defined for long-term optimal designs of the channel project. In this chapter, a new method to determine this overall risk by generalization of the ship maneuvering results is presented. For this purpose, several related issues should initially be discussed. Section 3.2 gives a brief description of applying this technique to generate data for the waterway design. Typically used procedures of risk analysis based on the simulation results for the design process are given. In Section 3.3, a short overview of existing approaches to the underlying problem is presented. Section 3.4 presents our method on generalization of the ship maneuvering results

---

1. Excerpts from this chapter were published as:
Quy, N.M. *et al.*, 2007. Identification and estimation of ship navigational limits for waterway designs using simulation. In *Proc. 4^{th} International Conference on Collision and Grounding of Ships*, Hamburg, Germany (pp. 79-85).
Quy, N.M. *et al.*, 2007. Long-term prediction of navigational risk for design of coastal approach channels and harbor waters. In *Proc. 4^{th} International Conference on Asian and Pacific Coasts*, Nanjing, China (pp. 1605-1616). Beijing: China Ocean Press. The extended version of this paper was submitted as: Quy, N.M. *et al.*, 2007. Generalization of ship performance for long-term prediction of navigation risk. *Journal of Marine Science and Technology.*

for overall risk assessments. In Section 3.5, a new method is developed to identify the navigation limits in association with the ship maneuverability, which is straightforwardly used for long-term optimization of channel widths. Finally, some conclusions are drawn in Section 3.6.

3.2 Typical analysis of the real time simulation results

The simulators are able to serve various needs of the assessment of the safety of ports and waterways, the research and development of safe operation and management of ships, and efficient education and training of the crews with its high reliable performance and wide range application. The most important data and results derived from simulator experiments for the use of waterway designs are (Iribarren, 1998):

- Track plot, a two-dimensional plot which includes the proposed channel contour and the ship position at predetermined time intervals;
- Time series tables of different variables (track distance, rudder angles, ship speed, turning rate, engine revolutions, etc.) throughout the simulation;
- Swept path graphs, the channel border and the area occupied by the ship during its navigation are presented in a two-dimension plot.

Fundamentally to evaluate how simulation can contribute to the design process is understanding the type of data that simulation generates. Important information which provides insight into the various navigation factors (parameters and dimensions of the waterway) and safety aspects (grounding or collision risks) can be obtained by interpretation of the simulated ship tracks. The analysis of the real time simulated tracks aims at finding the channel parameters and ship response characteristics (including human factors), including:

- Distribution of ship track distances (center of gravity and extreme starboard and port points of ships) in respect to center of the waterway;
- Distribution of ship courses; and
- Distribution of ship speed (horizontal, vertical and angular).

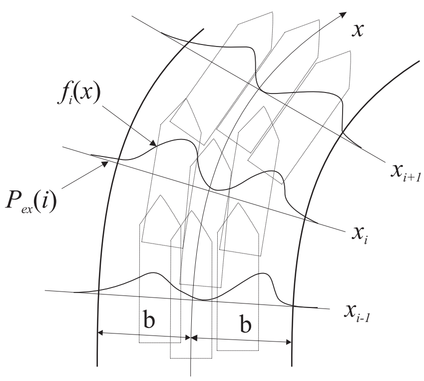

Figure 3.1: Probability calculation of ship accident

Utmost important information for the waterway width design is the probability of ship accidents in each of the waterway sections. The probability of ship exceeding a certain waterway width can be determined as follows:

$$P_{ex} = P(x > b|Env = h) = \int_{b}^{\infty} f(x)dx \tag{3.1}$$

where b is the half of channel width; $f(x)$ is the density function of the ship positions as shown in Figure 3.1.

The simulations are usually conducted in series, performed in different environmental conditions, each consists of several trials. In principle, the environmental conditions of wind, waves, and currents are divided into a number of regions or categories to facilitate the probability assessment of the navigation results. These environmental categories, reflecting the frequency of occurrence and severity, are selected to define the different combinations of the environmental conditions that might be present when the ship is transiting the approach channel. The different combinations of environmental conditions are divided into various classes (normally three or four), known here as “maneuvering scenarios”, by decreasing degree of affecting the ship maneuverability. The first maneuvering scenario involves combinations that are so extreme that the ship passage into the harbor will not be attempted due to the steering and propulsion capacity of the ship. The second scenario considers the less extreme combinations under which the ship passage might be attempted. In this scenario there may only be one high level among wind, waves and currents in the combinations. The next scenario involves the combinations which would always allow passage to be attempted. It can be recommended that effort should be made to consider this scenario in the simulation as much as possible. The last scenario is the gentle combinations that are no problems under environmental conditions. This scenario may not be needed in simulation experiments.

The probability of ship accident by exceeding the channel section borders during a given time period, P_{life}, can be determined as:

$$P_{life} = n \sum_{h=1}^{N_e} P_{ex} P_{oc}[Env = h] \tag{3.2}$$

where n is the expected number of ships presents in the channel during a given time period; N_e is the number of the maneuvering scenarios. $P_{oc}[Env = h]$ is the occurrence frequency of environmental conditions in the scenario h. Estimation of occurrence frequencies of the maneuvering scenarios is also an important topic. Two approaches could be found in the literature, which were based on a linear programming technique (Briggs et al., 2003) or classifying external forces on ship hull, as has been discussed in Section 3.5.

Figure 3.2, as an example, shows the distributions of ship track distance respectively with three environmental scenarios applying the above approach. The ship track samples normally fit well to a Gaussian distribution. The figure has been created based on the data of the study case at the entrance channel of Ennore Port (Vrijling, 1995). Real time simulations were performed with the use of container vessel 4.500 TEU capacity. Eighteen scenarios of environmental conditions carried out are grouped into three classes (extreme, normal and gentle conditions). For each scenario, several runs were executed.

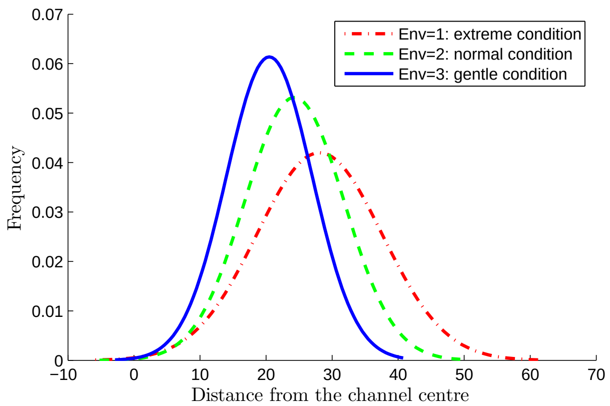

Figure 3.2: Density function of distance from the center of the channel fitted with normal distribution

Distribution of ship courses is strongly correlated with ship positions referred to the middle of the waterway. It can be straightforwardly explained that the more the ship is away from the center of the waterway the more the navigator changes the course to come back to the desired track. This phenomenon has been investigated by Gucma (2005) and could be seen in Figure 3.3. The result has been derived from real time simulated approach channel at Baltic Sea for a specified single section. To include such observable fact into the model it was proposed to use a simple linear regression model. The distance from the middle of the waterway could therefore be calculated by distribution of courses using this regression formula.

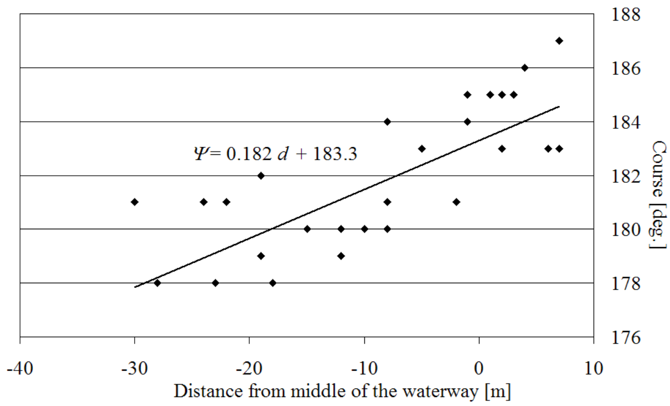

Figure 3.3: Linear correlation between distance from the waterway center and ship course for one investigated simulation trial (Gucma, 2005)

3.3 Existing approaches of overall risk assessment

Real time simulations should be executed for a wide range of environmental conditions (grouped into scenarios) and several repetitions for each condition in real time scale. So the time required would be comparable to the lifetime of the waterway. These requirements are really expensive and seem impossible due to time consumption (Webster, 1992). Thus arises the question of how to estimate the probability of a ship accident during the lifetime of the channel project, the so-called “overall risk”. The risk as defined in the previous section based only on a limited number of conditions and trials in each condition that does not equal to the overall risk. Generalization of the real time simulation results for long-term period research turns out to address the disadvantage of the ship handling simulator method. Finding ways of extending the real time simulation experimental results and applying them to the lifetime channel risk analysis is still challenging to researchers. Considerable efforts have been devoted to this and the research can roughly be categorized into three main groups.

The first group has focused on developing probabilistic simulation-based models to generate the data of ship passages and tracks applying the Monte Carlo method. The variables were introduced into these models through either probability distribution of navigation error (Vrijling, 1995) or by means of stochastic external disturbances (Huchison, 2003). The parameters of the simulated ship tracks were chosen by comparing with those obtained from the real time simulations. This approach is rather crude because the determination of distribution parameters of the random variables relies mainly on expert judgment. The second type focused on development of a new fast time simulation model, the so-called “probabilistic fast time simulation model”, which has been developed by the Dutch Institute MARIN (Lan, 2003). To make fast time simulation results more realistic, four random variables including the time intervals of command setting, rudder error, position threshold and rudder threshold, which all relate to human pilot behavior, were applied to the design of autopilot model. One of the most advanced models of this type is a ship navigator cognitive model developed by Itoh et al. (2001). The ship navigator cognitive model was constructed for simple course-tracking task based on cognitive task analysis of experimental navigation sessions using a maritime simulator. However, this model was programmed to control a ship only in a so-called simple single-ship situation. As pointed out by the authors, significant effort should be made to consider more complex navigation tasks (multi-ship situation) in order to extend the model to more realistic ship navigation as met in the real world. The third group comprises a model demonstrated by Gucma (2006), which differs from the above in several ways. The model is based on the assumption that the next ship position can be generated from the past consecutive position using two types of probability distributions. The first type describes the probability distribution of maximum and minimal points of ship track on starboard and port sides respectively. The second is the conditional distributions between the ship course and the generated track distance. The probabilistic parameters of the models were also obtained from statistic analysis results of the real time simulations. The critical point of this model retains further treatment in aspect of sudden changes in the generated tracks as pointed out by the author.

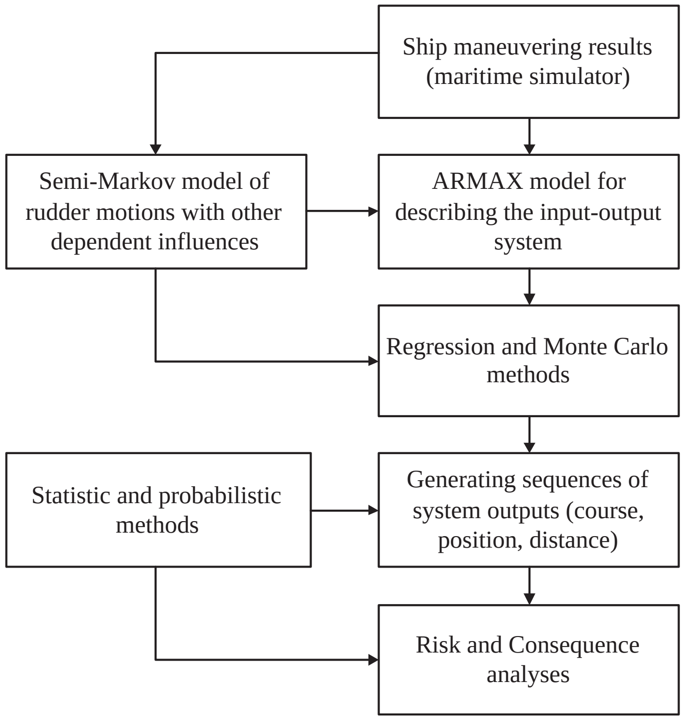

Figure 3.4: General procedure of the study

3.4 Our approach

This study is an ongoing effort that deals with the development of two models: the first model uses ARMAX (Regressive Moving Average eXogenous) technique to estimate the system outputs (course, position, etc.) from the inputs (rudder, engine, etc.) of the ship steering dynamics. The stochastic sequences of the inputs for the first model used are generated using a semi-Markov model. One implementation of the semi-Markov model for rudder actions has been studied. The study used input/output measurements from a ship handling simulator to estimate the model parameters. The human factor has therefore been included in the models. The method allows the results obtained from the simulator to be extended to predict the future conditions of system outputs. On the basis of the predicted results and using probabilistic approach, possible margins of ship maneuvering area will be identified and the long-term assessment of the navigational risk can be made involving a straightforward use of the optimal design of the channel widths. Good results were obtained even where there were only limited ship handling results. However, the study is confined to one failure mechanism when it comes to the matter of ships exceeding the channel limits and being viewed as grounding or colliding with surrounding structures. The general procedure for the study is presented in Figure 3.4.

3.4.1 ARMAX Model of ship steering dynamic

A ship operating in seawater is assumed to be a dynamic system with inputs $u(t)$, outputs $y(t)$ and white noises $e(t)$ as shown in Figure 3.5 (Fossen, 1994). The inputs can be rudder angle, propellers, and thrusters and so on. The outputs are ship heading (yaw), sway, surge, roll, yaw rate, sway velocity, surge velocity, roll rate and etc. There are several ways to represent the relationship between the outputs and inputs, for example, by means of a continuous time model (classical way or differential equation), a model in transfer function form, a model in time or frequency domain, and a discrete time model (digital technique or difference equation) (Fossen, 1994). In this paper, discrete-time Auto-Regressive Moving Average eXogenous (ARMAX) model is adopted.

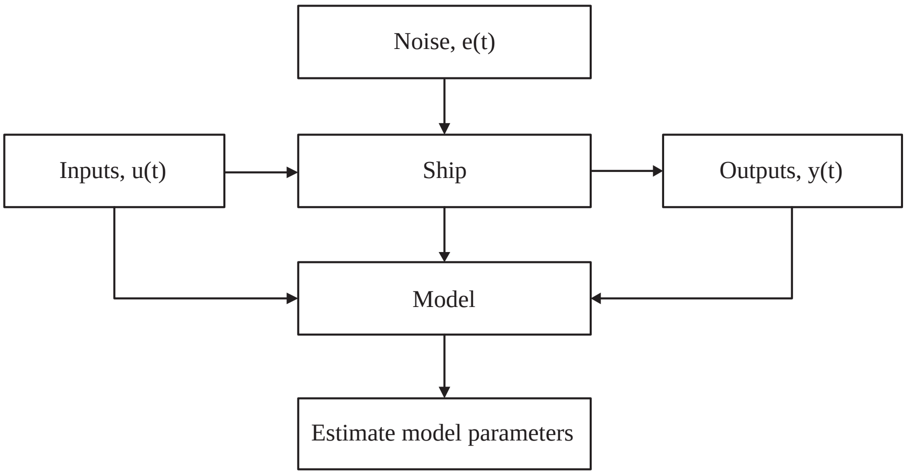

Figure 3.5: Concept of ship modeling

The ARMAX model applied to the above-described dynamic system can be assumed as a discrete-time model, a multiple-input and single-output (MISO) system in a transfer function form is defined as (Ninness et al., 2005):

$$y\left(t\right)=G\left(q\right)u\left(t\right)+H\left(q\right)e\left(t\right) \tag{3.3}$$

Where $u(t)$ and $y(t)$ are sequences of the multiple - input ($u(t) \in R^m$) and single-output ($y(t) \in R^1$) system with the same length; $G(q)$ is $1 \times m$ rational transfer function of the system and $H(q)$ is rational transfer function of the filter which is defined as:

$$G_i\left(q\right)=q^{-n_{ki}}\frac{B_i\left(q\right)}{A_i\left(q\right)}; \quad H_i\left(q\right)=\frac{C\left(q\right)}{A_i\left(q\right)} \tag{3.4}$$

Here n_{ki} is the number of delays from input to output of the i^{th} input, q^{-1} is the backward delay operator, $A(q), B(q)$ and $C(q)$ are polynomials of q^{-1} defined as:

$$A_i\left(q\right) = 1+a_1q^{-1}+a_2q^{-2}+\cdots a_{na}q^{-n_{ai}} \tag{3.5}$$
$$B_i\left(q\right) = b_o+b_1q^{-1}+b_2q^{-2}+\cdots b_{nb}q^{-n_{bi}} \tag{3.6}$$
$$C\left(q\right) = 1+c_1q^{-1}+c_2q^{-2}+\cdots c_{nc}q^{-n_c} \tag{3.7}$$

Where n_{ai}, n_{bi} and n_c are the orders of polynomials A_i, B_i and C, respectively. Having observed the input-output data (u, y), the most appropriate orders and the parameters of the polynomials can be determined using prediction error method, $e(t)$, (Ninness et al., 2005), which is available in the Matlab System Identification Toolbox.

The System Identification Toolbox in Matlab is a powerful tool, that can help us with this task. The process of the ARMAX model identification using this tool involves several steps, including: importing the measured data of rudders and courses into “ident” toolbox; preprocessing data; estimating models based on the data; analyzing the models and exporting resulting models for further use. Further detail about this process can be found in the help facility of System Identification (Matlab, 2005).

The model described in Eq. 3.4 with known A, B and C can then be applied to generate a random sequence ship course from the inputs $u(t)$. The following section will present how to apply a semi-Markov model to describe rudder motions based on measured rudder angles achieved from the real time simulation.

3.4.2 A semi-Markov model of rudder motions

Markov chains and semi-Markov models are powerful and commonly used techniques for the studying of the reliability and the characteristics of complex systems. In essence, these models use a set of data observed in present to predict system behavior in future by generating a random sequence that contains patterns of data characteristics. Details about this class of processes can be found in (Janssen & Manca, 2006).

Consider a finite set of rudder angles $R = r_1, r_2, ..., r_k$ (degree) respectively numbered and represented by rudder states $S = 1, 2, ...k$ that occur at random times during all the simulation trials, and denote $p(i, j)$ as the transition probability that the helmsman moves the rudder randomly from state i (at rudder angle r_i) at time t_i to state j (at rudder angle r_j) at time t_j. A Markov chain is a discrete-time stochastic process, where the conditional probability of any future event depends only on the present state; the transition probability $p(i, j)$ is expressed by this law as:

$$P\left(S_{t_j} = j | S_{t_i} = i\right) = p\left(i, j\right); \quad t_j > t_i \tag{3.8}$$

In practice, the transition probabilities $p(i, j)$ can be determined from the measured data as:

$$P\left(i, j\right) = \frac{m(i, j)}{n(i)}; \quad n\left(i\right) = \sum_{j=1}^{k} m\left(i, j\right) \tag{3.9}$$

Here $m(i, j)$ is the number of times that the rudder is moved from state i to state j. The quantity $p(i, j)$ is an element of square matrix, called the transition probability matrix (or transition matrix) in which the size $(k \times k)$ equals to the number of the states. All the transition probabilities of the Markov process can be estimated based on the data recorded in the simulator trials. Now we can extend the Markov chain to the semi-Markov model by taking into account the times that the helmsman used to move the rudder from state i to state j and retain it in each state.

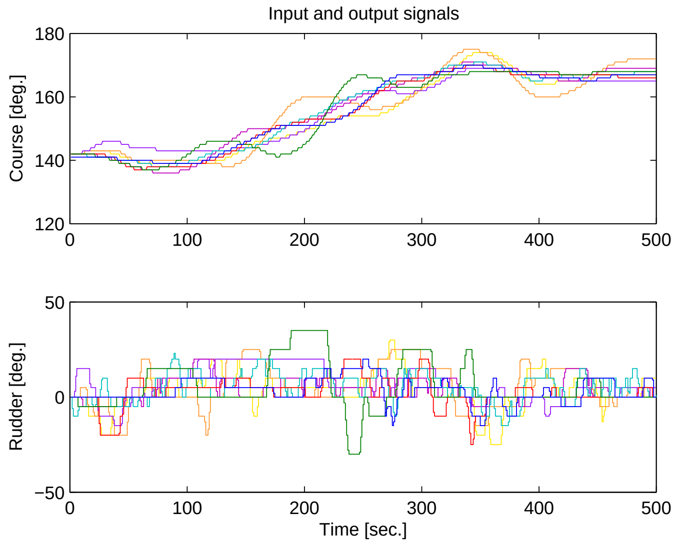

Figure 3.6: Measured rudder angles for total 15 real time simulation trials

The rudder motion records during a series of the simulator trials were obtained as shown in Figure 3.6 for an example. The real time simulations were carried out at the Piastowski canal, in the Baltic Sea. A total of 45 trials with various environmental conditions were performed at Paprotno Mielin straight part with the use of container vessel 4.500 TEU. The rudder of the ship can be adjusted from 35 degrees port to 35 degrees starboard with a unit angle $\Delta_r = 1$ degree.

It was observed that in all trials the helmsman tried to move the rudder with the same rudder rate, Vr. The time that the helmsman spent moving the rudder from state i to state j can therefore be determined as:

$$t\,(i,j) = t_j - t_i = \frac{|r_j - r_i|}{V_r} = \frac{|j-i|\Delta r}{V_r} \tag{3.10}$$

It is clear that in this case the time spent on the transitions (or moving rudder) is a deterministic quantity. The model thus has a transition time matrix analogous to transition probability matrix. Now the only thing left is to estimate the time (called sojourn time) that the helmsman maintains the rudder angle in every rudder state. The sojourn times $t(i,i)$ are, of course, random and dependent on many factors where the helmsman's competence, ship characteristics and navigational conditions are the main factors. Usually a certain distribution can be found to fit the sojourn times obtained from simulator trials. Figure 3.7 shows, for example, distribution of the sojourn times in the state with the 5 degree rudder angle fitted Lognormal distribution.

It should be clear that the sequence of rudder angles from the simulation is commonly recorded for every one second, the sojourn time in a state therefore exactly equals to the number of times, $m(i,i)$, that the same rudder angle values have continuously been recorded. It means that the length of the sojourn times increases proportionally to the transition probabilities $p(i,i)$. This makes it easier to generate the sojourn time in each state.

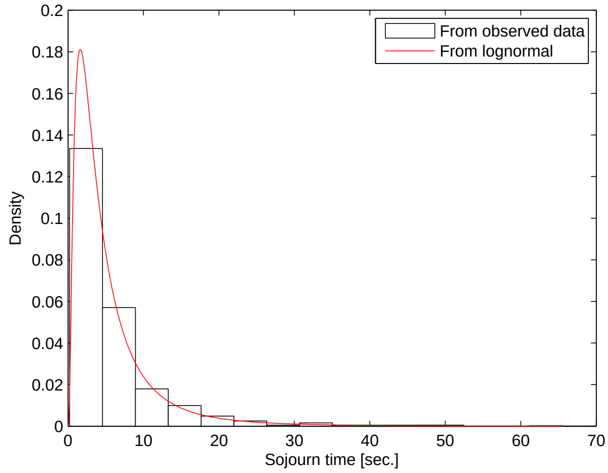

Figure 3.7: An example of distribution of the sojourn time fitted with Log-normal distribution

Figure 3.8 presents sequences of rudder angles generated randomly from the semi-Markov model developed in the above principle. The results seem similar to those measured from the simulator trials in time series. But some differences can be found in the shape of their probability distributions and power spectra as shown in Figure 3.9 and Figure 3.10.

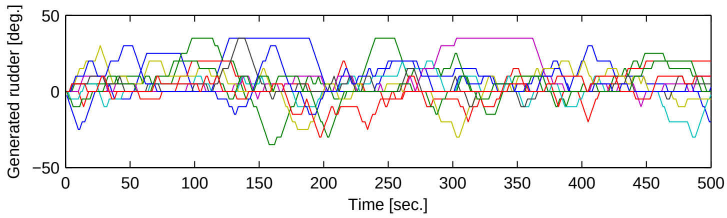

Figure 3.8: An sample of sequences of generated rudder angles from the semi-Markov model

It is more interesting to observe the results in the frequency domain. In both cases, the power spectra of the motions show significant peaks around zero frequency, but the higher peak is obtained in the generated rudders than in the simulator. However, the amount of the rudder motion in the simulator is larger by comparison in the frequency range from 0.2 to 0.7 (rad/s) and then both approximately drop to zero.

Here remained only the problem of estimating parameters of the ARMAX model. For the measured data of rudders and courses as shown in Figure 3.6, with the aid of the System Identification Toolbox, the resulting model has been found as follows:

$$A(q) = 1 - 1.878q^{-1} - 0.111q^{-2} + 2.465q^{-3} - 1.423q^{-4} - 0.5896q^{-5} + 0.537q^{-6} \tag{3.11}$$

$$B(q) = 0.056q^{-4} - 0.1714q^{-5} + 0.1408q^{-6} + 0.0858q^{-7} - 0.198q^{-8} + 0.0898q^{-9} \tag{3.12}$$

$$C(q) = 1 - 1.108q^{-1} - 0.8104q^{-2} + 1.744q^{-3} - 0.293q^{-4} - 0.592q^{-5} + 0.1367q^{-6} \tag{3.13}$$

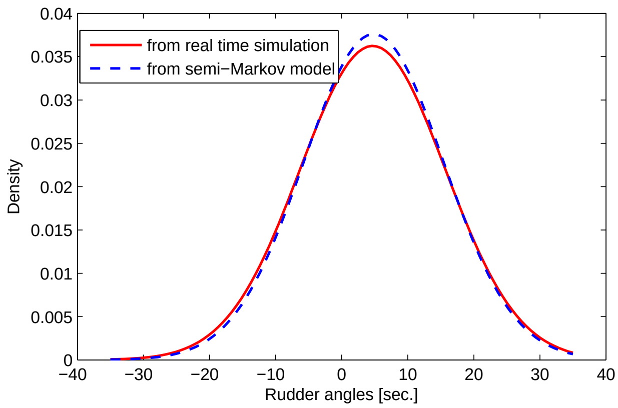

Figure 3.9: Comparison of rudder angle distribution between the real time simulation and the new model

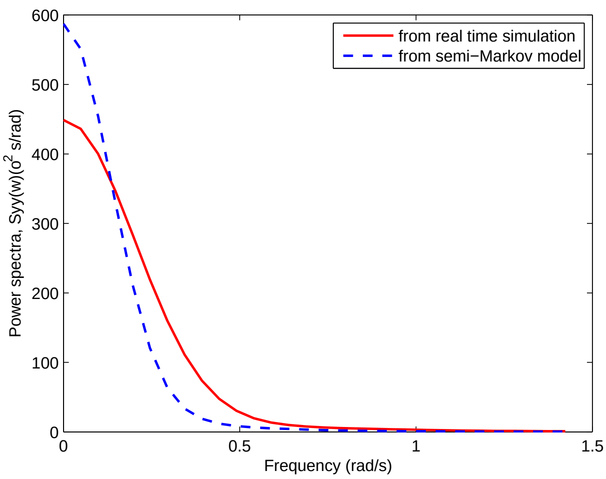

Figure 3.10: Comparison of rudder angle power spectra between two models

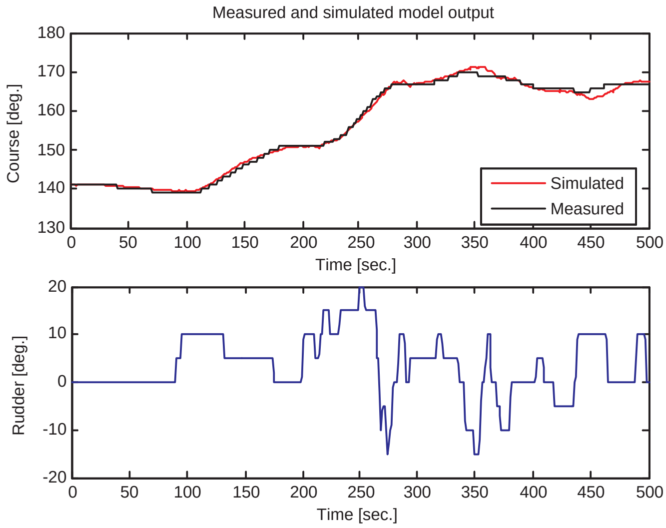

Figure 3.11: Comparison between the simulated and measured courses with the same generated rudder angle

It can be seen from Figure 3.11 that the simulated courses from the above ARMAX model compare well with those from the measurement (i.e. real time simulation) for the same generated rudder. However, there is still slight difference in aspect of a higher resolution in the simulated course. This requires more effort on finding the parameters of ARMAX model.

Having determined the semi-Markov model of rudder motions and the ARMAX model of the system, sequences of the course fluctuation can be achieved, which may represent "true" behavior of the ship-human performance. The ship positions can then be calculated from the regression formula as investigated in Figure 3.3. One of the most important aspects provided by the ship positions achieved from the regression formula might well be the validation with the use of extreme value distributions. The probability of the ship exceeding any margin of the designed channel section widths or navigable areas during a given period can be estimated using Eqs. 3.1 and 3.2.

3.5 Estimation of navigation limits

The previous section has dealt the method on generalization of real time simulation results of the maneuvering scenario for long-term channel study. Estimation of occurrence frequency, P_{oc} as described in Eq.3.2, of the scenario has been treated in this section.

To determine the frequency of occurrence of each maneuvering scenario for simulation experiment, a linear programming method was proposed by Briggs et al. (2003). The essential limitation of this method lies in the fact that it generates many unrealistic combination of environmental conditions. Moreover, unaccepted environmental combinations with regard to the ship maneuverability for navigation safety are not identified.

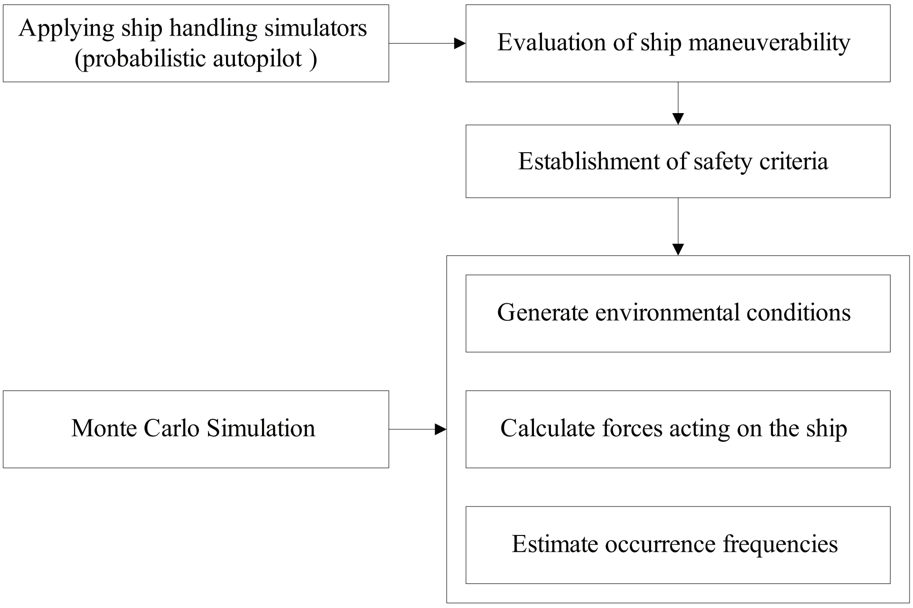

Figure 3.12: Procedures for estimation of navigation limits

This new method has been developed using Monte Carlo simulation in combination with a probabilistic approach. The method consists of several categories, as depicted in Figure 3.12. The final results would be useful not only for determining probability of ship accident but also for estimation of downtime and identification of navigational limits that amount to a straightforward optimal design of approach channels.

3.5.1 Previous works

The new method has been developed based on the useful investigation of the two following studies:

- Risk analysis of vessels exceeding horizontal boundaries in a channel (Welvaarts, 2001), and
- Probabilistic design of approach channel width (Giang, 2003).

Both the studies were carried out for the bulk carrier of 65,000 DWT at the entrance channel of IJmuiden port. The IJmuiden channel is about 25 km West of Amsterdam and has an azimuth of 100.5^o. In the first study, some navigation safety criteria were laid down on the basis of the steering and propulsion characteristics of the ship, including the maximum rudder angle use, the drift angle and the power burst. These criteria are presented in Table 3.1[2].

An investigation on the ship response as a function of external forces was carried out in the second research where the load limits that would prevent the ship sailing was defined. A probabilistic autopilot model of the ship handling simulator, which has been developed by the MARIN (Lan, 2003), was used for this investigation. Again, a critical point is how good the results derived from the probabilistic autopilot model should be verified using a real time simulator. Some results are given in Figure 3.13. It can be seen from this figure that the ship only being navigated with the forces acting on the hull

2. F is Feasible, no problem for ship maneuver; C is Critical, ship's passage might be attempted; U: is Unacceptable, ship's passage will not be attempted; and l: is half ship length

Table 3.1: Safety criteria relate the ship maneuvering

Criteria	Judgment[1]		
	F	C	U
Rudder angle 20^o when sailing with distances of	0-400m	400-550m	$> 550m$
Drift angle	$0 - 15^o$	$1 - 20^o$	$> 20^o$
Power burst with sailing distance	0-0.5l	$0.5l - l$	$> l$

are less than 2,000 kN; or the maximum moments are less than 180,000 kN×m. By contrast, several lower couples of the force and moment result in the same effect.

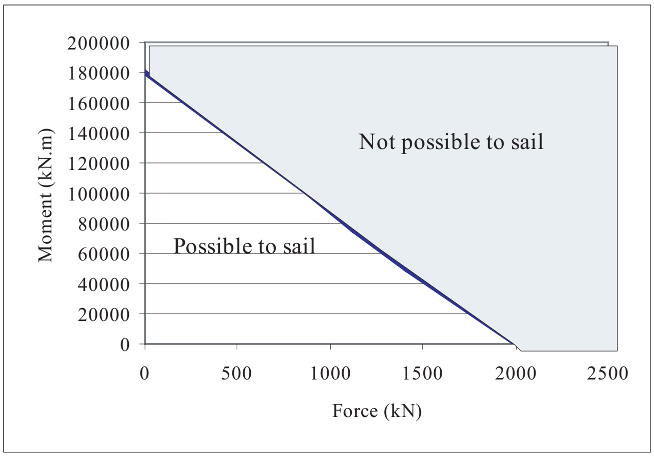

Figure 3.13: The navigation limits based on the forces acting on the ship for sailing speed of 10 knots (The figure created based on the results by Giang, H.H. (2003))

3.5.2 Establishment of navigation safety criteria

To establish navigation safety criteria, some assumptions have been made as follows:

- There is a boundary limit of the loads acting on the ship, so that the ship cannot sail in the case of any couple of the force and moment lie on or upper this boundary (see Figure 3.13);
- It can be seen that the ship seems very strong resisting the moment impact. When the ship is progressing in the channel, it is almost never the case that the resultant moment caused by environmental conditions is up to 50,000 kN×m. For example, if wave height Hs=3.5 m, wind speed 30 m/s and current 3 knots acting simultaneously in the same direction of 45 degree (the most dangerous angle for moment) on the ship, the total moment is only 49,000 kN×m. However, the above combination is never allowed in connection with the ship transit in the restricted channel. The effect of the moment on the ship maneuverability can, therefore, be neglected in this study; and
- The lower values around the boundary limits of the force are seen as maneuvering scenarios so that the ship can attempt to sail.

Table 3.2: Classifying safety criteria for bulk carrier 65,000 DWT by force impact

Maneuvering scenarios	Criteria (kN)	Remarks
Ao: not possible to sail	$F < 1000$	Safety factor = 2
$A1$: can attempt to sail	$600 < F < 1000$	The safety margin depends mainly on mariner's competence
$A2$: no problem to sail	$F < 600$	No problem for any mariner

Based on these assumptions and on the boundary limits defined in the above, the criteria can be formulated to classify the maneuvering scenarios, as presented in Table 3.2.

3.5.3 Calculation procedure

The calculation procedures consist of several steps as described in Figure 3.14.

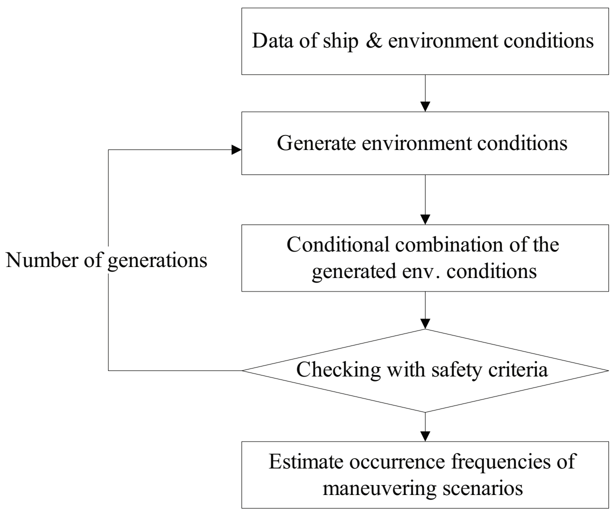

Figure 3.14: Calculation procedure

Generating environmental conditions

Environmental conditions (winds, waves and currents) of the IJmuiden channel have been gathered for this study, as presented in Appendix B. Data of winds, waves and currents are the tables of frequencies distinguished by classes of different directions and values.

Generation of winds and currents: the frequencies of winds and currents in all directions can be fitted to a certain distribution function, as presented in Figure 3.15, where "Chi2" distribution has been found for the wind speed. Based on that, one may first generate stochastically a value of wind or current speed according to the predefined distribution functions. Then, a uniform random number can be generated to obtain a desired direction by using the inverse transformation method (Wendy & Angel, 2002). To confirm the generated results, Chi-square test method could be useful. A Matlab Code has been developed for this purpose. It can be seen from Figure 3.16 that the generated frequencies of wind speeds compared well to those observed after the number of generations is 300.

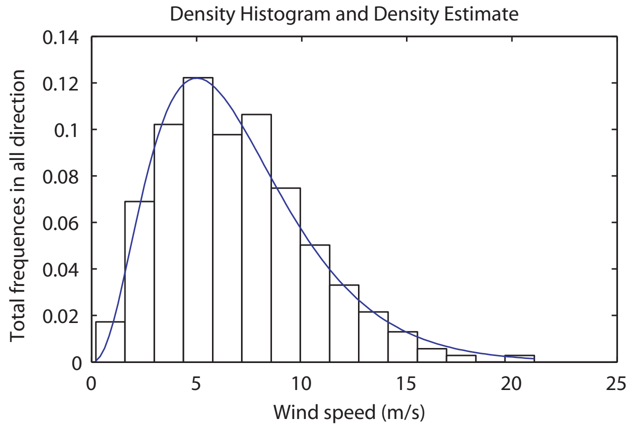

Figure 3.15: Frequencies of wind speed fitted to "Chi2"

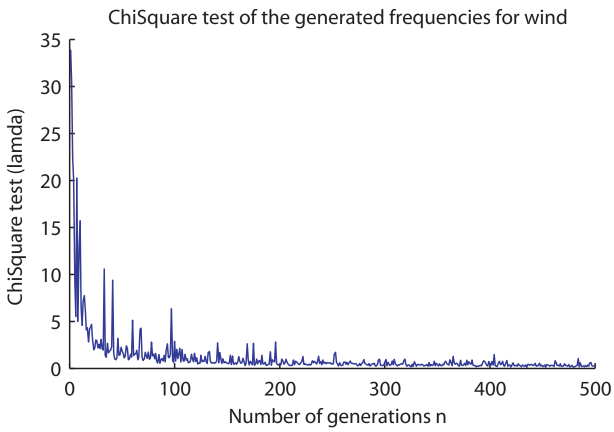

Figure 3.16: Chi-square test versus number of generations

The Chi-square, λ , is estimated by:

$$\lambda = \frac{\sum_{i,j}^{l,m} \left[p_o\left(i,j\right) - p_g\left(i,j\right)\right]^2}{p_o\left(i,j\right)} \tag{3.14}$$

where $p_o(i,j)$ and $p_g(i,j)$ are the observed and generated frequencies of the wind and current in class i and direction j, respectively; l, m are respectively the numbers of the value classes and directions.

Conditional generation of waves from wind conditions: this procedure aims at rejecting as many as possible undesired combinations in the maneuvering scenarios, as remained in the former approach. For instance, the combination of very low wind speeds but very high waves, which hardly ever occur, should be removed. To overcome this shortcoming, the physical relations between the environmental conditions should be defined. Those relations can properly be modeled by using probabilistic and mathematical tools.

Teng and Liu (2000) proposed a conditional probability function to examine the validity and accuracy of estimating the wave height from the corresponding wind speed distribution using long-term wind and wave data from five of the National Data Buoy Center (NDBC) buoy stations in the Pacific Ocean. The technique of estimating wave height distribution from wind distribution is to relate the marginal probability distributions of significant wave height, $P(H_s)$, and wind speed, $P(Wd_i)$, in terms of a parametric model of the condition probability of the wave height at given wind speeds, $P(H_s|Wd_i)$, as:

$$P\left(H_s\right) = \sum_{i=1}^{N} P\left(H_s|Wd_i\right)P\left(Wd_i\right) \tag{3.15}$$

The conditional probability $P(H_s|Wd_i)$ can be assumed to be Lognormal distribution such as:

$$P\left(H_s|Wd_i\right) = \frac{1}{H_s p\sqrt{2\pi}} \exp\left(-\frac{\ln H_s - q}{p}\right) \tag{3.16}$$

In which the wind speed is divided into N equal intervals; p and q are the parameters that can be determined from empirical coefficients. These coefficients in the nonlinear function can be numerically estimated from values of the mean and standard deviation of the wave height for various wind speed intervals. Figure 3.17, for example, presented the condition probabilities of the wave height with the wind speeds of 10 m/s, 15 m/s and 20 m/s for the IJmuiden channel applying the above-mentioned technique.

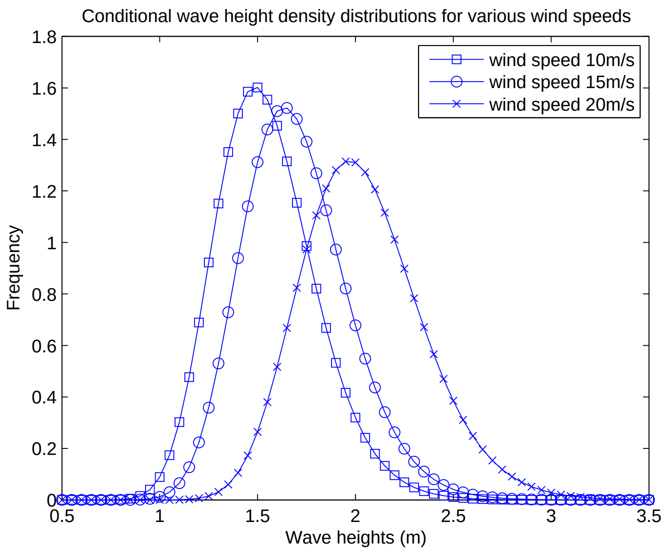

Figure 3.17: Conditional wave height for various wind speed fitted to Log-normal distributions assumed for the IJmuiden channel

Calculations of the forces and moments

The forces and moments acting on the ship for each ship passage are estimated according to the generated environmental conditions (winds, waves, currents and their directions), ship size and ship

Table 3.3: Frequencies of the maneuvering scenarios for the different approaches

Maneuvering scenarios	From the former approach	This study
Ao	0.0082	0.0010
$A1$	0.0804	0.1928
$A3$	0.9114	0.8062

speed. The total force exerted perpendicularly to the ship hull will, then, be obtained by synthesizing the individual forces of winds, waves and currents from the different directions. The mathematic models of environmental forces on the ship hull recommended by OCIMF (1977) are used, as described in Eqs. 2-13 to 2-21 in Section 2.5.2, in which the coefficients for wind and wave forces were derived from the Towing Tank Test Project at the Dutch institute MARIN (Giang, 2003) and coefficients for current forces were derived from the OCIMF (OCIMF, 1977).

Calculations of the occurrence frequencies of the maneuvering scenario

The occurrence frequencies of each maneuvering scenario are determined as:

$$f_{Ao} = \frac{n_{Ao}}{N} \tag{3.17}$$

$$f_{A1} = \frac{n_{A1}}{N} \tag{3.18}$$

$$f_{A2} = \frac{n_{A2}}{N} \tag{3.19}$$

$$n_{Ao} + n_{A1} + n_{A2} = 1 \tag{3.20}$$

where N is the number of environmental combinations, which are grouped into three maneuvering scenarios ($Ao, A1$ and $A2$); n_{Ao} is the number of times that the calculated force $F \geq$1000 kN, n_{A1} is the number of times that F lies in 600$\leq F <$1000, n_{A2} is the number of times that F is less than 600 kN.

Results

Table 3.3 shows the different results of the occurrence frequencies for the environmental conditions being calculated from the former approach (Briggs et al., 2003) and those from the conditional probability between winds and waves. A sample of environmental combinations in the scenario Ao for the conditional generation is given in Table 3.4.

3.5.4 Discussions

The environmental combinations can be established reasonably by applying the conditional generation of wind speeds and wave heights except the combination Ao_2 in Table 3.4. However it might be accepted with a certain small rate due to swell (developing wave after wind decayed). It is noted that swell wave can also be taken into account in the conditional probability in Eq. 3.16.

Much attention should be focused on the combinations between wave heights from 2-3 m and wind speeds from 15-20 m/s. These combinations lie somewhere around the boundary between maneuvering

Table 3.4: Environmental combinations in the scenario Ao for the conditional generation

Combination	Environmental conditions		
	Wind (m/s)	Wave (m)	Current (m/s)
Ao_1	17.176	2.503	0.493
Ao_2	3.134	2.328	0.552
Ao_3	19.246	2.959	0.137
Ao_4	19.683	2.547	0.000
Ao_5	18.177	2.633	0.611

scenarios of Ao and $A1$ and provide extremely important distribution functions concerning the ship course and position, from which the probabilities of the ship excursion from a predefined channel width will be estimated.

The major part of total forces in the maneuvering scenario Ao is contributed by waves. The minimum wave height must be more than 2.0 m in the maneuvering scenario Ao.

Downtime due to the so extreme weather conditions making it impossible for ship to sail can be obtained in cases of the total calculated force exceeding the criteria defined in Table 3.2. It is obvious that the higher criteria the maximum force, the safer navigation for the ship passage, but the higher downtime will then have to be accepted.

One thing we have to consider is how many hours should be allowed for the downtime when ship encounters the maneuvering scenario Ao. This depends very much on whether winds, waves or currents play a major part in producing high forces and on the duration of their effect. Individual forces of winds, waves and currents in each environmental combination have, therefore, to be sorted out and statistical analysis should be carried to define the time period of their impact on the basis of the recorded hydrometeorology data. It should be remembered that downtime might be due not only to extreme weather conditions but also to an acceptable probability of ship accidents. The latter has been discussed in the following chapters.

3.6 Conclusions

In this chapter, typically used procedures of the analysis of simulation results and a brief review of the existing approaches to generalize the simulation results for long-term risk assessment have been given. Development of a probabilistic model of autopilot or a cognitive simulation of navigator is a promising approach. However, such procedure requires reliable description of human behavior, which is still beyond today's possibilities. The other approaches focus on generation of ship passages and track distances using either the probabilistic-based model or the Monte Carlo method. However, they generally fail to achieve satisfactory model parameters.

The main body of this chapter presented a new method with the two newly developed models that can be used for long-term prediction of navigational risk in restricted channels. Information that can not be provided by real time simulation due to the necessary limitation number of trials can be realized in the new models that will thus provide more accurate readings of the system behavior. The parameters of the system outputs achieved from these models can satisfy the need for the several aspects of risk and consequence analysis in long-term study. However, the method is restricted to the problem when the trajectories of ship passage are "stationary" random process. Definition of the "stationary" random process of the ship trajectories is another important issue, as will be discussed in Chapter 4. This restriction produces issues that we will use to develop an improved comprehensive model in the future. First, the transition matrix should be time-dependence conditional probabilities. It means that the next state of the rudder is not only dependent on the present state but also the space (position) given that state. The calculation procedure is the same as presented in this chapter but greater complexity because more than one transition matrix is being estimated. Secondly, more efforts should also be made on the analysis of dependence between ship speed and rudder states.

There is a difficulty for engineering designers to define the appropriate orders (n_{ai}, n_{bi} and n_c), and the accurate parameters (A_i, B_i and C) of the polynomials in the ARMAX model of ship steering dynamic, as described in Eq. 3.3. However, this problem may easily be undertaken by consultation of automatic control system designers.

The method of estimating the frequency of navigation limits provides a rational and quantitative way for evaluating the effect of environmental conditions on the ship maneuverability by which downtime and probabilities of ship accidents for the lifetime of the channel can be determined. The results using this method are more reasonable than those presented in the literature because unrealistic environmental combinations can mostly be rejected. The advantage of the method is that a lot of simulation runs can be reduced and maneuvering scenarios will be distinguished by taking into account the behavior of ship maneuverability.

Chapter 4

Integration of the navigation risk along the channel

[1]

4.1 Introduction

Recall from the previous chapter that the main application of ship handling simulators in waterway design aims at indicating the ship maneuvering area and possible accident occurrence in relation to a certain navigation condition. The estimation of accident possibility along the waterway on the basis of ship track and swept path is something that has drawn much attention to researchers. In current practice, the most common estimation methods are those that consider critical points of the waterway only. Such practice can result in the waterway of questionable safety because of missing the information on the process of ship passage through the waterway (Gucma, 2005). This method thus concentrates on defining the individual starboard and port side distribution functions. The probability of collision or grounding in each of the sections can then be computed by defining the lateral limits exceeding the navigable zone in the Gaussian distributions (Iribarren, 1998). The essential limitation of these methods lies in the fact that there is interdependency between transits in subsequent cross sections of a waterway. The analysis of the separate cross sections can only give separate estimates of the probability of exceeding the channel border in each particular cross section, it can never indicate for the channel as whole (PIANC, 1992). A relatively simple way of determining the risk level of the entire waterway is by dividing it in a few homogeneous parts then determining for each part the probability of the waterway border being exceeded. The length of an independent part relates to a half wavelength of the ship tracks in the waterway, which was estimated by Vrijling (1995) on 4-5 ship length. Again, the critical point resides in the fact that the estimated wavelength of the ship tracks was defined simply by using judgment and expert rating based upon the simulation runs. The other method using a different focus was presented by Burgers and Kok (1989). Essentially the principle of this method

1. Excerpts from this chapter were published as:

Quy, N.M. *et al.*, 2007. On the probabilistic analysis of non-stationary ship maneuvering results for waterway design. In *Proc.* 31st *PIANC Congress* (pp. 1-4). Estoril: PIANC.

Quy, N.M. *et al.*, 2007. On the statistical analysis and probabilistic modeling of ship maneuvering results for waterway design. In *Proc. Maritime transport 2006* (pp. 189-198). Barcelona.

is based on the interdependence of successive passage sections, either using a linear regression model or Markov chains to determine the interdependency of transits in subsequent cross sections. However, this methodology still needs considerable effort to develop and it is also very costly because it requires the execution of a large number of the real time simulations (Iribarren, 1998).

The effort of this chapter will concentrate on development of a new method of interpreting the ship maneuvering results to integrate risk along the waterway, the so-called "entire risk". To do that, we assume that trajectories of ship track or swept path are considered as the response ensemble of either a stationary or a non-stationary random processes, the study then concentrates on estimating the response characteristics by analyzing their power spectrum density. On the basis of the estimated results and applying the Poisson model, the probability of a ship exceeding the channel limits that will occur in a certain period of time (duration of a ship passage) can be determined, which is considered as an indication of the entire risk.

4.2 Stationary process of ship-pilot behavior

The balance between the competence required by navigational environment and the competence that a mariner can attain for safe ship operations should be maintained (Murata & Kobayashi, 2003). To ensure that the required navigational safety is achieved, the mariner must keep the ship stable so that the fluctuations during the ship maneuvering process are minimized in order to keep the track as close as possible to the desired track throughout the transit. The magnitude of these fluctuations varies, depending not only on the different environmental conditions but also on the different competencies of mariners, which may be randomly changing for one mariner with different tests in the same condition. However, the fluctuations for a certain maneuvering condition and one mariner will become "stable" or "stationary" after he has taken several tests; in other words, "non-stationary" or "unstable" process of ship maneuver should be avoided. It is therefore possible that the ship response (track, swept path, course, etc.) can be viewed as the output signals of a random stationary process and, as indicated above, as having the Gaussian distribution.

Real time simulation results (Lan, 2003; Nakamura, 2005) were collected for the verification of the above statement; one of which has been presented in Section 4.2.3 as a typical example. The method so-called "Reserve Arrangement Test" proposed by Bendat and Piersol (1986), as given in Appendix C, can be used as a useful tool for detecting stationarity or non-stationarity of any random process.

4.2.1 Properties of a random Gaussian stationary process

In engineering design the whole channel should be designed according to different parts so that the variations in local maneuvering conditions of each part during a transit can be neglected, and the technical specifications (width, depth, slope, ...) assigned along each part should be equal. Assuming that a real time simulation is set up for a part of the channel with the length L (m), a mariner completes the trial with the period T_h (sec), and $x_i(t)$ is the sample record (sample function) of the ship which is the ship position recorded at predetermined time intervals during trial i^{th}. Let us assume that the ship exceeds the channel border rarely that successive up-crossings of a specified level are independent and can therefore be modeled as Poisson processes. Under these assumptions probability $P(b, T_h)$ that the response ensemble $\{x(t)\}$ (the symbol $\{\}$ denotes an ensemble with the number of the sample records is (simulation trials) n_s, we omitted n_s to simplify the notation) will cross at level $x = b$ (b is considered as a half of the channel width) at least once during a period T_h(sec) given by Lin (1967) as:

$$P(b, T_h) = 1 - exp(-\nu_b T_h) \tag{4.1}$$

where ν_b is the mean rate of crossing with level b, for the Gaussian response process, ν_b can be expressed as:

$$\nu_b = \frac{1}{2\pi}\sqrt{\frac{m_{2x}}{m_{ox}}} exp\left[-\frac{1}{2}\frac{(b-\mu_x)^2}{m_{ox}}\right] \tag{4.2}$$

here m_{ox} and m_{2x} represent zero and second moments of the ensemble $\{x(t)\}$, respectively and μ_x represents the ensemble mean value of $\{x(t)\}$, which can be determined by the following equations:

$$\mu_x = \frac{1}{n_s T_h}\sum_{i=1}^{n_s}\sum_{j=1}^{T_h} x_i(j) \tag{4.3}$$

$$m_{ox} = \int_{-\infty}^{\infty} S_{xx}(\omega) d\omega \tag{4.4}$$

$$m_{2x} = \int_{-\infty}^{\infty} \omega^2 S_{xx}(\omega) d\omega \tag{4.5}$$

where n_s is the number of simulation trials; $S_{xx}(\omega)$ is the power (response) spectral density(PSD) describing the distribution of the mean-square value of the ensemble $\{x(t)\}$ over the frequency domain. Based upon the ensemble $\{x(t)\}$, $S_{xx}(\omega)$ can be determined by digital computer using fast Fourier transform algorithm (Bendat & Piersol, 1986).

4.2.2 Record length requirement

One of the most important features to this approach is to determine a total record length requirement, T_r, of the response ensemble (i.e. a minimum total number of observations, N, in an ensemble) to obtain a predetermined degree of accuracy of the power spectral estimate. It is somewhat similar to the required number of trials n_s per environmental condition, generally between 8 and 15 (Iribarren, 1998), in the other methods. The relationship between them can be clearly expressed by:

$$N = \frac{T_r}{\Delta t} = \frac{T_h}{\Delta t} n_s \tag{4.6}$$

where Δt(sec) is the time interval for which the observations are recorded; N is the total number of observations.

In practice, to measure a precision of the spectral estimate, its normalized random mean square error (rms) is widely used. A minimum total number of observations required for a specified rms error, ϵ, can be determined by using the following equation (Priestley, 1994):

$$\epsilon^2 = \frac{3.5044}{(NB_h)^{5/4}} \tag{4.7}$$

where B_h is the spectral bandwidth (SB), it is measured (Priestley, 1994) as the distance between the half-power points ω_1, ω_2 ($\omega_1 < \omega_0 < \omega_2$; ω_0 is the peak frequency) which are defined by $S_{xx}(\omega_1) = S_{xx}(\omega_2) = 0.5S_{xx}(\omega_0)$. Thus, $B_h = \omega_1 - \omega_2$. In case the PSD has a single peak at $\omega_0 = 0$, B_h is thus approximated to ω_2 (Priestley, 1994).

Eq. (4.7) implies that for a prescribed degree of the precision, N can be estimated as a function of the spectral bandwidth B_h. Unfortunately, this is not always possible since B_h is usually unknown parameter prior to data collection. Certain assumptions based upon a prior knowledge of the spectral estimates and engineering judgement should therefore be required.

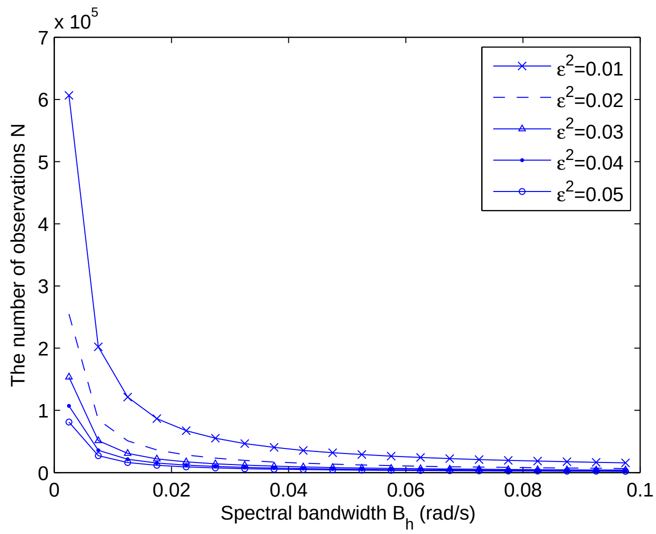

Figure 4.1: Relationship between N and B_h for various ϵ^2

However, in preliminary stage (e.g. for setting up experiments), we are hardly ever interested in estimating just one value of N; in general we would wish to estimate N over a possible range of B_h (because data are usually limited and actual parameter of B_h is likely never known). Then we can select a value of B_h in lower bound and increase N for a higher precision. Concerning the study under discussion, it is highly probably supposed that the response ensemble has commonly very long wavelength components; its spectral bandwidth is mostly lower than 0.1 (rad/s). Figure 4.1 shows the relationship between N and this range of B_h for various normalized rms error values. For example, in a specified case, we wish to achieve $\epsilon^2 = 0.01$, using prior information we may choose B_h, let's say between $0.005 - 0.01$. From Eq. (4.7), a value of N can be defined between 10,000 and 15,000 for the first trials.

4.2.3 Real time simulation example

A real case is used for analysis and verification of the foregoing approach. The real time simulations were carried out at the Southern entrance channel to Ennore Coal Port, India (Lan, 2003). The modeled channel with the length of 6 km is aligned 345° North. The simulations were executed with a bulk carrier 65,000 DWT by four local pilots. A total of 37 trials with various environmental conditions were performed, in which 8 succeeded swept path tracks of the extreme conditions from $km + 1,000$ to $km + 6,000$ were taken for this study. Since the procedure of calculation on the starboard side is the same as those on the port side, only the latter is considered in the following; an ensemble of the ship tracks is described in Figure 4.2.

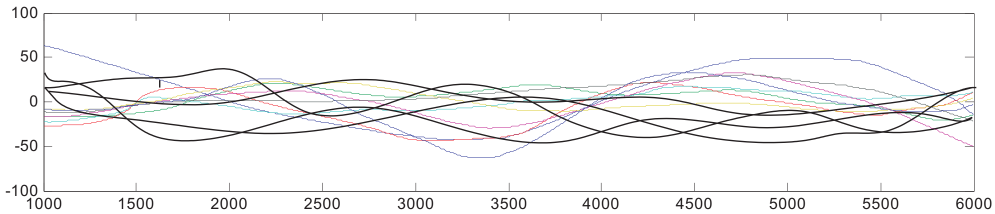

Figure 4.2: Sample records of ship track with additional post-processing (trial condition: wind $7Bft$ (SE), wave $H_s = 2m$ (SE) and current velocity $0.6m/s$ (SN))

Test for stationarity

Data of the port swept path from 8 trials are considered as a response ensemble $\{x(t)\}$ (i.e. 8 sample records). For each having $N = 900$ data values recorded at time interval $\Delta t = 1$ (sec.) thus making the total time period of a transit $T_h = 900$ (sec.).

Divide the ensemble record into 90 equal time intervals, the number of the observations in each interval therefore is $(900/90) \times 8 = 80$. Compute a mean square value for each interval $(\bar{x}_1^2, \bar{x}_2^2, \ldots, \bar{x}_{90}^2)$ and align these values in time sequence. Count the number of times that $x_i > x_j$ for $i < j$ (each such inequality is called a reverse arrangement). From Eq. (C.3) in Appendix C, the total number of reverse arrangement, denoted by A, is 1786.

Now let it be hypothesized that the ensemble is stationary. From Table C.1 in Appendix C, for $\sigma = 0.1, A_{90,1-\sigma/2} = A_{90,0.95} = 1766$ and $A_{90,\sigma/2} = A_{90,0.05} = 2238$. Hence the hypothesis is accepted at the level 1% of significance, since $A = 1786$ falls within the acceptance region between 1766 and 2238. Meaning that the response ensemble is identified as being stationary.

Normalized rms error of the power spectral estimate

As revealed in the previous section, before the normalized rms error being able to be evaluated, the spectral bandwidth has been preliminarily defined. First, using the ensemble $\{x(t)\}$, determine an estimate of $S_{xx}(\omega)$, the result is as shown in Figure 4.3. Then we try to estimate B_h based on the estimated spectral density $S_{xx}(\omega)$. As the definition of B_h, the value of B_h may be derived from Figure 4.3 about 0.04. Hence, for $N = T_h \times n_s = 7200$ and from Eq. (4.7), ϵ^2 will be 0.0378. Now, one may wish to gain ϵ^2 with a precision of 0.05 only, the value of N needed is about 5070 and the respective number of trials will be reduced to six. It can be realized that the precision of this approach depends only on the number of the observations, whereas the number of trials must be required large enough in the other methods.

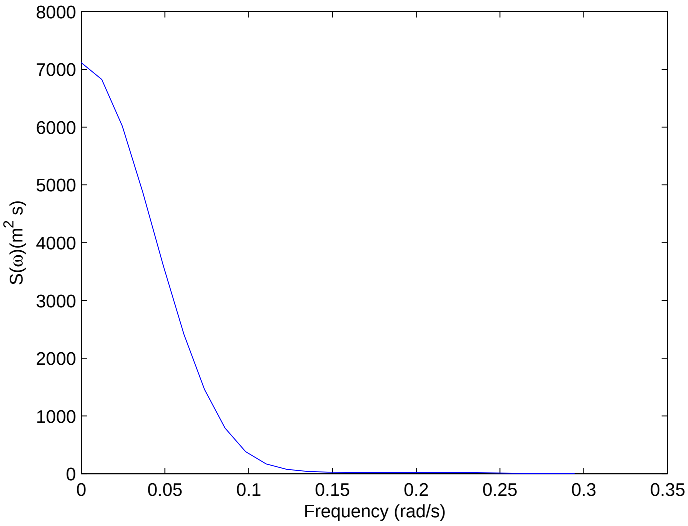

Figure 4.3: Power spectrum of the ensemble of the swept path

4.2.4 Results and comparison

When the estimate of $S_{xx}(\omega)$ is available, from Eqs. (4.1) to (4.5) the probabilities of ship grounding can be quickly determined for a certain half of channel width. These probability results versus various half channel widths are plotted in the upper curve of Figure 4.4.

As discussed above, if the entire channel is viewed as consisting of a number of homogeneous parts, which relate to a half wavelength of the ship swept path Vrijling (1995), the probability of ship grounding can also be expressed by:

$$P(b, T_h) = \left(\frac{L}{T_h}\right)\left(\frac{T_c}{2}\right)\int_b^{\infty} f(x)dx \tag{4.8}$$

where $f(x)$ is the density function of ship positions (swept path), which can, as indicated, be well described by Gaussian distribution; T_c is the mean zero-crossing period of the wavelength given as:

$$T_c = 2\pi\sqrt{\frac{m_{ox}}{m_{2x}}} = 2\pi\sqrt{\frac{371.25}{2.34}} = 79.13s \tag{4.9}$$

The results for various half channel widths are also plotted in the lower curve of Figure 4.4. It can be seen from this figure that these results become very slightly different from those computed by the proposed approach when b is greater than 110 m. The values of b within this area is very close to the designed point since an acceptable probability of ship grounding is quite low, let us say about 3×10^{-5} (Vrijling, 1995).

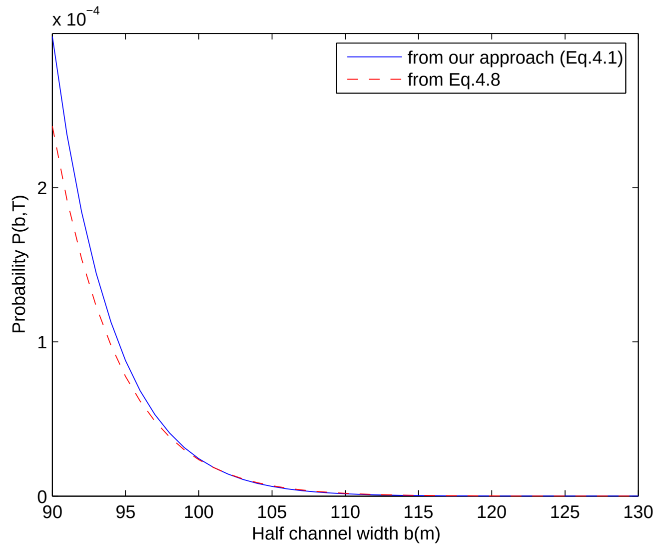

Figure 4.4: Probabilities of ship grounding vs. half channel width

4.3 Non-stationary process of ship-pilot behavior

The response process $\{x(t)\}$ may be non-stationary in such a special case that meteorological and hydrodynamic conditions vary so frequently and considerably along the channel (e.g, a ship passes through a sharp bend). However, it is highly likely that the response process $\{x(t)\}$ may become stationary when the mariner is getting adapted to such condition. This can be explained by realizing that the trajectories of ship track and swept path could be non-stationary random process when the balance between the competence required by navigation condition and the mariner competence would no longer be maintained along the passage. The output signals of the ship maneuvering results should therefore be treated as a non-stationary random process. This phenomenon was observed at the real time simulations of the Piastowski canal in Baltic Sea with the use of a gas vessel, as shown in Figure 4.5. However, much effort should be made to investigate the characteristics of ship response in this particular case.

4.3.1 The analysis of a non-stationary process

Similarly to the analysis for stationary response process $\{x(t)\}$, the core of this approach is to determine the power spectrum for non-stationary process of the sample records $\{x(t)\}$ by using the Wigner distribution (WD). The analysis procedures of the WD for non-stationary processes have essentially the same type of physical interpretation as the spectra of the stationary processes, the main distinction being that whereas the spectra of a stationary process describes the power-frequency distribution for the whole process (i.e. over all time), the WD is time dependent and describes the local power-frequency distribution at each instant time (Bendat & Piersol, 1986). The WD of a real signal $x(t)$ is given by Mecklenbrauker and Hlawatsch (1997) as:

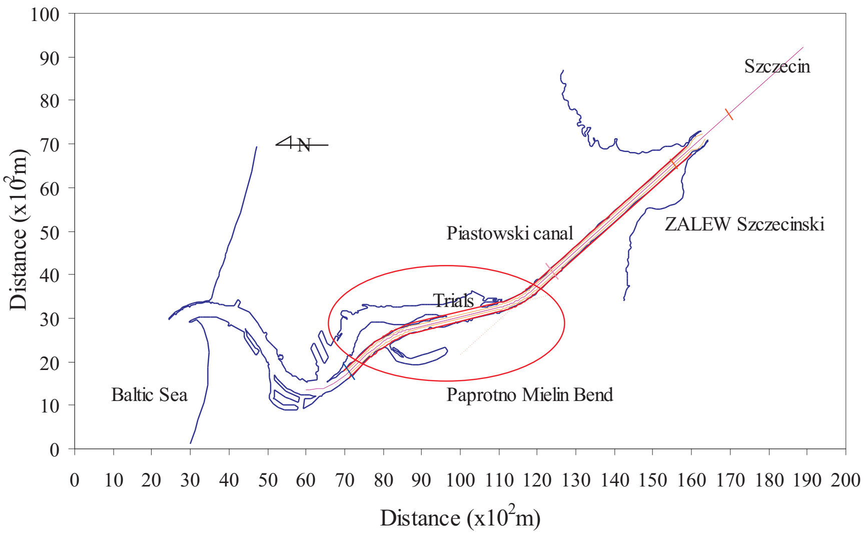

Figure 4.5: The layout and investigated band part of the Piastowski canal in the Baltic Sea

$$WD\,(t,\omega) = \int_{-\infty}^{\infty} s\,(t+\tau/2)s^*\,(t-\tau/2)\,e^{j2\pi\omega\tau}d\tau \tag{4.10}$$

where $s(t)$ is the analytic signal associated with $x(t)$; $s^*(t)$ represents the complex conjugate of $s(t)$, which can be defined using the Hilbert and Fourier transform techniques, which are available in the Matlab Signal Processing Toolbox.

The response process $\{x(t)\}$ is a non-stationary when viewed as a whole. However, in the (t,ω) plane it may be possible to separate the non-stationary power spectral function into piecewise stationary segments. The location and the number of segments for separation can be found by detecting the WD (Bendat & Piersol, 1986). So integration of $WD(t,\omega)$ over any time interval gives the spectral density function of $\{x(t)\}$ at frequency ω. Also integration of $WD(t,\omega)$ over all T_h gives the power spectral density function, $\overline{S}_{xx}\,(\omega)$, of $\{x(t)\}$.

$$\overline{S}_{xx}\,(t_1 \leqslant t \leqslant t_2,\omega) = \int_{t_1}^{t_2} WD\,(t,\omega)\,dt \tag{4.11}$$

Probability of the ship excursion from the borders for any part of the waterway as defined in Eq. (4.1) with the parameters determined in Eqs. (4.2) to (4.5) will therefore be applicable to the present context. Eq. (4.1) can be rewritten as (Corotis et al., 1972):

$$P\,(b,\Delta t = t_2 - t_1) = 1 - \exp\left\{-\int_{t_1}^{t_2} \nu_b(t)dt\right\} \tag{4.12}$$

4.3.2 Results

An ensemble of 30 trials of the ship passage handled in the simulated wind condition (wind speed 15 m/s from West) was used for the analysis of its non-stationary power spectrum.

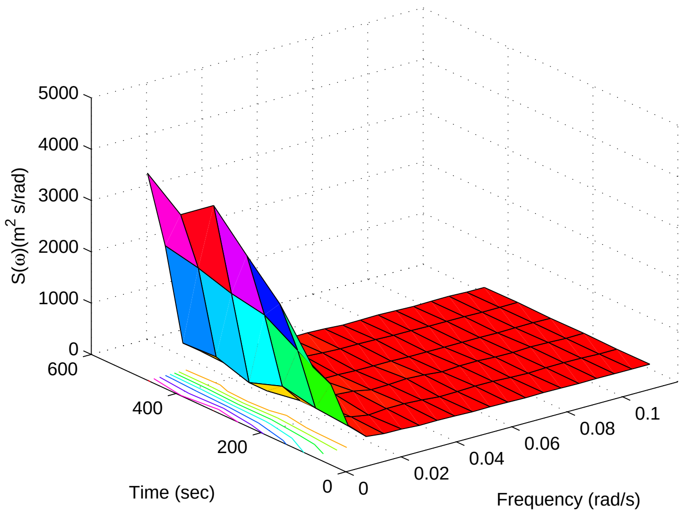

Figure 4.6: Time-dependent spectral density function of the response ensemble (at Paprotno Mielin bend part)

It was observed that almost all the ship tracks deviated from the referred line when the ship passed through the bend. This can also be seen in the analyzed result of the non-stationary power spectrum of the response ensemble as described in Figure 4.6, where the power spectrum density in the first part is much smaller than those in the latter part of the bend. The time axis, with zero value calculated at starting investigated point of the trials, is defined by ratio of the channel distance to the average ship speed.

Having determined the time-dependent spectral density of the response ensemble, the probability of the ship excursion from a certain half width for a give part of the channel can be estimated using Eq. (4.12).

4.4 Conclusions

In current practice, the conventional estimation methods consider critical points along the waterway only. Such practice can result in the waterway of questionable safety because of missing the information on the process of ship passage through the waterway. This chapter proposed a new method to integrating risk of entire waterway using a spectral analysis technique in combination with a probabilistic approach. The new method is based on the ship maneuvering data (tracks, swept paths, courses, etc.), which can be viewed as the output signals of a random process, obtained from real time simulation experiments. The calculation procedure of integrating risk for entire waterway when the process is stationary as the following steps:

- Using the Reserve Arrangement Test to detect stationarity of the ship maneuvering data;
- Estimating the power spectral density function, $S_{xx}(\omega)$, based on the data of initial simulation runs;
- Preliminarily determine a spectral bandwidth B_h using the above estimated $S_{xx}(\omega)$;
- Estimating the record length requirement as well as the minimum number of simulation runs for a given rms error;
- Applying Eqs (4.1) to (4.5) to determine the probability of the ship exceeding a certain level of half waterway width, which is considered as an indication of the risk for entire waterway.

However, even if the process is non-stationary, there is a possible solution to this problem, as presented in Section 4.3. The core of this approach is to determine the power spectrum for non-stationary process of the sample records $\{x(t)\}$ by using the Wigner distribution (WD) that is time-dependent spectrum and describes the local power-frequency distribution at each instant time (Bendat & Piersol, 1986).

It can be concluded that the ship maneuvering process will attain stationarity when the balance between the competence required by navigation condition and the mariner competence is maintained. The method could also be useful for the evaluation of the mariner competence by exploring behavior of power spectral density function of the ship maneuvering process along the waterway.

Chapter 5

Modeling of ship motion response for channel depth design and operation

[1]

5.1 Introduction

In the two previous chapters methods for estimating the overall and entire risks have been developed for two types of accidents, possibility of running aground on a bank or collision with a fixed object due to the ship excursion from a navigable area. The results could be useful for designing waterway widths associated with an acceptable risk level. This chapter involves in channel depths and deals with modeling the ship motion responses induced by waves for both aspects of channel operations and optimal designs.

The optimization of channel depths is aimed at determining a depth to balance between the benefit of increment in transport capacity, downtime reduction and increase in costs of initial/maintenance dredging for a long-term channel project. It should be realized that the optimization of channel depths in long-term requires a guidance for minimum underkeel clearance allowances for the entrance accessibility to facilitate a required navigation safety. A level of the safety for the accessibility, in this context, can mainly be expressed in terms of probability of the ship grounding. From this point forward we will consider the two following questions:

- How should the water depth and the transit conditions (sailing speed and minimum underkeel clearance) be in combination to adapt to wave conditions for a safe transit?
- How should a channel depth be for trade-off between the required depth and the navigation safety?

---

1. Excerpts from this chapter were published as:

Quy, N.M. *et al.*, 2007. Parametric modeling of ship motion responses for risk-based optimization of entrance channel depths. In *Proc.* 11^{th} *World Conference on Transport Research* (paper ID-212). University of California, Berkeley, USA.

Quy, N.M. *et al.*, 2007. Modeling of ship motion responses and its application to risk-based design and operation of entrance channel depths. *Journal of Maritime Research*, 4 (2), 47-62.

The first question deals with the establishment of a reliability policy for ship entrance, while the second question relates to a long-term optimization of channel depths.

Recall from Chapter 2 that the determination of a channel depth and an allowance for underkeel clearance to prevent accidents due to grounding depends on many factors including ship draft, squat, water variations, wave-induced vertical motion of the ship and other reservations; such as advanced maintenance, bottom type and dredging error. Commonly used formula to determine underkeel clearance allowance is an expression of Z as given here:

$$Z = d + H_t - (T + S_{\max} + \beta) \tag{5.1}$$

where Z is the limit state function, a failure occurs when Z has negative value; d is the channel depth to an authorized level (m), considering dredging error and the effect of siltation; H_t is the tidal elevation above the chart datum; T is the fully loaded draft of design ship (m); $S_{\max}$ is the maximum sinkage due to squat (m); β is the vertical motion response due to wave (m). Other factors with minor effects were omitted in this equation.

As pointed out in Chapter 2, the present design guidelines for underkeel clearance allowances for coastal entrance channels and shallow waterways are not comprehensive and practical (Demirbilek & Frank, 1999). One of the most important aspects is the prediction of the wave-induced vertical motion, β, for "short-term" establishment of accessibility entrance policy as well as "long-term" optimization of channel depth, which has been received a lot attention. In the absence of reliable information on waves and ship response, a simple general guideline for minimum depth clearance requirements in channels influenced by waves is given by PIANC (1997). It is defined by ratios of water depth to ship draft for different significant wave heights. The wave periods and directions are unfavorable. It should be mentioned here that the PIANC guideline on design of approach channel is now under review to be updated and expended by its Working Group "MarCom WG 49." Whereas U.S. Army Corps of Engineers (USACE, 1998) states that "net depth allowance for waves is $1.2H_s$ for deep-draft and $0.5H_s$ for shallow-draft channels". It should be noted that the wave period contributes a certain effect to ship motion. Hence, an adequate guidance for ship accessibility, the so-called accessibility policy, should consider wave conditions (both H_s and wave period, T_z) in association with transit conditions (sailing speed and minimum underkeel clearance) for the navigation safety.

There has been a growing tendency in the application of the above-mentioned formula with the aid of a probabilistic approach to the risk-based optimization of entrance channel depths both in design (Andrew & John, 1998; Briggs et al., 2003; Vantorre & Laforce, 2002) and navigational operation (Howell, 2002; Moes et al., 2002; O'brien, 2002). Following this approach all of the parameters in Eq. 5.1 are considered as stochastic variables and can then be described by probability distribution functions. The probability of failure (i.e. ship grounding) is determined on the basis of Monte Carlo simulations. Random values are drawn from the stochastic input variables which are used to compute Z. A failure occurs when Z has a negative value. Very often fluctuations or variations of bed level, tide and siltation are assumed to have a Gaussian distribution. Probability distribution of $S_{\max}$ can be defined from the found probability distribution of the ship speed during the transit. For the probability distribution of the wave-induced motion of a ship, a Rayleigh distribution was used by some authors (Journee, 2002; Kristiansen, 2005); some others assumed it as a Poisson distribution (Andrew & John, 1998; Vantorre & Laforce, 2002). On the top of that this requires a reliable estimation of the ship vertical motion responses or characteristics due to the wave effects, as has been discussed in the following.

Recent efforts have focused on developing a system to predict ship dynamic underkeel clearance (DUKC) along ship passage. The predicted results are implemented by using a numerical ship motion model and real time measurements of wave conditions in combination with probabilistic computation (Briggs et al., 2003; Moes et al., 2002; Vantorre & Laforce, 2002). Based on these results, a minimum underkeel clearance allowance can be selected, which indicates a safety level of a particular channel transit. However, the costs for installation and operation of such systems are still prohibitive to developing countries like Vietnam. Moreover, this system can not be applicable during design stage.

This chapter is mainly based on the papers published in (Quy et al., 2006; Quy et al., 2007d; Quy et al., 2007c). Section 5.2 thoroughly reviewed the existing approaches used to model the ship motion response in waves; then a new method dealing with this problem as a central part of this chapter was presented. In Sections 5.3 and 5.4, some applications of this model for assessment of ship grounding risk as well as long-term optimization of channel depths, as posed in the two above questions, were discussed. A numerical example has been implemented to qualify the developed model, as presented in Section 5.5. Finally, some conclusions for this chapter were given in Section 5.6.

5.2 Modeling ship motion response

5.2.1 Introduction

The response spectrum of wave-induced ship motions, $S_r(\omega_e)$, can be achieved either from towing tank experiments or by numerical models based on the ordinary or the modified strip theory. Following these approaches, the response spectrum is, however, only obtainable for a particular transit condition and a specified sea state. While for a long-term assessment of a ship response, much broader sea states and continuous variation of the parameters V (ship speed) and T (ship draft) are to be requested (Cramer & Hansen, 1994). Moreover, these two approaches can not account for uncertainties present in these parameters in calculating the response spectrum, and later applying to performance of risk analysis. Hence, a demand is emerging for a high resolution and continuous description of the response spectrum for the problem at hand. A simple linear regression model of the response spectrum related to the frequency wave spectrum was presented by Savenije (1995), as has been discussed in the following section. The regression coefficients of the model depending on the transit conditions are defined by minimizing the mean squared error between the observed data and the predicted model values. A more advanced model was demonstrated by Cramer and Hansen (1994). The authors proposed a stochastic field model in the modulus squared of the transfer function $H(\omega_e)$, which is defined as a ratio of ship motion to wave amplitude for a given wave encounter frequency, and then by use of the Kriging technique to better minimize the variance of the estimate error. However, as pointed out by the

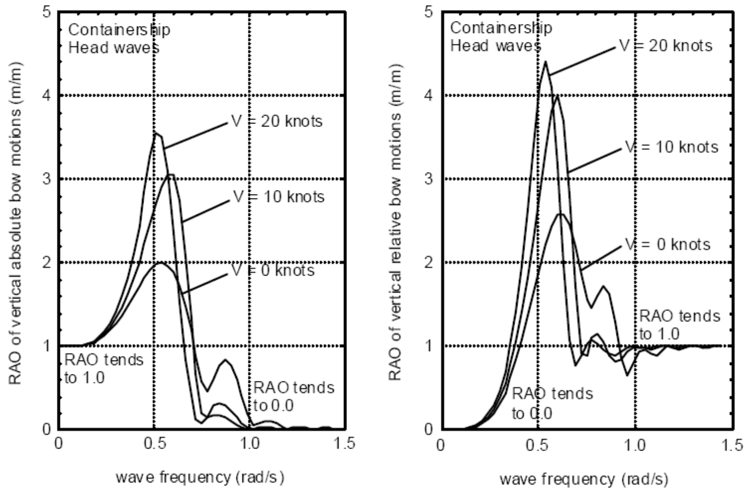

Figure 5.1: Absolute and relative vertical motions at the bow (Journee, 2002)

authors, there is a significant challenge to formulate a general model for the stochastic field governing the modulus squared of the frequency response function. Unfortunately, no numerically measured error for the qualification of these models has been found in the published papers.

Most recently, U.S. Army Engineer (USACE) Research and Development Center has been developing a ship motion response model to use on the ship simulator. However, according to USACE (2006), this model is still considered a research tool and needs further verification.

5.2.2 The wave-ship motion regression model, HARAP

A linear model between wave height and ship motion was developed by AVV Transport Research Center, the Netherlands. This model is currently used in the computer program HARAP (HARbour APproach) (Vrijling, 2004) as an indispensable part of a risk-based prediction system for real time operation of channel depths in the port of Rotterdam (Thompson-Clarke, 2007).

Large ships only react to relatively long waves, like swell. If the shapes of the long wave spectra do not fluctuate much, they could be described by one parameter as an example for the case for the port of Rotterdam (Bouw, 2005). A characteristic wave height of the low frequency wave energy, H_{E10} is used as a parameter of the regression model. The shape of the ship motion spectrum is obtained on the basis of the wave spectrum and the Response Amplitude Operators (RAO) function, which is so-called transfer function. In the case of Rotterdam it is possible to describe the motion spectrum also with one parameter, β_s, the significant vertical ship motion.

To determine the ship motion spectrum as well as to find the linear relation between H_{E10} and β_s, a numerical model of ship vertical motion, named “SEAWAY” (Journee, 2001), was used. The SEAWAY is frequency-domain ship motion model, based on the modified strip theory, to calculate the wave-induced loads and motions with six degrees of freedom of hull ships. The program has been validated for the motion calculation in a very shallow water area (Vantorre & Johan, 2003).

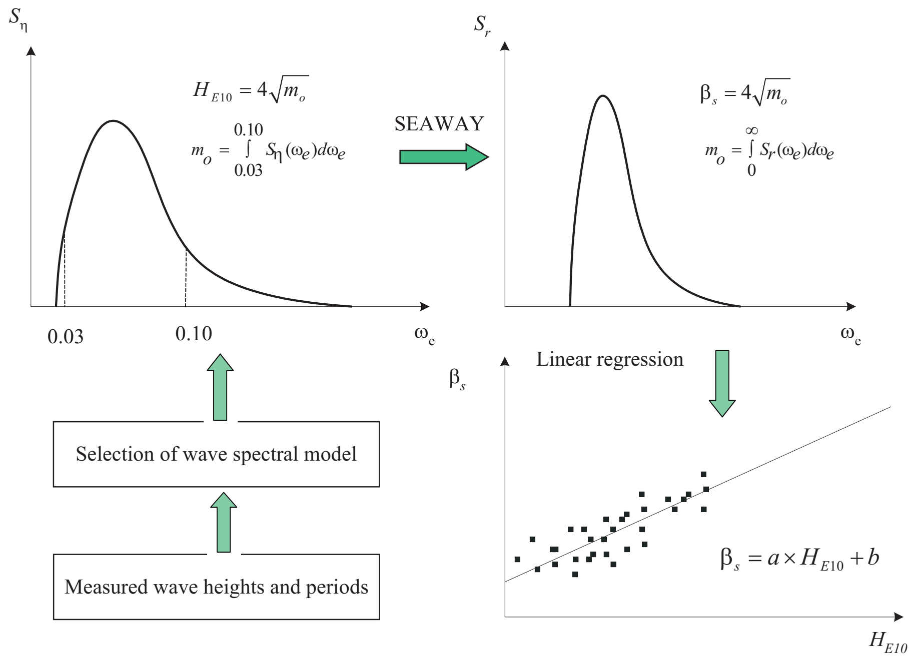

Figure 5.2: Calculation procedure of the wave-ship motion linear model (HARAP)

The output of SEAWAY consists of Response Amplitude Operators for a particular sailing speed, depth/draft ratio and approach angle of the waves with respect to a specified ship. The RAO function gives the relation between a wave spectrum and a motion spectrum of the ship. Figure 5.1 shows, as example, the speed dependent transfer functions of the absolute and the relative vertical bow motions of a container ship in head waves.

Having the estimated RAO function, the ship motion function can be determined as a function of the measured wave spectrum. Finally, the significant vertical ship motion, β_s, can be estimated from the wave height H_{E10} by doing a linear regression method, as described in Figure 5.2. It is obvious that the more available measured wave spectrum the more accurate the linear regression model achieved.

The linear regression model between β_s and H_{E10} can be expressed as:

$$\beta_s = a \times H_{E10} + b \tag{5.2}$$

$$\sigma_s = a_1 \times H_{E10}^2 + b_1 \times H_{E10} + c_1 \tag{5.3}$$

where β_s is the significant vertical motion; σ_s is the standard deviation of the normally distributed scatter around the regression line; a, b, a_1, b_1, c_1 are the regression coefficients; H_{E10} is the significant wave height defined from low frequency ranging from 0.03 to 0.1 rad/s.

5.3 Our approach

This study is an ongoing effort that deals with the problem of modeling the ship motion response applying a parametric modeling method. The model can determine the ship motion directly from any wave spectrum for a certain navigation condition. Obviously this approach provides the results more accurately than those from the regression model, as can be recognized in Figure 5.3. The application of this model to navigation risk assessment and model qualification has also been discussed in a numerical example.

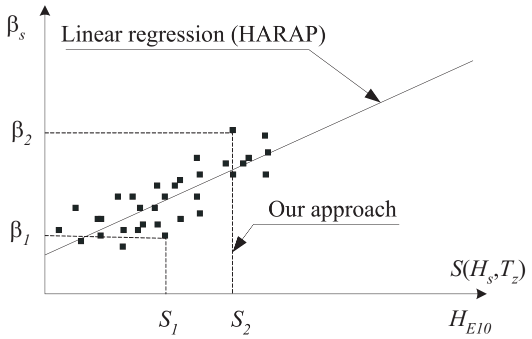

Figure 5.3: Difference between the two models

5.3.1 The wave-ship motion system

For restricted entrance channels and shallow waterways, the wave climate is generally not excessive; and since the ship dimensions are usually large relative to the wave length, ship response problems can be treated with linear models (all directly proportional to wave height) (Journee, 2002). The response spectrum of the ship motion based on the linear model is directly given by the wave spectrum as:

$$S_r\left(\omega_e\right) = \left|H\left(\omega_e\right)\right|^2 S_\eta\left(\omega_e\right) \tag{5.4}$$

where ω_e is the encounter frequency; $|H(\omega_e)|$ is the encounter frequency transfer function, which depends on ship speed, sailing angle, loading condition and water depth (or underkeel clearance); $S_\eta(\omega_e)$ is the wave spectrum in encounter frequency. For a given wave direction and a loading condition, Eq. (5.4) can be rewritten as:

$$S_r\left(\omega_e | H_s, T_z, V, kc\right) = \left|H\left(\omega_e | V, kc\right)\right|^2 S_\eta\left(\omega_e | H_s, T_z\right) \tag{5.5}$$

The encounter frequency for shallow waters is determined as:

$$\omega_e = \omega - \mu V \cos(\delta) \tag{5.6}$$

$$\mu = \frac{\omega^2}{g \tanh(\mu d)} \tag{5.7}$$

where V (m/s) is the forward speed of ship; kc (m) is the average instantaneous underkeel clearance; d (m) is the water depth; δ (degree) is the angle between wave direction relative to the ship speed vector (δ=0 for waves from astern); T (m) is the ship draft depending on loading condition; ω (rad/s) is the wave frequency; μ is the wave number.

It can be seen from Eq. (5.5) that if the transfer function can be formulated as a function of the transit conditions (V and kc), the response spectrum of the motion, $S_r(\omega_e)$, can be determined for all possible sea states described by wave spectrum $S_\eta(\omega_e)$.

With the assumption that the wave-ship motion is a linear input-output system, whose transfer function is faithfully modeled by an "all-pole" model as:

$$H(s) = \frac{b(0) + b(1)s^{-1} + \ldots + b(n)s^{-n}}{1 + a(1)s^{-1} + \ldots + a(m)s^{-m}} = \frac{\sum\limits_{k=0}^{n} b(k)s^{-k}}{1 + \sum\limits_{k=1}^{m} a(k)s^{-k}} \tag{5.8}$$

Here, s is the angular frequency vector for which the transfer function $H(s)$ is determined by the (real or complex) numerator and denominator polynomials represented in the vectors b and a, respectively. For known $H(s)$ and s, nonlinear optimization to define $a(k)$ and $b(k)$ is generally realized in the iterative techniques proposed by Prony or Shank, both are available in the Matlab Signal Processing Toolbox (Matlab, 2005). For the problem under discussion, Eq. (5.8) can be rewritten as:

$$H(\omega_e|V, kc) = \frac{\sum\limits_{k=0}^{n} b(k|V, kc)\omega_e^{-k}}{1 + \sum\limits_{k=1}^{m} a(k|V, kc)\omega_e^{-k}} \tag{5.9}$$

We assume the form of $a(k)$ and $b(k)$ as the polynomial functions of V and kc as:

$$a(k|V, kc) = \sum_{j=1}^{p+1} \left[\sum_{i=1}^{q+1} \theta_{i,j} V^{q+1-i} \right] kc^{p+1-j}; k = 1 \div m \tag{5.10}$$

$$b(k|V, kc) = \sum_{j=1}^{p+1} \left[\sum_{i=1}^{q} \phi_{i,j} V^{q+1-i} \right] kc^{p+1-j}; k = 0 \div n \tag{5.11}$$

The idea given to define the response function is that a parametric modeling technique is applied to find the parameters a and b in Eq. (5.9), which corresponds to define the coefficients θ and ϕ in the proposed mathematical model given in Eqs. (5.10) and (5.11). The estimation of the model parameters is achieved in two steps: the encounter frequencies and response functions considered as the data samples are obtained from either physical model tests or numerical ship motion model for various class values of V and kc, from which the corresponding parameters $ao(k)$ and $bo(k)$ can be estimated using Prony's algorithm (Jones, 2005). The estimated parameters are then used to define the coefficients θ and ϕ by doing a least square fit, which minimizes the sum of the squares of the deviations of the data from the model as:

$$\varepsilon_\theta = \min_\theta \sum_{i=1}^{M}\sum_{j=1}^{N}\left[a\left(\theta|V_i, kc_j\right) - ao\left(V_i, kc_j\right)\right]^2 \tag{5.12}$$

$$\varepsilon_\phi = \min_\phi \sum_{i=1}^{M}\sum_{j=1}^{N}\left[b\left(\phi|V_i, kc_j\right) - bo\left(V_i, kc_j\right)\right]^2 \tag{5.13}$$

Thus, the parametric modeling problem for the model given in Eq. (5.9) is reduced to finding the minimum points of the function ε_θ and ε_ϕ in Eqs. (5.12) and (5.13), which is called a prediction error method.

5.3.2 Estimating model parameters

Suppose we have sample data of $|H(\omega_e)|$ at various values V_i and kc_j $(i = 1 \div M, j = 1 \div N)$. Using Prony's algorithm, we can find the $(M \times N)$ vectors bo each having n parameters $bo(k)_{ji}$, $k = 0 \div n$ and the $(M \times N)$ vectors ao each having m parameters $ao(k)_{ji}, k = 1 \div m$. The parameter ao_{ji} (here we omitted k to simplify the notation) can be expressed as a nonlinear p-order polynomial model of kc_j for a given V_i as:

$$r_{1,i}kc_j^p + r_{2,i}kc_j^{p-1} + \cdots r_{p,i}kc_j + r_{p+1,i} = ao_{ji} \tag{5.14}$$

in the matrix form:

$$\begin{bmatrix} kc_1^p & kc_1^{p-1} & \cdots & kc_1 & 1 \\ kc_2^p & kc_2^{p-1} & \cdots & kc_2 & 1 \\ \cdots & \cdots & \ddots & \cdots & \cdots \\ kc_N^p & kc_N^{p-1} & \cdots & kc_N & 1 \end{bmatrix} \begin{bmatrix} r_{1,i} \\ r_{2,i} \\ \cdots \\ r_{p+1,i} \end{bmatrix} = \begin{bmatrix} ao_{1,i} \\ ao_{2,i} \\ \cdots \\ ao_{N,i} \end{bmatrix} \tag{5.15}$$

For all $V_i, i = 1 \div M$, Eq. (5.14) in matrix form is:

$$\begin{aligned} \left[kc_{N,p+1}\right]\left[r_{p+1,M}\right] &= \left[ao_{N,M}\right] && (5.16) \\ \text{here:} \quad kc_{l,j} &= kc_j^{p+1-l};\ l = 1 \div p+1; j = 1 \div N && (5.17) \end{aligned}$$

There are N equations and $(p+1)$ unknowns. For regression solution N must therefore be larger than $(p+1)$. We can easily define the coefficients r represented by the $M-$by$-p+1$ matrix using nonlinear regression techniques. It is clear from Eq. (5.14) that r_{ji} is as the coefficient in the $(p+1-j)$ order polynomial model of kc_j for a given value of V_i. Thus, for instance, the equation of r at the p-order of kc is:

$$\theta_{1,1}V_i^q + \theta_{2,1}V_i^{q-1} + \cdots \theta_{q,1}V_i ... + \theta_{q+1,1} = r_{1,i};\ i = 1 \div M \tag{5.18}$$

For all V_i, $i = 1 \div M$ at the p-order of kc in the matrix form:

$$\begin{bmatrix} V_1^q & V_1^{q-1} & \cdots & V_1 & 1 \\ V_2^q & V_2^{q-1} & \cdots & V_2 & 1 \\ \cdots & \cdots & \ddots & \cdots & \cdots \\ V_M^q & V_M^{q-1} & \cdots & V_M & 1 \end{bmatrix} \begin{bmatrix} \theta_{1,1} \\ \theta_{2,1} \\ \cdots \\ \theta_{q+1,1} \end{bmatrix} = \begin{bmatrix} r_{1,1} \\ r_{1,2} \\ \cdots \\ r_{1,M} \end{bmatrix} \tag{5.19}$$

For all orders of kc in the matrix form:

$$\left[V_{M,q+1}\right]\left[\theta_{q+1,p+1}\right] = \left[r_{p+1,M}\right]^T \tag{5.20}$$

$$\text{here: } V_{l,i} = V_i^{q+1-l}, \; l = 1 \div q+1, \; i = 1 \div M \tag{5.21}$$

We have M equations in the $(q+1)$ unknowns with the condition that $M > (q+1)$. Having determined the r from Eq. (5.15) we can then use them to obtain θ from Eq. (5.19) with the prediction error given in Eq. (5.12). In the same way, we can also define ϕ.

Minimizing ε_θ and ε_ϕ in Eqs. (5.12) and (5.13) leads to the error of the response function over the $(N \times M)$ samples is minimized, which is given by:

$$\varepsilon_H(\omega_e) = \sum_{i=1}^{M}\sum_{j=1}^{N}\left[H(\omega_e|V_i, kc_j) - H_0(\omega_e|V_i, kc_j)\right]^2 \tag{5.22}$$

It is clear that the found curve fits in Eqs. (5.14) and (5.18) in some cases may not perfectly approximate the data. To improve the approximation, the order (p and q) of the polynomial equations can be increased, which subsequently leads to increased sample data and therefore requires a higher computational effort. This, however, does not amount to a problem with the mathematical model programmed in recent powerful computers.

One might prefer to use a regression coefficient R^2, as given in Eq. (5.23), for assessment of the estimated response function, and thus we have to choose p and q that satisfy the condition $R > R_0$ (R_0 is an expected fitting coefficient). Hence, minimizing ε_H in Eq. (5.22) is equivalent to maximizing R in the following:

$$R^2 = 1 - \frac{\sum\left(H_{oi} - H_i\right)^2}{\sum\left(H_{oi} - \overline{H}_o\right)^2} \tag{5.23}$$

where H_{oi} is the sample value of the transfer function; and H_i is the regression prediction value; and $\overline{H}_o$ is the mean of the sample values.

The above procedure of defining the model of the transfer function given in Eq. (5.9) as well as for determining the response spectrum in Eq. (5.4) can be summarized as follows:

- Use either numerical ship motion model or physical model to calculate the transfer functions for the concerned ranges of ship speeds and water depths. The numerically calculated transfer functions are considered as the sample functions, denoted here $H_o(\omega_e)$, for the parameter modeling progress. Note that the sample function values are calculated at the relatively discrete encounter frequencies, which are derived from Eq. (5.5);
- The estimated sample functions $H_o(\omega_e)$ and ω_e are then used to define the model parameters $ao(k)$ and $bo(k)$ by solving invert function of Eq. (5.8) using Prony's algorithm. We calculate the parameters $bo(k)$ and $ao(k)$ by trying to find appropriate values of n and m;
- Define $a(k)$ and $b(k)$ as the functions of V and kc as given in Eqs. (5.10) and (5.11). This leads to a system of $M \times N$ equations in $(q+1)(p+1)$ unknowns which can be solved to find the best fitting coefficients (θ and ϕ) to fit the data, $a(k)$ to $ao(k)$ and $b(k)$ to $bo(k)$;
- Finally, $H(\omega_e)$ will be found at the relatively discrete encounter frequencies using Eq. (5.8), the corresponding ε and R^2 will also be estimated in Eqs. (5.22) and (5.23). In practice, we usually consider choosing parameters $a(k)$ and $b(k)$ to maximize R^2.

5.4 Applications

5.4.1 Short-term assessment of grounding risk

Because of the random nature of waves, the resulting ship motions have to be treated as a random process in which the probability of contact with seabed during transit must be maintained at an acceptable minimum level. The probabilistic model is a promising tool for calculating the probability of touching bottom. Subsequent to these studies safety criteria can be established in relation to use of the channel. The phrasal word of "short-term" is defined in the present study that the grounding probability calculation is applied to uniform conditions of the sea state and ship operation.

There are two commonly applied models to assessment of the grounding risk. The investigation of two these models are presented in the followings.

First-passage failure model

A widely accepted assumption is that the wave-induced vertical motion of a ship is a stationary random process and well described by the Gaussian distribution. So the Poisson law described in Eq. 4.1 is still useful for the problem under discussion. This equation was firstly used by Strating et al. (1982) in the optimization of the approach channel depth of Rotterdam port and latter on it has been mentioned in many researches in both design and operation of channel depths. Eq. 4.1 is rewritten for a random process, $z(t)$, of a ship vertical motion induced by waves as:

$$P(\beta, T_h) = 1 - \exp(-\nu_\beta T_h) \tag{5.24}$$

where $P(\beta, T_h)$ is the probability of ship touching the bottom at once during a period T_h (sec.) with the average instantaneous underkeel clearance $kc = \beta$; and ν_β is the mean rate of crossing with a level of β, ν_β can be then expressed as:

$$\nu_\beta = \frac{1}{2\pi}\sqrt{\frac{m_{2z}}{m_{oz}}}\exp\left(-\frac{1}{2}\frac{\beta^2}{m_{oz}}\right) \tag{5.25}$$

where m_{oz} and m_{2z} represent zero and second moments of the vertical motion process, respectively; which can be determined by the following equations:

$$m_{oz} = \int_0^\infty S_r(\omega_e)d\omega_e \tag{5.26}$$

$$m_{2z} = \int_0^\infty \omega_e^2 S_r(\omega_e)d\omega_e \tag{5.27}$$

$S_r(\omega_e)$ is the vertical motion spectrum of the ship as defined in the previous section.

In engineering design, it is highly desirable to know a certain level of the underkeel clearance for which a probability of bottom touches is smaller than an acceptable value α. For example, before the ship entrance we wish to know a specified level of the vertical motion corresponding to an acceptable probability of the ship grounding, α. So let $P(\beta, T_h) = \alpha$, from Eqs. (5.24) and (5.25), a crossing level for which the probability of ship touching the bottom at once $= \alpha$ can be expressed by (Quy et al., 2006):

$$\beta = \sqrt{m_{0z}}\sqrt{-2\ln\left\{-\frac{\ln(1-\alpha)}{\frac{T_h{}^2}{2\pi}\sqrt{\frac{m_{2z}}{m_{0z}}}}\right\}} \tag{5.28}$$

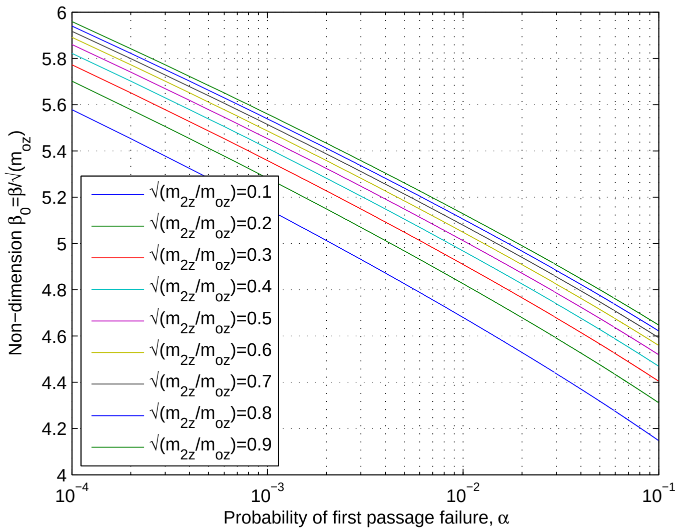

Figure 5.4: Non-dimensional β_0 vs. α for $T_h = 10$ hours

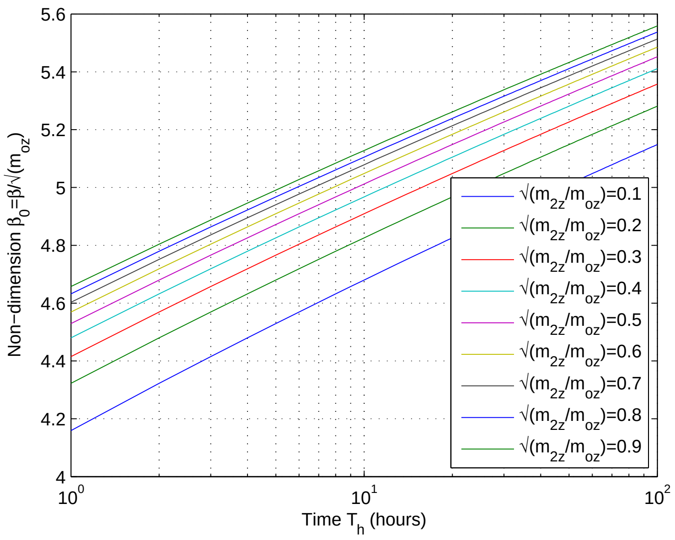

Figure 5.5: Non-dimensional β_0 vs. T_h for $\alpha = 10^{-4}$

Now let the non-dimension of crossing level, denoted by β_0, be given by $\beta_0 = \beta/\sqrt{m_{oz}}$. Figure 5.4 shows the non-dimensional crossing level β_0 for $T_h = 10$ hours computed from Eq. 5.28 as a function of the first-passage failure $= \alpha$ when β and $\sqrt{m_{2z}/m_{oz}}$ are independent each other. As can be seen in this figure that there is no significant difference in the values of β_0 for $\sqrt{m_{2z}/m_{oz}}$ up to 0.7, this is true for β_0 derived as a function of time T_h as shown in Figure 5.5 for first-passage failure $\alpha = 10^{-4}$.

If β is larger the available underkeel clearance, kc, the ship entrance will not be allowed. This is one of the most important conditions to establish the ship entrance policy.

Extreme theory

Supposing the first-passage failure is viewed as ship grounding is somewhat pessimistic. It can be realized in the fact that even with a number of the bottom touches during a transit; the ship can be still underway without grounding. The study (Savenije, 1998) indicated that the possibility that the vessel touches the bottom and penetrates 0.25 m does not always resulting in the grounding and the major damage. It is, of course, only true for the soft bottom. The application of extreme value theory in the evaluation of the penetration is therefore meaningful. The definition of extreme value, $\bar{\eta}$, is shown in Figure 5.6. It means that for the probability of first-passage failure with a crossing level, β, and a corresponding extreme value, $\bar{\eta}$, a penetrated depth onto the bottom is thus defined by:

$$\Delta = \bar{\eta} - \beta \tag{5.29}$$

For the problem under discussion, consider $z_1, z_2, ..., z_n$ are negative minima values taken from a response $z(t)$ of the vertical motion of a ship during period T_h. The response $z(t)$ is as well-defined a stationary and Gaussian with zero mean. If the values of the sequence $(z_1, z_2, ..., z_n)$ are rearranged in an increasing order $\eta_1 < \eta_2 < ... < \eta_n$ of magnitude in which $\eta_j = |z_i|$, $i, j = 1 - n$. Then the p^{th} member of this new sequence is called "the p^{th} order statistic of the sample". Due to the fact that the

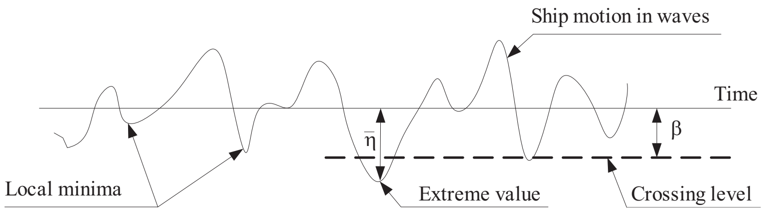

Figure 5.6: Definition of extreme value $\bar{\eta}$ and crossing level β

maxima is the last order statistic, the following probability density function of maxima distribution is obtained by (Vrijling & Gelder, 2004):

$$g(\eta_n) = n\{F(\eta)\}^{n-1} f(\eta) \tag{5.30}$$

where $g(\eta_n)$ is the probability density function of the largest value in n observations; $f(\eta_n)$ and $F(\eta_n)$ are respectively probability density and cumulative distribution functions of the maxima in the new sequence, which are well-known that (Ochi, 1990):

$$f(\eta) = \frac{2}{1+\sqrt{1-\varepsilon^2}} \begin{bmatrix} \frac{\varepsilon}{\sqrt{2\pi}} \exp\left\{-\frac{\eta^2}{2\varepsilon^2}\right\} + \eta\sqrt{1-\varepsilon^2}... \\ \times \exp\left\{-\frac{\eta^2}{2}\right\}\left\{1-\Phi\left(-\frac{\sqrt{1-\varepsilon^2}}{\varepsilon}\eta\right)\right\} \end{bmatrix} \tag{5.31}$$

$$F(\eta) = \frac{2}{1+\sqrt{1-\varepsilon^2}} \begin{bmatrix} -\frac{1}{2}\left(1-\sqrt{1-\varepsilon^2}\right) + \Phi\left(\frac{\eta}{\varepsilon}\right) - \sqrt{1-\varepsilon^2}... \\ \times \exp\left(-\frac{\eta^2}{2}\right)\left\{1-\Phi\left(-\frac{\sqrt{1-\varepsilon^2}}{\varepsilon}\eta\right)\right\} \end{bmatrix} \tag{5.32}$$

here:

$$\varepsilon = \sqrt{1-\frac{m_{2z}^2}{m_{oz}m_{4z}}} \tag{5.33}$$

$$\Phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-\frac{u^2}{2}} du \tag{5.34}$$

$$m_{4z} = \int_{-\infty}^{\infty} \omega^4 S_r(\omega) d\omega \tag{5.35}$$

Now, let $P(\bar{\eta}_n, T_h)$ be probability of the extreme value of n observations of the response process within the period T_h. We wish to obtain the extreme value $\bar{\eta}$ with the probability of being exceeded the value $= \alpha$ Thus, we have:

$$P(\bar{\eta}_n, T_h) = \alpha \tag{5.36}$$

If α is small and n is large, the solution of Eqs. 5.30 and 5.36 yields the value $\bar{\eta}$ as (Ochi, 1990):

$$\bar{\eta} = \sqrt{m_{oz}}\sqrt{2\ln\left\{\frac{T_h^2}{2\pi\alpha}\sqrt{\frac{m_{2z}}{m_{oz}}}\right\}} \tag{5.37}$$

The non-dimension of $\bar{\eta}$ is defined as $\eta_o = \bar{\eta}/\sqrt{m_{oz}}$. From Eqs. 5.28 and 5.37, the difference, Δ, between crossing level of the first passage failure and the corresponding extreme value can be defined as a function of the time period T_h, the response characteristics m_{oz} and m_{2z}, and α. Since the penetrated depth of ship hitting the bottom has been determined, the grounding risk and ship damage can therefore be quantitatively assessed. Figure 5.7 shows the non-dimension of Δ_0 value, defined as $\Delta_0 = \Delta/\sqrt{m_{oz}}$, for $T_h = 10$ hours as a function of period for various values $\sqrt{m_{2z}/m_{oz}}$. As can be seen that there is almost no difference in the values Δ_0 for all values of $\sqrt{m_{2z}/m_{oz}}$ with small values of α. The values Δ_0 and the differences between these lines increase with increasing of α and $\sqrt{m_{2z}/m_{oz}}$.

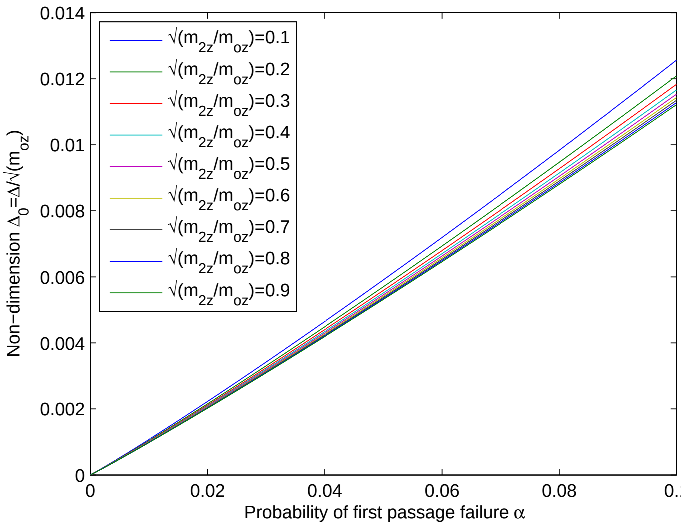

Figure 5.7: Non-dimensional Δ_0 vs. α for $T_h = 10$ hours

5.4.2 Long-term optimization of channel depth

Having determined the model of the ship motion response, a simulation model can therefore be developed. It can be used as a decision support tool for channel performance evaluation and optimization. In general, the procedure of a long-term optimization of channel depths is presented in Figure 5.8.

As discussed in Section 5.1, a long-term optimization of channel depths should be considered a two-stage process, consisting of: (1) first, establishing ship entrance guidance to facilitate a required navigation safety with respect to a possibility of touching the channel bed as discussed previously. This step is the so-called short term establishment of entrance policy for safe navigation. (2) secondly, using the Monte Carlo method and based on the established entrance policy, a simulation model is developed to define a minimum safe underkeel clearance allowance and simultaneously determine downtime that correspond to an acceptable grounding risk for a specified ship and a generated sea state. The

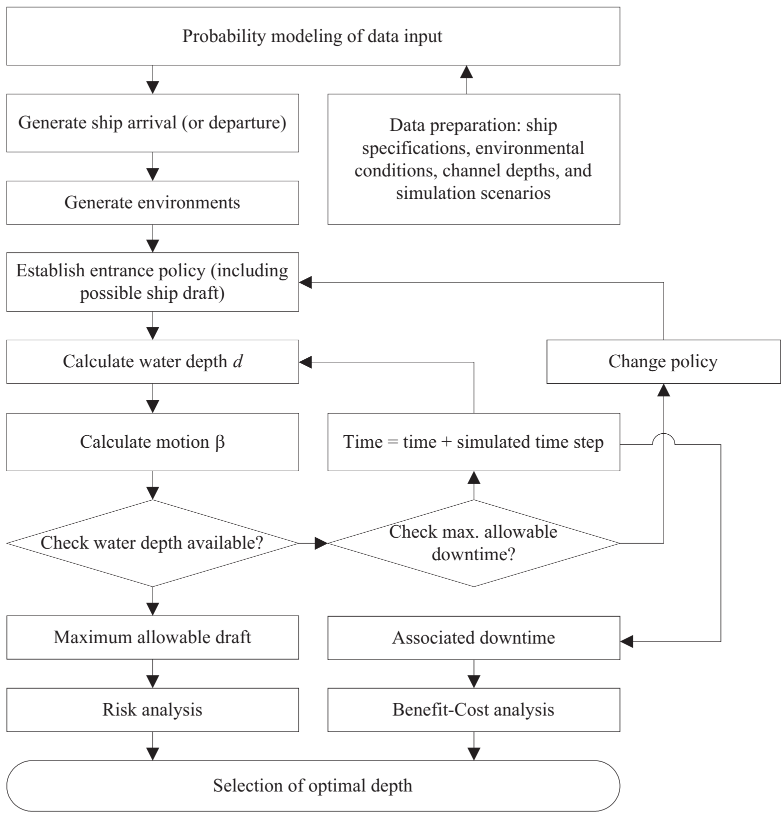

Figure 5.8: General procedure for the optimization of channel depths.

process can be repeated over for a given time period and for all possible alternatives of the channel depths. To enable this, stochastic models of the environmental conditions and ship arrivals on the basis of historical recorded or forecasted data have to be set up. Since the ship response spectrum has been defined as a function of the transit conditions and sea states, the model uncertainties can be assessed and included in the simulation. The final results derived from the simulation model can be considered as the key parameters in analysis and selection of an optimal depth. This application has been discussed in detail for a case study, as will be presented in Chapter 6.

5.5 Numerical example and model qualifications

5.5.1 Data input

The design ship is a bulk carrier 65,000 DWT with the main representative dimensions as presented in Table 5.1.

To obtain sample data for parametric modeling of the frequency transfer function, a numerical ship motion model, called SEAWAY (Journee, 2001), has been used. Five values of the ship speed ranged from 5 knots to 15 knots and seven values of water depth, d, with ratios of d/T varied from 1.25 to 1.55 were used in the calculation, amounting in total to thirty fives transit conditions.

Table 5.1: Ship's main dimensions

Items	Unit	Values
Overall length (L_P)	m	274
Beam (B)	m	32
Full loaded draft (T)	m	13
Block coefficient (C_B)	m	0.8142
Wetted surface hull	m^2	3487

Two parameters (H_s and T_z) of significant wave height and mean zero crossing period of the modified Pierson-Moskowitz spectrum have been proposed to calculate the ship motions. The spectrum is generally agreed for describing the sea surface elevation due to wind speed for a fully developed sea at infinite fetch. The modified Pierson-Moskowitz spectrum parameterizations used is:

$$S_\eta(\omega) = \frac{124H_s^2}{T_z^4\omega^5}\exp\left[-497\left(\omega T_z\right)^{-4}\right] \tag{5.38}$$

The calculation focused on the hull motion at stern for incoming waves, because the risk of bottom touch is most critical for this part of the ship (Quy et al., 2006).

The ship squat has also been taken into account to reduce the underkeel clearance. The empirical expression, proposed by Barrass (PIANC, 1997), has been used as follows:

$$S_{\max} = \frac{C_B S_2^{2/3} V^{2.08}}{30} \tag{5.39}$$

where C_B is the block coefficient; V is the ship speed (knots); S_2 is the blockage factor defined as a ratio of midship section area to the wetted cross section area of the waterway.

5.5.2 Modeling results

The parameters in vectors $ao(k)$ and $bo(k)$ were found with the average regression coefficient over all the sample data was 0.994 for the orders n and m in the numerator and denominator polynomials of 25 and 16 respectively, where the fit presented in Figure 5.9 with $V = 10$ knots and $kc = 3.25$ m represents the case having the smallest value of all fits performed. These results confirmed that the "all-pole" model represents well the behavior of the ship response in the linear wave-motion system.

Figures 5.10 and 5.11 present the results of the model parameters in Eqs. 5.10 and 5.11 as a function of kc and $V = 10$ knots with the index $k = 3$ based on the estimated values of $ao(k)$ and $bo(k)$. The $q-$ and $p-$orders of the polynomials were 3 and 2, respectively. It can be primarily concluded that the polynomial model can fit well the data with low orders only. It is more interesting to find that the error in the estimated response spectrum is very insensitive with the errors in the model parameters $a(k)$ and $b(k)$ because the all-pole model is usually computed with the high $n-$ and $m-$ orders.

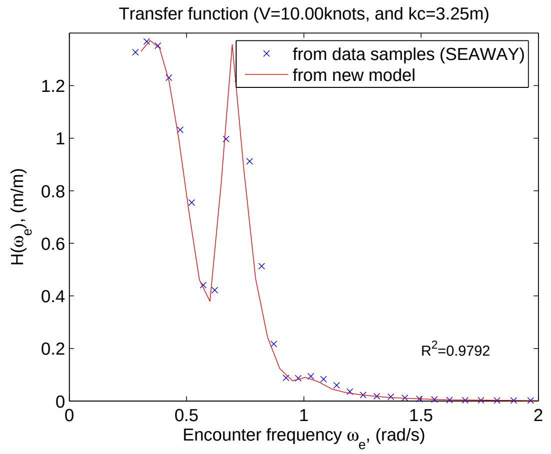

Figure 5.9: Comparison between the theoretical transfer function calculations (SEAWAY) and the results from the parametric model

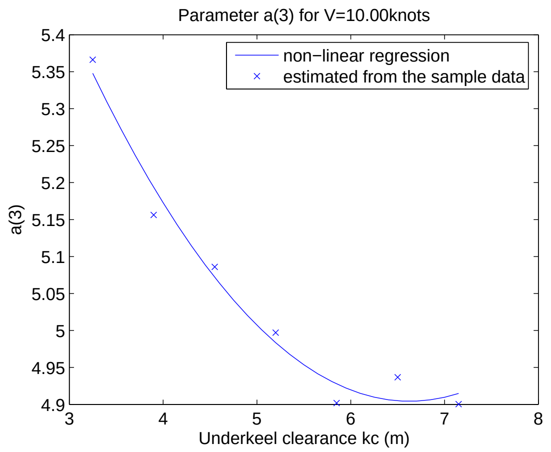

Figure 5.10: An example of non-linear regression parameter a

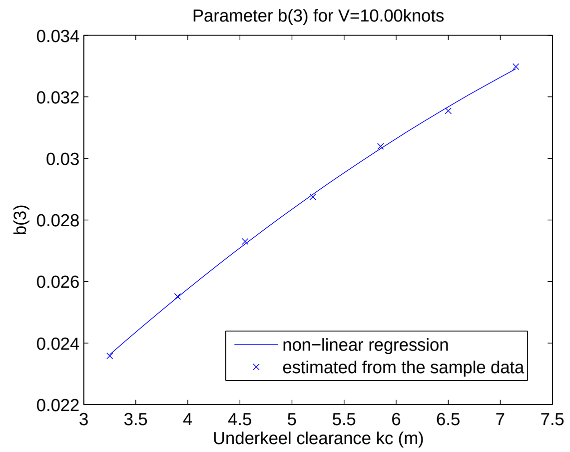

Figure 5.11: An example of non-linear regression parameter b

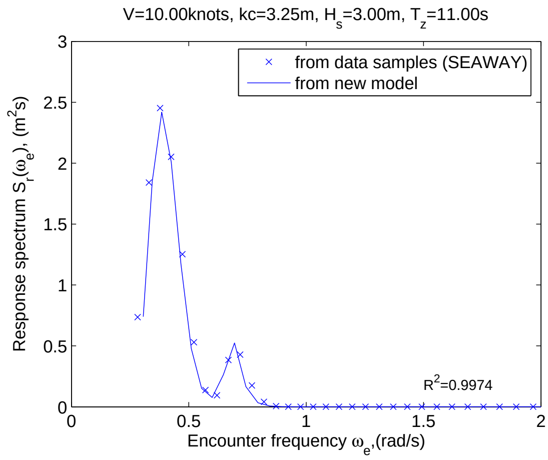

Figure 5.12: Comparison between the theoretical ship response calculations (SEAWAY) and the results from the parametric model (a)

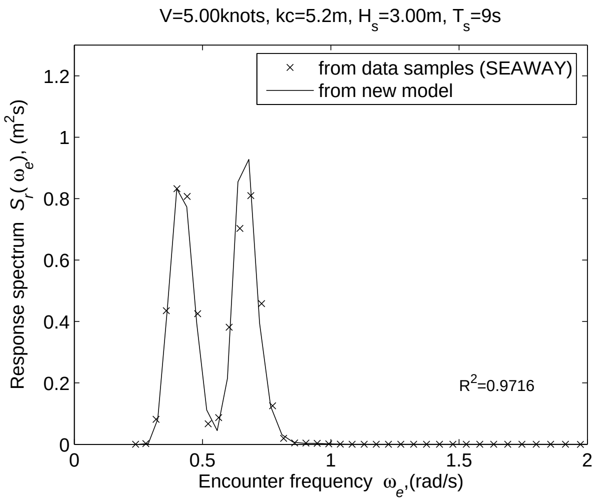

Figure 5.13: Comparison between the theoretical ship response calculations (SEAWAY) and the results from the parametric model (b)

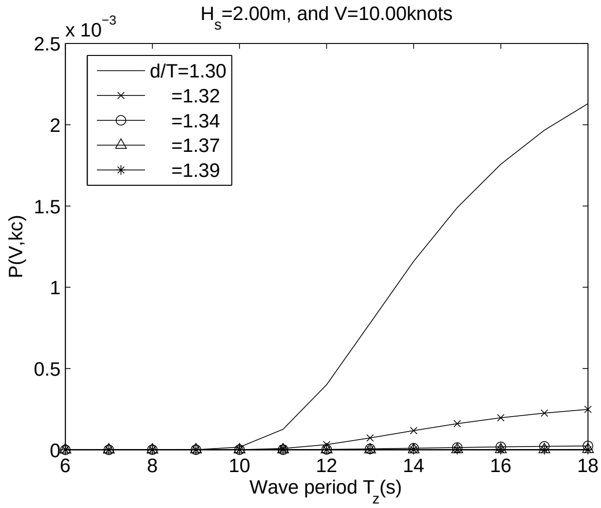

Figure 5.14: Relationship between probabilities of the grounding per transit and wave periods for different values of d/T (relates to the PIANC)

The response spectral estimations based on the parametric model were also compared well to those obtained from the numerical ship motion model, as presented in Figures 5.12 and 5.13 for the reason. Many sea states were randomly generated from which five hundreds of response spectra for thirty fives transit conditions (five speed classes and seven values of underkeel clearance, kc) were estimated to test the model fit. The average fit coefficient was 0.991 and the smallest fit was 0.9716 as shown in Figure 5.13. Finally, a minimum allowable underkeel clearance with a predefined acceptable grounding risk can be estimated using the first-passage failure model given in Eq. 5.28.

5.5.3 Comparisons with the existing guidelines

Concerning the PIANC guideline, the ratio of water depth to ship draft (d/T) has been investigated for various sea states and transit conditions, as shown in Figures 5.14 and 5.15. It can be seen from these figures that the risk levels indicated by the probabilities of ship grounding are strongly dependent on the wave period. The probability increases quickly with slowly decreasing ratios of d/T or with increasing wave period. However, for small value of the acceptable probability of grounding, let say $\alpha = 3 \times 10^{-5}$ (3 per 100,000 ship movements) as an observed value for Northern European Ports (PIANC, 1997), the results are less sensitive to the wave period.

Regarding the USACE guideline, considering the ratio of net depth allowance to wave height, β/H_s, the wave period has considerable effect to the results of the grounding risk, as shown in Figure 5.16. For $\alpha = 3 \times 10^{-5}$ and V=5 knots, the required net depth allowance varies from $0.90H_s$ for the wave periods of 8 seconds to $1.8H_s$ for wave periods of 18 seconds. This requirement is higher for faster ship speeds and larger wave periods. With the value of $1.2H_s$ as recommended by USACE for deep-draft channel, the ship speed should be less than 10 knots for wave periods less than 10 seconds. For the higher sea states, the depth requirement is almost impossible to fulfill.

It is recommended from the engineering point of view that the ratio of water depth to ship draft for

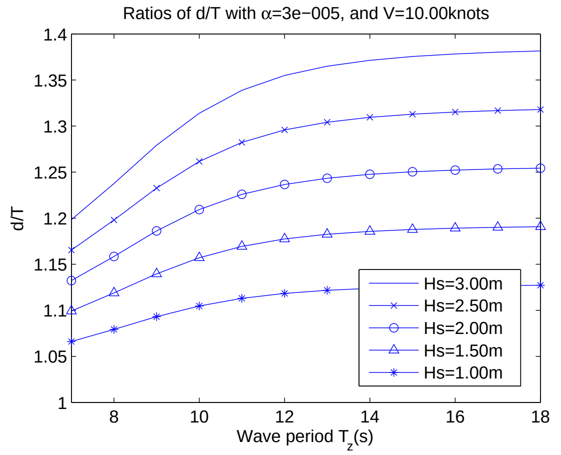

Figure 5.15: Relationship between ratio of d/T and wave periods for different values of H_s with an acceptable grounding value $\alpha = 3 \times 10^{-5}$

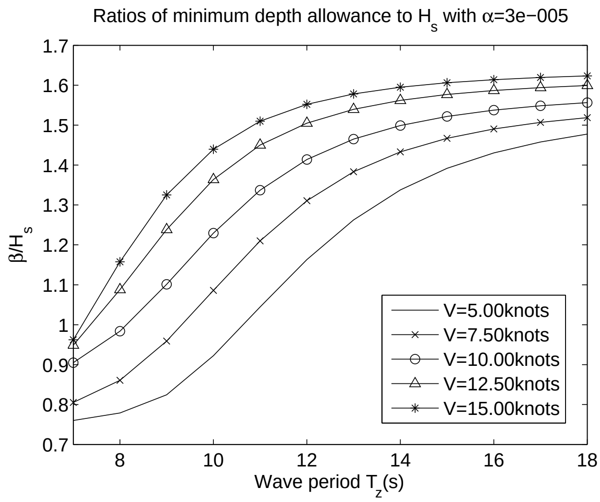

Figure 5.16: Relationship between ratio of β/H_s and wave periods for different ship speeds with an acceptable grounding value $\alpha = 3 \times 10^{-5}$ (relates to the USACE)

Table 5.2: Wave allowances for the bulk carrier 65,000 DWT

Wave height (m)	Wave period (sec.)		
	< 8	$8 \sim 12$	> 12
< 1	1.10	1.13	1.15
$1 \sim 2$	1.20	1.25	1.30
> 2	-	1.35	> 1.35

the examined bulk carrier with the speed of 10 knots should be chosen as presented in Table 5.2.

5.6 Conclusions

Parametric modeling of ship motion responses, of how transit conditions and waves affect the ship motion and grounding risk, has been presented. The model is useful for many purposes: risk management of ship operation in harbor and waterways; simulation-based optimization of channel depths in which all uncertainties involved can be introduced into the simulation; for use on ship handling simulator; and study behavior of ship structure itself. The model could be applicable for "closer analysis" in near real time to predict ship dynamic underkeel clearance along ship passage (Howell, 2002) for maximizing allowable ship draft.

The results of the regression confirmed that the new model with its parameters expressed by polynomial functions represents well the behavior of the ship motion response in the linear wave-motion system.

It should be concluded that the wave periods have great effect on the ship grounding risk with very different degrees depending on the transit conditions.

These results could be useful for the improvement of the existing guidelines with a condition that an acceptable probability of ship grounding should be allowed; the accessibility policy for the ship entrance as well as for approach channel designs will therefore be more accurately and practically established.

Chapter 6

Application: Simulation-based optimization of Cam Pha channel depths

[1]

6.1 Introduction

Simulation-based optimization techniques are frequently used for many applications in research of different systems including urban, economic, transportation areas. Recall from Chapter 2 that the macro-simulation models in the maritime field have generally been used for the studies of port operations and ship traffic flow. The purpose of the traffic flow simulation is to reveal whether the proposed channel design, with its operation rules and environmental conditions, can handle the existing traffic volume and to determine ship waiting time (downtime) and turnround times (PIANC, 1997). The environmental conditions for which a ship entry is considered safe or unsafe are referred to as "channel entrance policy". If the channel is designed to allow ship navigation in more severe environmental conditions, downtime will be reduced; but dredging cost will be increased. Alternatively, starting from a maximum acceptable waiting time and an investment policy with a level of navigation safety, the simulation can estimate a maximum channel capacity as the basis for a trade-off between cost and benefit.

Most of the existing traffic simulations place the emphasis on the study of traffic rules and the entrance regime on port capacity, with little attention to the safety aspect of a particular transit. As discussed in the previous chapters, the risk of a particular ship transit is very often independently determined using either the risk models with the aid of simulators or the numerical vertical models of wave-induced vertical motions. A combination of the two methods is therefore a promising approach to make the simulation models in the maritime research more powerful and comprehensive.

1. Excerpts from this chapter were published as:
Quy, N.M. *et al.*, 2007. Modeling risk and simulation-based optimization of channel depths at Cam Pha Coal Port. In *Proc. IASTED Asian Conference on Modeling and Simulation* (pp 192-198). Beijing, China, ACTA Press.
Quy, N.M. *et al.*, 2008. Risk- and simulation-based optimization of channel depths: Entrance channel of Cam Pha Coal Port. *SIMULATION*, 84 (1), 41-55.

The contribution of this chapter is an introduction of the ship motion response model and the risk model developed in Chapter 5 into a simulation model for the expansion study of the entrance channel of Cam Pha Port in Vietnam. However, the study deals with the channel depth only. In Section 6.2, a brief description of Cam Pha channel project is given. The detailed simulation model developed for this case study is presented in Section 6.3. Analysis of the simulated results for optimal design of the channel depth is described in Section 6.4. As far as this chapter is concerned a brief description of the application of a widely used decision support system for near real time establishment of a policy before ship entering the channel is presented in Section 6.5. Finally, some conclusions and recommendations are drawn in Section 6.6.

6.2 Project description

Cam Pha Port in the North Sea of Vietnam is the largest specialized port serving export of coal to Europe, Japan and China. The Cam Pha approach channel is about 44.5 km long determined from the sea entrance to the port. The layout of the approach channel is highlighted in Figure 6.1. Presently, the entrance channel is being used by bulk carrier vessels of up to 40,000 DWT (partly loaded) with a single lane traffic. In recent years, the demand on coal export to Europe and Japan has increased rapidly and ships entering the port are becoming larger and in fully loaded state beyond the present capacity of the entrance channel. Therefore, in 2001, Vietnam Coal Incorporation had initiated a feasibility project of the Cam Pha Port expansion (Quy, 2001) in which the entrance channel was to be enlarged to allow ships of up to 65,000DWT (fully loaded) using a tide up for leaving the port. But till now, the rehabilitation of the channel has not yet been commenced. The main reason of this delay is that the outer entrance channel, named “Dong Trang channel”, with the length of about 12 km is very shallow (only -10.0 m on average from the sea datum) and some parts of the seabed is hard soil, this results in a very high cost in dredging work. Hence, economic and environmental pressures have revealed the need to minimize the dredging when determining a depth of the entrance channel. Establishment of an appropriate and reliable policy for the ship entry also gives an opportunity to reduce the dredging depth requirement. This study, as a part of the mentioned project, deals with the rehabilitation of the entrance channel with the following objectives:

- Establishing an entrance policy by which the pilots can use it with a sufficient confidence to decide the transit conditions before leaving the port;
- Optimizing the channel depth in the long-term with regarding to an acceptable probability of the ship grounding on the basis of the established accessibility policy.

6.2.1 Port facilities and location of water areas

The port consists of four quays for ship loadings: a newly constructed quay for bulks carrier up to 65,000 DWT, the other side of this quay for coal barges of about 6,000 DWT, and two quays for ships 10,000 DWT. There are two coal ship-loaders with capacities of 18,000 and 20,000 ton/hour for ships of more than 10,000 DWT; and two gantry crane loaders used for barges and smaller ships.

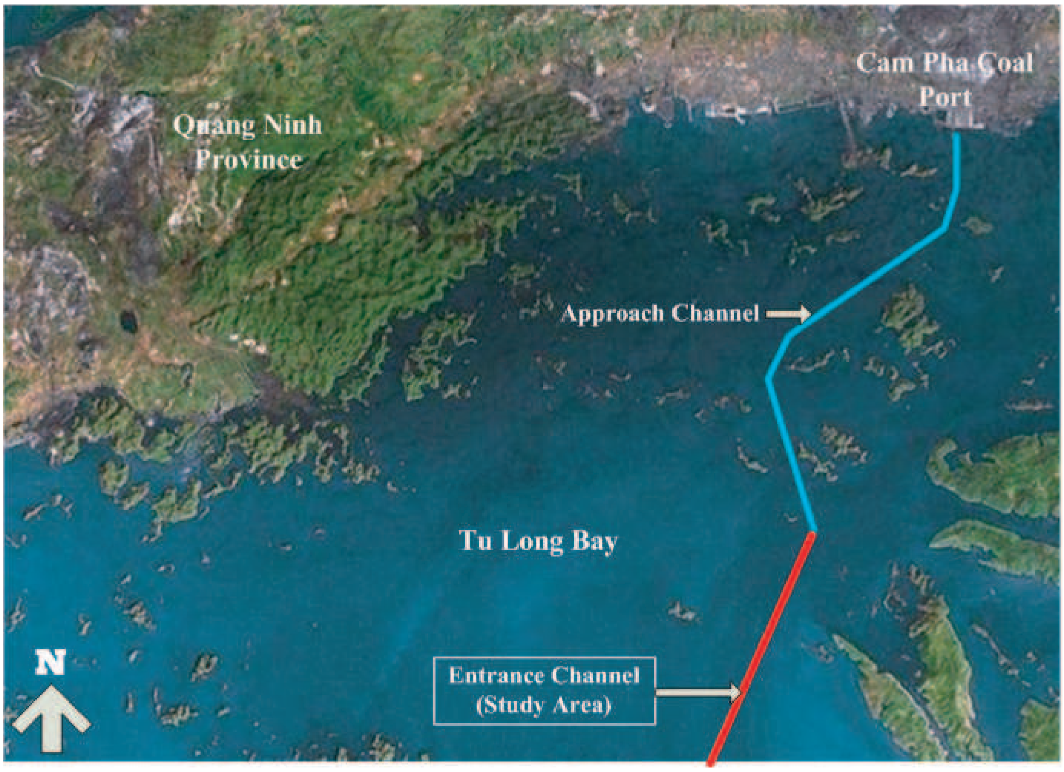

Figure 6.1: General layout of Cam Pha approach channel and studied area

The turning basin with diameter of 400 m is located in front of these quays. Nearby, there is one mooring water for ship accommodation before sailing if no possible navigational water level is found. In some circumstances, due to a low water season, ships can not be loaded fully at the quay, the remaining amount can continue to be loaded on ship at the floating point, which is located in the end of the outer entrance channel.

6.2.2 Present operational procedure

Since the port is solely for export of coal, all ships arriving the port are empty with a ballast draft. Such ballasted ships can use the channel at mean low water level without delay. On arrival at berth, the ship anchors or secures and waits for permission to load. For the study of the channel dimensions only, the model does not include the downtime due to waiting for a berth availability, loading equipment and other delays, which can be considered in a port simulation model. The scheme of ship loading operation procedures is illustrated in Figure 6.2.

There are two possible options of loading the ship: fully loaded and partly loaded. The port authority will determine a maximum possible tidal window available during the next few days taking into account the loading time at berth to decide how much coal should be loaded into the ship. After the completion of the loading (fully or partly), the ship may have to wait at the waiting area, located in front of the berth and locally dredged deeper, before it can sail out. In case of no tidal window being available for full loading at the berth, the ship can continue to an anchorage area near buoy No.0 at the end of the

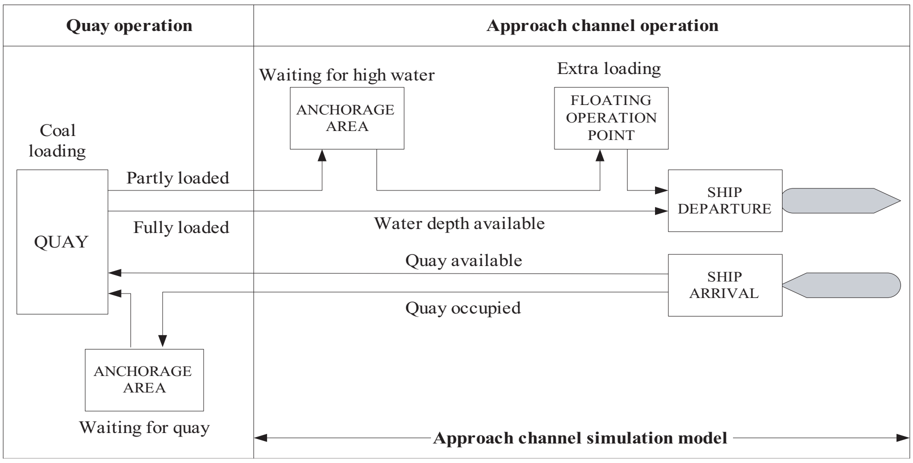

Figure 6.2: The scheme of ship operation sequence at Cam Pha coal port

outer entrance channel to get a topping up of coal from a fleet of 500 DWT barges. The additional cost for this floating loading operation is 20 USD/ton, in comparison with loading at the quay.

6.2.3 Deterministic method of existing admittance policy

So far a deterministic admittance policy has been used for Cam Pha coal port. The entrance admittance of ships is based on a fixed underkeel clearance ratio. The relation between the minimal underkeel clearance and the maximum draft has been calculated by adding the squat, wave allowance and other effects to establish the clearance as explained in Chapter 2. As a rule, the ratio between the gross underkeel clearance and the maximum draft should be 25% for a 65,000 DWT bulk carrier using this channel, where the sea bottom is composed of soft soil. Using this ratio the accessibility of the channel can be determined, adapting to a certain water level. Obviously, this entrance policy considered water level deviations and the ship draft, but does not make any distinction regarding other ship characteristics and wave conditions.

6.3 Simulation model

The developed simulation model in this chapter has been designed in the MATLAB programming language. This model is a discrete-event and compressed-time-stepping traffic simulation for the navigation channel exposed to the open sea where the safety of ship navigation is threatened by wave impacts. The simulation model, which is based on a probabilistic approach, is characterized by the inclusion of tidal variations in the channel and effects on the risk of ship grounding. The key element of the probabilistic method is a determination of the probability of ship touching the bottom during a transit. This requires a reliable estimation of the ship vertical motion response due to the waves and squat effects. The model of the ship motion response developed in Chapter 5 would therefore be useful for this purpose.

The simulation model, as outlined in Figure 5.1, consists of several procedures. First, the data of the ship and the wave condition are generated as input of the model. The risk-based model as presented in Eq. (5.28) is used to determine whether a ship entrance is allowed by comparing a calculated minimum safe underkeel clearance with an available underkeel clearance, kc. Finally, the model will provide various results of simulation for optimum process of channel depth.

The simulation model can be divided into three modules: an input data module, a calculation program and an output data module.

6.3.1 Input data and and generation model

Comprehensive data about the channel environments and design ship should be available. The form of the input data can then be derived. The data are analyzed to find appropriate probability distributions, averages, and other input parameters which are later on used to generate data for the simulation model.

Arrival/departure pattern of ship at the quay

The model assumes that the ship arrival at the quay follows an exponential distribution function of the form:

$$F(t) = 1 - e^{-\lambda t} \tag{6.1}$$

where F is the cumulative distribution function; λ is the arrival rate. For a given λ a sequence of ship arrival time, t, can be generated as follows:

$$i = rand(1, n) \tag{6.2}$$

$$t_i = -log(i)/\lambda \tag{6.3}$$

Here n is the number of ship arrivals. The simulation starts by generating a date and a time of the first ship after receiving permission to load. On the basis of the possible maximum tidal window to be found available in the next few days, the model will calculate a value of the ship draft to which the ship shall be loaded. The other dimensions of the ship have, of course, to be available in advance for definition of the ship motion response. The ship speed is considered to be constant over the complete passage. In this study the bulk carrier 65,000 DWT as mentioned in Chapter 5 is used.

Tide

Tide in the Cam Pha indicates a K_1 - O_1 regular diurnal component (a tidal period is about 24 hours and a complete tidal cycle is about 13.5 days) with mean sea level of 2.3 m and mean highest water level more than 4.0 m. The statistical analysis results of the water levels are shown in Table 6.1 and a sample of predicted astronomic tide for this case study is described in Figure 6.3[2]. Tidal data for the study period have to be available in the model. There are two types of water level, astronomic

2. Source from Marine Hydrometeorological Center, Vietnam

Table 6.1: Water level statistics

Items	Level (m)	Recorded time
The highest high water level	+4.67	17/08/1963
The lowest low water level	+0.07	12/01/1968
Mean water level	+2.30	
The mean highest water level ($P_{1\%}$)	+4.22	
The mean lowest water level ($P_{99\%}$)	+0.38	

and meteorology. The predicted astronomical water level for a given period of simulation should be available as a function of date and time. Meteorological water level is defined as the difference (predicted error) between astronomical water level and real water level measured during the same period. A certain water level regarded as the real water level is determined by adding astronomical water level and a predicted error (Lin et al., 1998). A Gaussian distribution function of the predicted error, with parameters mean value is 22.3 mm and standard deviation is 13.2 mm, was found based on the statistical water level data recorded during the past five years. By relating to the channel bed profile, the water depth at any time and location of the channel can be calculated.

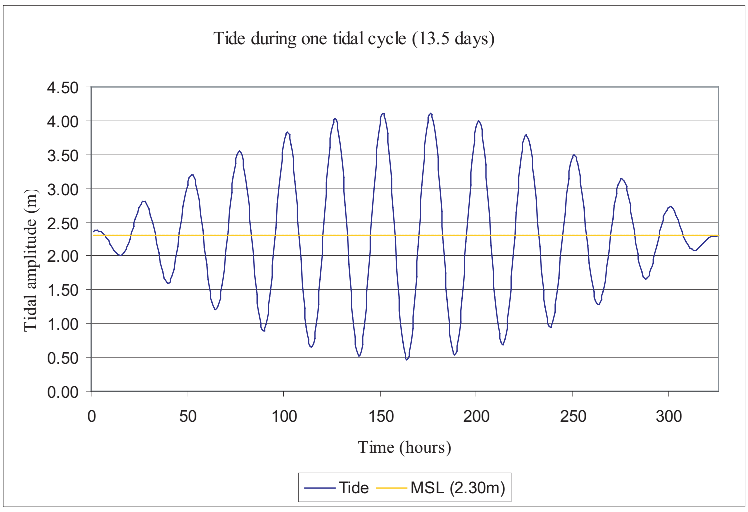

Figure 6.3: A sample of predicted astronomic tide of Cam Pha area

Local wave climate

The best way to obtain a local wave climate is to conduct measurements for a number of locations along the entrance channel. However, this is very costly and impossible in the frame of this research. For the purpose of the feasibility study, wave characteristics at the area were studied by Vietnam Marine Hydrometeorologic Center in one part of the technical report on “Regional study of wind and wave characteristics of Vietnam Coasts” (Thuy et al., 1998). It was done by reviewing and analyzing all the existing long-term data of the waves at Bai Tu Long Bay, and by calculating the local wave climate at the area of the entrance channel. The most useful results of the wave analysis provided unofficially by Client for this application are:

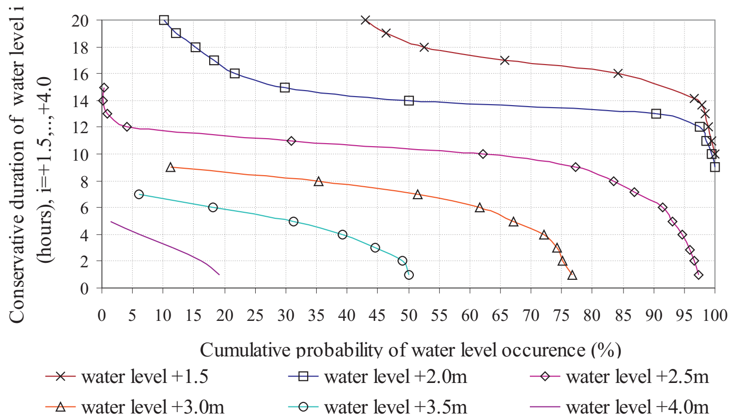

Figure 6.4: Relationships between cumulative probability and its time windows of water levels

- The local wave climate conditions were calculated by a numerical model (SWAN) based offshore wave database at the South China Sea obtained from satellite observations.
- The hindcast wave conditions by a computer program of spectral wave hindcast model based on the wind data of the Cam Pha station (two hour intervals for two years 1993 and 1994).

Due to lacking of on-site wave measurements of the wave for validation of the wave transform model, the accuracy and reliability of the results are still questionable. It is strongly recommended that measurements of the wave must be conducted for detailed design phase.

Sets of calculated wave condition values are grouped and arranged as given in Table 6.2 for all wave directions. The number in each cell of this table indicates the chance that a significant wave height is between the values in the left column and in the range of wave periods listed at the top of the table.

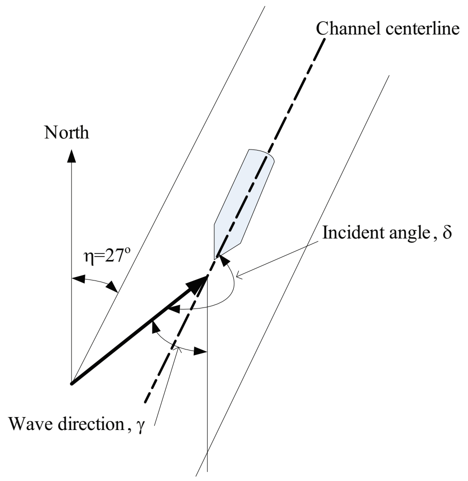

Figure 6.5: Angle of incidence of the wave relative to the outgoing ship

Since the wave angle used in the simulation is an angle relative to the ship these angles have to be defined for different wave directions. Ship is assumed to sail parallel to the axis of the channel. In reality this is not always the case. However, for determination of the ship motion response, this assumption needs to be made in order not to make the simulation extremely complex. The following wave is defined either 360^o or 0^o and the heading wave is 180^o. Because of the exporting coal port, only coming waves for outgoing ships are considered. An incident angle of the waves relative to the outgoing ship described in Figure 6.5 is determined as: $\delta = 180^o + \gamma - \eta = 153^o + \gamma$. All the concerned incident angles corresponding to the wave directions are determined and given in Table 6.3.

Two parameters, H_s and T_z, of Modified Pierson-Moskowitz spectrum have been proposed to calculate the ship motions. The technique for generation of wave conditions as presented in Section 3.4 can be used. It was found that a Gamma distribution fits fairly the significant wave heights in all direction classes (last column of Table 6.2). Based on this distribution we can first generate stochastically a value of significant wave height, H_s. Then a uniform random number can be generated to obtain a desired direction by using the inverse transformation method (Wendy & Angel, 2002). Finally, a wave period, T_z, can be determined using a conditional distribution between two these parameters, H_s and T_z (Memos & Tzanis, 2000). However, in this study, a wave period, T_z, is independently generated because of insufficient data of wave characteristics.

Table 6.2: Frequency of wave height versus mean zero-crossing wave period for all wave directions

	Wave period, T_z								
Wave height	0.00	5.00	6.00	7.00	8.00	9.00	10.00		Total
(m)	4.99	5.99	6.99	7.99	8.99	9.99	10.99	≥ 11	
0.00-0.49	12.25	13.26	8.95	6.58	1.44	0.48			42.96
0.50-0.99	5.32	7.54	6.56	3.65	1.35	1.05			25.47
1.00-1.49	0.85	3.21	4.50	3.89	1.63	1.15	0.04		15.27
1.50-1.99	0.35	1.86	3.21	2.53	1.06	0.82	0.01	0.00	9.84
2.00-2.49	0.02	0.76	1.65	1.27	0.42	0.06	0.01	0.00	4.19
2.50-2.99	0.00	0.35	0.62	0.85	0.30	0.11	0.02	0.01	2.26
3.00-3.49	0.00	0.01	0.04	0.11	0.12	0.06	0.02	0.01	0.37
≥ 3.5	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Total	18.79	26.99	25.53	18.88	6.33	3.73	0.10	0.02	100.37

The parametric model of the ship motion response, as developed in Chapter 5, has been defined as a function of wave parameters and navigation conditions. The calculation focused on the hull motion at stern; because the risk of touching the bottom is most critical for this part of the ship. The reason for this is the export function of the port where the outbound ships-loaded to full draft faces incoming waves (Quy et al., 2006).

6.3.2 Calculation program

The core of this simulation model is a calculation program. Attention is paid to a successful approach by Vantorre and Laforce (2002), on which the calculation program described in this section is based. General calculation procedure of the simulation is illustrated in Figure 6.6. The program consists of following calculation steps:

Table 6.3: Frequency of wave height versus wave direction and incident angle relative to outgoing ship (heading wave is 180^o)

Wave height	Wave direction (incident angle relative to outgoing ship)								
	SE	SSE	S	SSW	SW	WSW	W	Others	Total
(m)	108	130.5	153	175.5	198	220.5	243		
0.00-0.49	2.18	3.20	6.38	10.88	7.02	3.89	2.35	7.06	42.96
0.50-0.99	0.98	1.86	3.88	6.72	4.73	1.78	1.20	4.32	25.47
1.00-1.49	0.52	1.31	2.75	3.80	3.36	1.03	0.15	2.35	15.27
1.50-1.99	0.21	0.47	1.86	2.85	2.19	0.89	0.12	1.25	9.84
2.00-2.49	0.06	0.15	0.75	1.20	0.65	0.45	0.08	0.85	4.19
2.50-2.99	0.00	0.03	0.21	0.75	0.52	0.32	0.08	0.35	2.26
3.00-3.49	0.00	0.00	0.02	0.05	0.04	0.03	0.03	0.20	0.37
≥ 3.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Total	3.89	6.84	15.85	26.25	18.51	8.39	4.01	16.39	100.37

Determination of the depth: An instantaneous water depth at the ship position is calculated based on a generated departure time and a selected ship speed, taking account of the local bottom depth and the tidal data. For practical use in the grounding model, the whole passage should be divided into sub-passages in which the water depth is approximately constant. The difference between the deepest and shallowest point of each sub-passage should not exceed a limiting value. The actual water depth d in each point of the passage is replaced by a certain minimum depth d_j of the sub-passage.

Estimation of squat: when ship draft and water depth in each sub-passage are available, a database of the navigation (T, d and V) is formulated. The empirical expression, proposed by Barrass (PIANC, 1997), has been used to estimate the ship squat of the critical point on the ship hull.

Calculation of the motion characteristics: for each sub-passage and generated wave parameters H_s and T_z, Modified Pierson-Moskowitz spectrum density will be calculated. The motion characteristics of the ship response can therefore be defined using the parametric modeling method as developed in Chapter 5. This allows computation of the amplitude characteristics of the vertical motion of the critical point as presented in Eqs. 5.24 and 5.25.

Calculation of a minimum safe underkeel clearance in each sub-passage: a value β_i, as defined in Eq 5.28, can be determined which is considered as "a minimum safe underkeel clearance" for ship entrance in sub-passage i. It should be noted that $P(\beta, T_h)$ is the probability of ship grounding estimated for the channel as whole, which is obviously different from one determined for each sub-passage. If the channel consists of m segments (sub-passages), $P(\beta, T_h)$ defined in Eq. 5.24 can be rewritten as:

$$P\left(\beta, T_h\right) = 1 - \exp\left\{-\int_0^{T_h} \nu_\beta(t)\mathrm{d}t\right\} \approx 1 - \exp\left\{-\sum_{i=1}^{m} \nu_\beta(i)\Delta t(i)\right\} \tag{6.4}$$

here $\Delta t(i)$ is the duration that a ship passes through sub-passage i; $\nu_\beta(i)$ is the mean rate of crossing

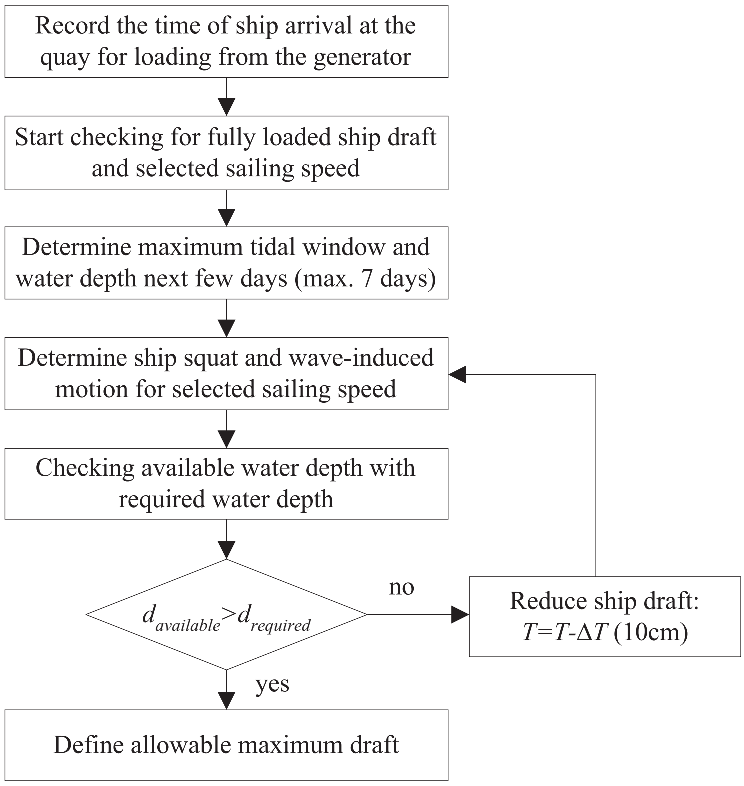

Figure 6.6: Procedure for determination of a maximum loaded draft

with a level of β_i as defined in Eq. 5.25 for sub-passage i.

Now let P_i be the probability of ship grounding in sub-passage i. Suppose all sub-passages are independent each other. The probability of ship grounding for the channel as whole with an acceptable risk of α can be defined as:

$$P(\beta, T_h) = 1 - \prod_{i=1}^{m} (1 - P_i) = \alpha \tag{6.5}$$

Let P_i be equally for all sub-passages, from Eqs. 6.4 and 6.5, a minimum safe underkeel clearance in sub-passage i can be expressed as:

$$\beta_i = \sqrt{m_{oz,i}} \sqrt{-2 \ln \left\{ -\frac{\ln\left(\sqrt[m]{1-\alpha}\right)}{\frac{\Delta t(i)}{2\pi}\sqrt{\frac{m_{2z,i}}{m_{oz,i}}}} \right\}} \tag{6.6}$$

This value will be compared to an available underkeel clearance, kc_i, with the condition that $kc_i > \beta_i$. If this is not satisfied, the ship has to wait at the anchor area. The model will accumulate the downtime until achieving a higher tidal level and tidal window to meet the condition.

6.3.3 Model verification and validation

For purposes of verification, the data of wave, tide and ship arrival were generated from the generation models as formulated above. The statistics for wave heights, tidal levels and ship arrival times were then calculated. Finally, probability density functions of the generated data were determined and compared with those from the observation. Goodness-of-fit tests were found to verify that the parameters fit reasonably well with the generated data. Figure 6.7 displays an example for the wave performed.

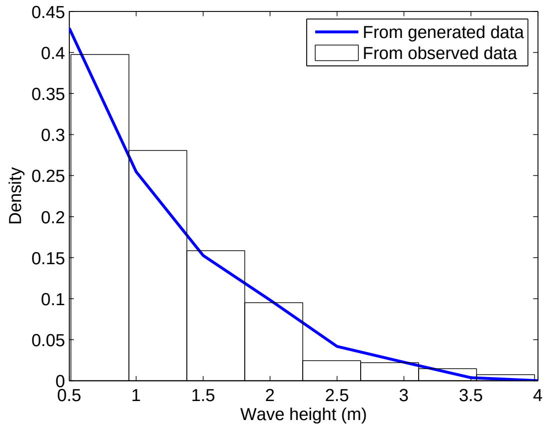

Figure 6.7: Comparison between the generated and observed wave frequency

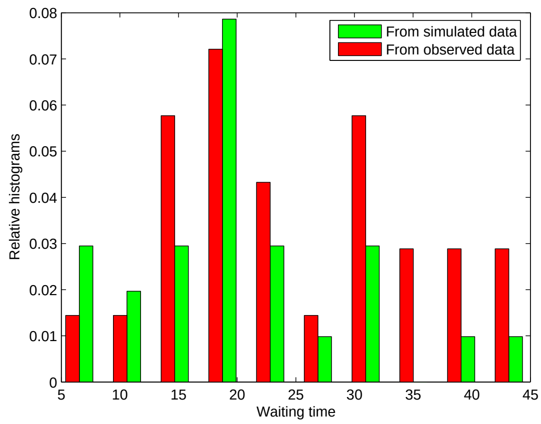

Figure 6.8: Relative histogram comparison of waiting times between the observed and simulated data

For purposes of validation of the simulation model, waiting times for 25 of the ship arrivals during the past were gathered. This means that the simulation experiment should be conducted for the existing condition of the port. Figure 6.8 compares the relative histograms of waiting times taken from the simulated data (number of runs 50) and the observed data. It is expected that the model would be acceptable, although some differences were evident from this comparison. Reason for these differences, evaluated by the author and a number of port authority experts, include the following:

- The observed data are too limited, so the parameters of the statistics have not approached the “true” data;
- The quality of the observed data is considered low;
- The wave data acquired for this study may not reflect properly actual wave climate at the location.
- The simulation model considers waiting times for high tidal level and acceptable weather conditions only, while other factors with high uncertainty such as queuing, pilot and documentation delays are sometimes included in the data.

6.3.4 Simulation output

The simulation output contains the following:

- Ship waiting time for each transit and the total waiting time for the period of simulation;
- Average number of times and the average amount of coal (m^3) loaded onto ships at the floating point (when there is no available water depth for ships loaded fully at the quay);
- Average amount of coal that has to be loaded at the floating point; conversion of all of the above to monetary units if prices are available; and
- Channel utilization ratio, the ratio of the time that ships occupy channel to the period of simulation.

6.4 Simulation results

Until now, due to the limited channel depth, only a small number of ships of 65,000 DWT or larger have called at the port. However, it is expected that this number will increase after the channel is deepened. The objective of this simulation is therefore to investigate the effect of changes in the channel bed level and in the expected number of ship arrivals on the channel performance measures (waiting time, extra operation cost and dredging cost) in comparison to the existing condition. The simulation is based on the assumption that all ships are fully loaded either at the quay or at the floating point before leaving. The throughput is therefore equal for all alternatives of the channel depths and sailing speeds, and this throughput is dependent upon the expected number of ship arrivals only. The operation and dredging costs are certainly different between alternatives. These results will be used to determine the best design for the channel depth associated with acceptable navigation conditions.

6.4.1 Simulation scenarios

The study established five options of channel bed levels and three scales of the sailing speed (slow, moderate and normal speeds) with five options of the expected number of ship arrivals, which amounted to 75 simulation scenarios to be investigated. The input details are listed in Table 6.4.

Table 6.4: Simulation scenarios

Items	Unit	Data input	Remark
1. Simulation time, T_{sim}	hours	360x24	
2. Ship characteristics			
The expected number of ships per year, n	No.	10, 20, 30, 40 and 50	five options
Distribution of the departure time	type	exponential	
Average time between departure $1/\lambda$	hours	$=T_{sim}/n$	
Ship specification		see Table 5.1	
Ship speed, V	knots	5.0, 7.5 and 10	three options
3. Channel characteristics			
Channel length	m	12,000	
Channel depth level			five options
Option 1(Existing condition)	m	-10	from chart datum
Option 2, 3, 4 and 5	m	-11, -12, -13 and -14	from chart datum
4. Cost parameters			
Waiting cost	USD/hour	35	
Dredging cost	USD/m^3	4.0	
Extra loading cost at the floating berth	USD/ton	20	the cost difference in comparison with loading at the quay

6.4.2 Safety criterion

Safety criterion or risk acceptance, α , is one of the key issues in the design or operation of any approach channel. The safety criterion is defined for a particular to satisfy the condition that a calculated probability of bottom touch does not exceed this value. PIANC reported a grounding probability for Northern European ports of 3 per 100,000 (i.e. 3 $\times 10^{-5}$) ship movements. Statistics in the literature (Briggs et al., 2003) provides accident probabilities ranging from a low of 4 per 100,000 (i.e. 4 $\times 10^{-5}$) to a high of 83 per 100,000 tanker movements. These figures should, of course, include all types of accidents. From the safety point of view and the fact that the study concerns one failure mechanism of the bottom touch only, the risk acceptance = 3 $\times 10^{-5}$ as observed in Northern European ports might be reasonably assigned for this case.

6.4.3 The number of simulation runs per scenario

The simulation execution method selected for the model is the replication method (Emrullah, 2003). This method requires a certain number of experiments (simulation runs). Logically, more repetitions of the simulation will give more exact information on the channel performance, this requires of course much more computation effort.

Figure 6.9 demonstrates the variations in the downtime according to the number of repetitions. The first ten replications are the initial transient period. The results seem to be dispersive and sensitive. After this period, the variations in the downtime become less and seem to be constant for 50 repetitions. It is therefore recommended that 50 repetitions should be made for each scenario.

6.4.4 Results

Based on the above data of environmental conditions and the established scenarios, various simulation results have been achieved.

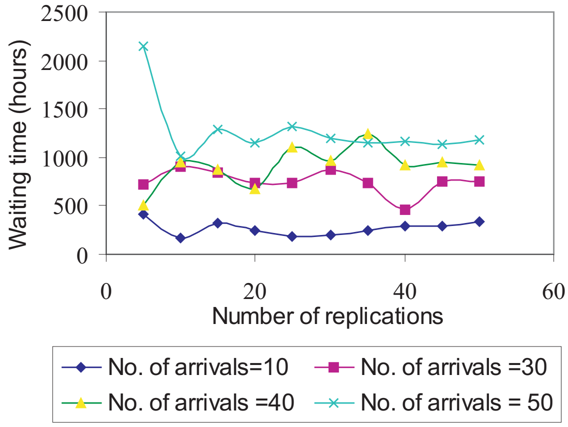

Figure 6.9: Effect of the number of replications on average waiting times

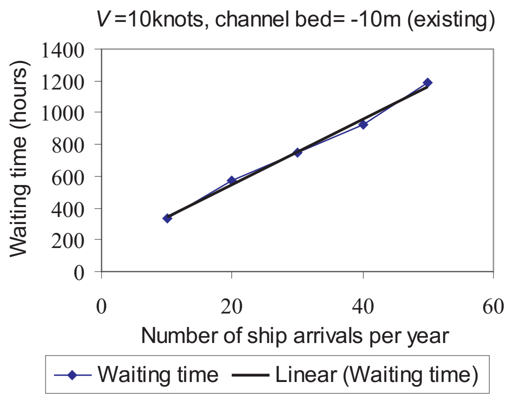

Figure 6.10: A linear relationship between waiting times and No. of ship arrivals

The average waiting time of the ship as a function of the number of the ship arrivals, for the case of channel bed level -10.0 m (existing level) and a sailing speed of 10 knots, is shown in Figure 6.10. It should be noted that this waiting time do not include the time that ships spend on the extra loading at the floating point.

Figure 6.11 shows the relationship between extra operation costs, which comprise the waiting cost and the extra loading cost at the floating point, and the number of ship arrivals for different channel bed levels. The extra operation cost increases quickly with decreasing channel depth (i.e. lower bed level). Moreover, they are much reduced and even approach zero in the cases of a channel bed deeper than 12.0 m. It can be seen that extra operation costs and waiting times are almost a linear function of the number of ship arrivals. This observed fact enables an extrapolation of the results and a reduction of simulation time in the case of larger numbers of ship arrivals considered in the future study.

The total cost, defined as a sum of the extra operation and dredging cost, is expressed in terms of the number of ship arrivals and channel bed levels for alternative sailing speeds, as shown in Figure 6.12. It is interesting to observe that there is only one point of the minimum total cost given at the channel

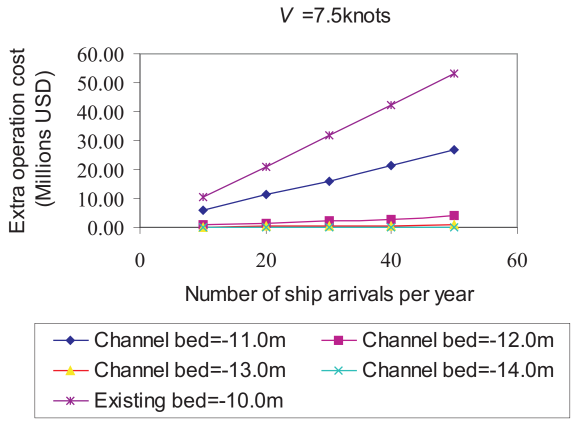

Figure 6.11: A linear relationship between operation costs and No. of ship arrivals for different channel bed levels

bed of 11 m and the speed of 5.0 knots with any number of ship arrivals (see Figure 6.12*a*). However, this differed from the two other cases of ship speeds where the minimum total costs corresponded to channel bed of 10 m (existing condition) as the number of arrivals was less than 10. When the number of arrivals exceeds 10, the minimum total cost corresponded to a channel bed of 12 m and 13 m with ship speeds 7.5 knots and 10 knots, respectively (see Figures 6.12*b* and 6.12*c*). This phenomena can be also observed in Figure 6.13, where the minimum point is moved from the channel bed of -11 m (in case the ship speed of 5 knots) to the bed of -12 m and -13 m correspondingly sailing speeds of 7.5 knots and 10 knots.

The minimum total costs for the channel bed of 12 m are presented as a function of the ship speed and the number of arrivals, as shown in Figure 6.14. It can be seen that the effect of ship speed on the cost varies in a certain pattern. When sailing speed is less than 7.5 knots, the total costs seem equally and only slightly dependent on the number of ship arrivals. In contrast, in cases of sailing speed exceeding 7.5 knots, the total costs increase quickly and the effect of the number of arrivals on the total costs becomes larger with the increase in sailing speeds. This can be explained as the reduction of underkeel clearance due to the squat becomes significant when the ship speed exceeds 7.5 knots. Hence, higher water levels are needed to satisfy the required safety of the ship navigation; in other words, the fewer water levels are available during the channel service period. Subsequently, waiting time and extra operation costs are increased.

It is preliminary concluded that the ship is navigated at a speed of 7.5 knots with the channel bed of -12 m will result in the best alternative when the number of ship arrivals is more than 10. Figure 6.15 shows the cost details of this alternative in case the number of ship arrivals is $n = 30$. It is interesting to observe that the operation cost will be increased quickly if the channel bed is shallower than -12 m.

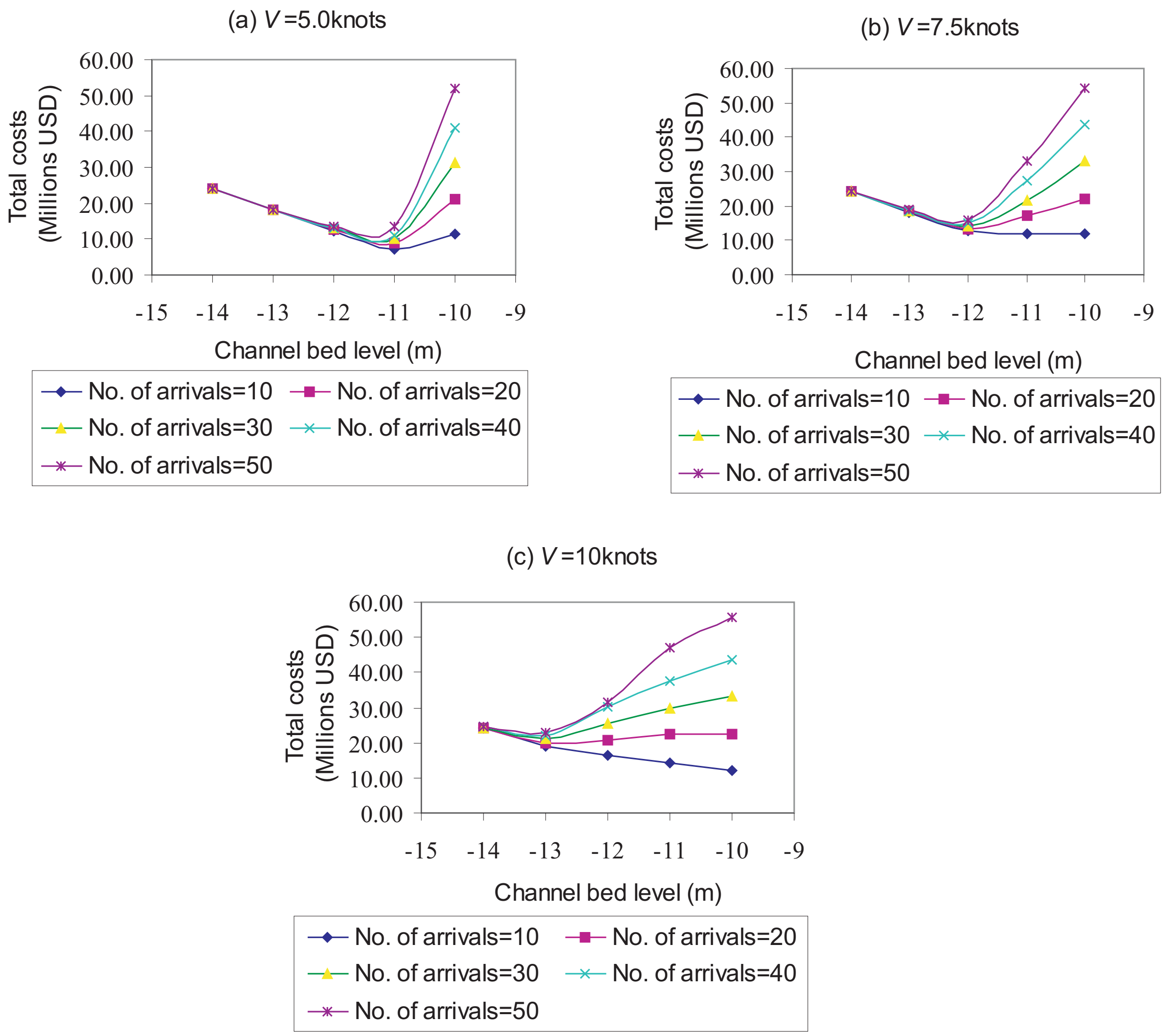

Figure 6.12: Total costs vs. bed levels for various ship speeds and No. of ship arrivals (a)

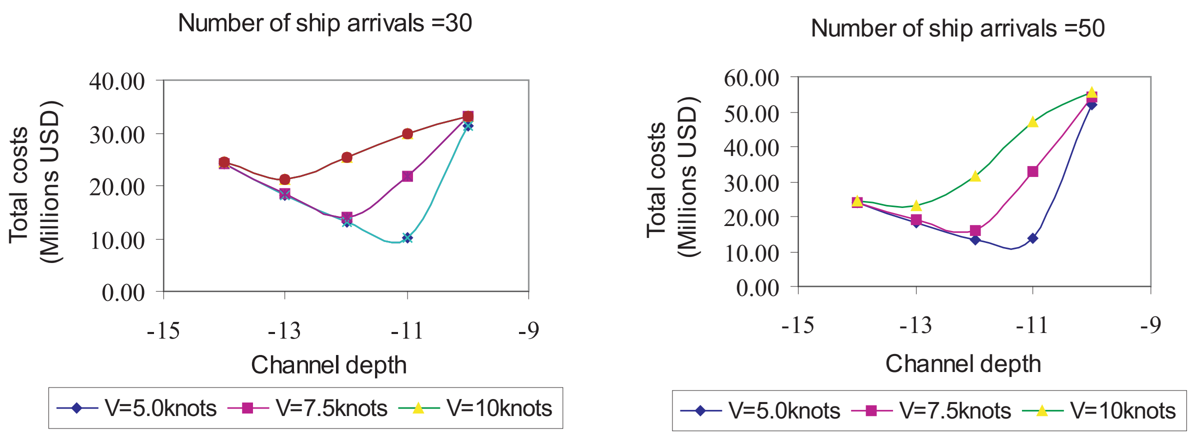

Figure 6.13: Total costs vs. bed levels for various number of arrivals and ship speeds (b)

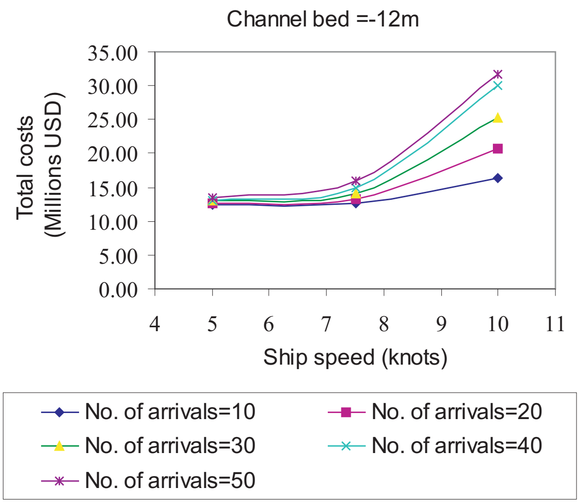

Figure 6.14: Relationship between total costs and ship speeds for various number of arrivals

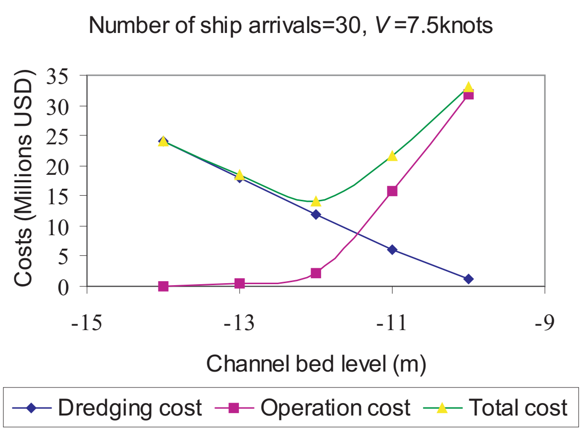

Figure 6.15: Cost details for the selected design

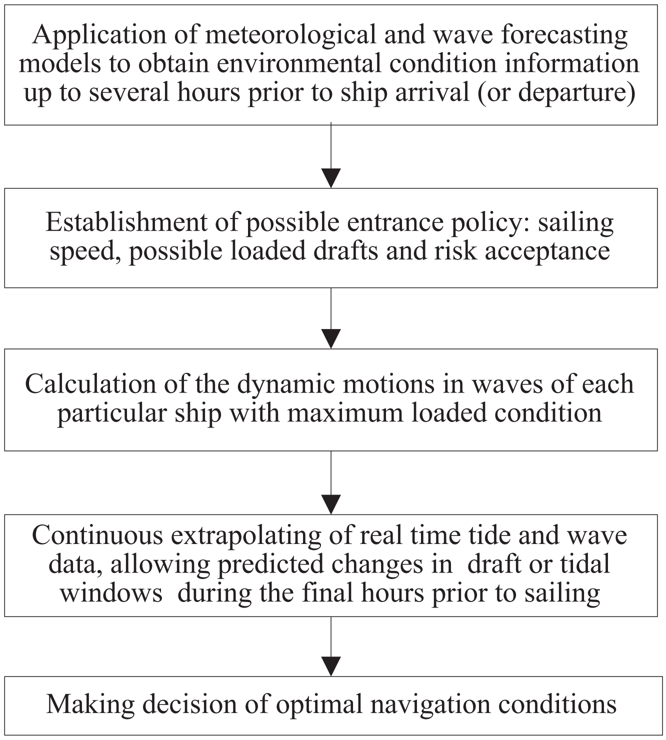

Figure 6.16: Procedure for establishment of probabilistic accessibility policy

6.5 Establishment of probabilistic accessibility policy

As revealed in the previous chapter that for the operation of any approach channel the marine staffs at the ports need an adequate decision support system to make a decision whether a ship is allowed or not to enter the channel. Such channel operation support system can now be developed based on a modern computer technology, ocean monitoring and forecast models and in-depth knowledge of ship behavior in waves (Moes et al., 2002). Based on the data derived from this system such as the ship speed, wave conditions, water variation, a maximum safe underkeel clearance will be determined for ship entrance with an acceptable probability of ship grounding. Such calculation procedure, as shown in Figure 6.16, is often called near real time establishment of the probabilistic entrance policy for the ship entrance. However, due to the stochastic variation of speed and dynamic underkeel clearance; and ship response characteristics are also a function of these factors, the calculation results should therefore be refined in association with the ability for a closer analysis in near real time during the ship passage. Since the response of ship motion in waves can be modeled as a function of ship parameters and wave conditions, the calculation results are not only provided some hours before ship entrance but also being able to be adjusted during the transit if all necessary data are available at the same time of the ship progress. It is hoped that such channel operation system can be applied to Cam Pha Port in near future.

6.6 Conclusions and recommendations

This chapter has demonstrated the application of an appropriate simulation model for investigation of the channel performance in Cam Pha Coal Port. The simulation has been executed for a bulk carrier of 65,000 DWT, which is the most common ship calling the port. However, the approach can be developed and applied to all kinds of ships and entrance channels, especially for the channel which is exposed to open seas. A key component of this model is the application of a wave-induced ship motion model to determine accurately a minimum underkeel clearance with acceptable navigation conditions for a safe transit. A significant part of this study relates to analyzing the effect of water depth fluctuations (the changes in tidal and channel bed levels) and navigation conditions on the channel performance measures such as downtimes, operation and investment costs. The channel simulation model developed for this application has been used to determine the effect on these measures under alternative operating and investment policies. The simulation model includes four main components: (1) an exponential probability law for a number of ship departures; (2) a parametric model of the wave-induced motion response; (3) modeling effects of tidal variations on the channel performance; and (4) a Poisson probability law for a grounding model in a single random ship departure.

Based on the simulation results, we are confident in concluding that a ship which is navigated at a speed of 7.5 knots with a channel bed of 12 m will result in the best strategy when the number of ship arrivals is more than 10. It can be observed in Figure 6.15 for the selected design that the operation cost will be reduced quickly if the channel bed is deeper than 12 m.

However, sailing speed is an important factor which is strongly interactive with the ship maneuvering and steering behavior. The probability of bottom touches decreases with decreasing speed. In many situations, the lower the sailing speed the wider the channel width is required due to the effect of cross wind or current. Further effort needs to be made to incorporate an optimal study of the channel width, so that the whole channel can be optimized in an integrated manner. Moreover, the research should also combine both the channel and quay operation modes.

Finally, it is believed that this approach will provide a more accurate estimate of the required underkeel clearance and the long-term navigation safety or likelihood of a vessel accident than the standard design guidelines when sufficient physical data are available; the accessibility policy for ship entrance as well as the long-term optimization of channel depths will therefore be more accurately and practically achieved.

Chapter 7

Conclusions and recommendations

7.1 Conclusions

The focus of this thesis has been on the development of new computational methods and models for ship accident risk assessment involving restricted or shallow waterway design and operation. The methods, based on the results derived from real time simulations and numerical ship motion models, address two aspects of ship accidents (running aground or colliding with a fixed object) in terms of occurrence probability. The results of risk assessment can be directly applied to the optimal design of waterway dimensions. The following conclusions have been drawn from this research:

7.1.1 The use of the ship handling simulator

There is no doubt that real time simulation is the most highly developed technique and therefore an indispensable tool for the assessment of navigation risk as well as for the designing of waterway. The main application focuses on the optimal design of channel widths to indicate ship maneuverability and possible accident risk in relation to mariner competence and navigation conditions. This design approach usually consists of the following two-step process: first, a ship handling simulator must be implemented to generate the data of ship motion; and then navigation risk can be assessed based on this data.

Recently, much effort has been devoted to the development of these techniques for use in maritime research, especially in the validating of mathematical models of ship motion in shallow waterway at low speed. The results provided by such newly developed simulators will therefore be more and more frequently applied to this particular area of research.

7.1.2 Risk assessment with regard to optimal waterway width designs

The main drawback of real time simulation is that it is time consuming and costly. Only a limited number of maneuvering trials can therefore be investigated. So the calculated risk based on limited simulations can result in under or over-design. Addressing the constraints of real time simulation still remains subject to on-going research. Developing a probabilistic model of an autopilot or a cognitive simulation of navigation is a promising approach. However, despite much effort, this model is still far from complete and suitable for possible application in maritime engineering design and operation.

On-going effort to overcome this limitation, as described in Chapter 3, is continuing in the form of a newly developed method that makes use of ARMAX and semi-Markov models. These models use a set of data measured from real time simulation experiments and geared to predicting ship behavior in “future”. The results derived from the new models are comparable with those obtained from real time simulation. However, the method is restricted to the problem of ship passage tracks forming a stationary process. This necessitates the development of a more advanced model in future.

The evaluation of ship handling difficulty and the question of how to determine the navigation limits caused by a restricted waterway area and heavy weather conditions constitute yet another concern. Much simulation effort is required to formulate an operation rule and to provide reliable guidance for the operation of any channel. Not many comprehensive studies relating to this problem have so far been carried out. On the other hand, estimating the occurrence frequency of such conditions during the lifetime of the channel project, which amounts to the downtime of the waterway service, is of great concern in conjunction with the optimal design process. Utilizing the results of the two previous studies (Welvaarts, 2001; Giang, 2003) a new simulation-based method is proposed to estimate this frequency, as presented in Section 3.4. The initial results are reasonable and encouraging. However, much more effort is needed to refine and validate the safety criteria presented in Figure 3.13.

The ship response (track, course and speed) can be viewed as the output signals of a random process (PIANC, 1997), and as being stationary when mariners have adapted to environmental conditions and have experience with ship characteristics and behavior. This makes it possible to apply the spectral analysis technique to assessing the entire risk level, which is determined for the waterway as a whole by integrating risk along the waterway.

The spectral analysis method and the Poisson description technique are widely applied when it comes to exploring the characteristics of random stationary processes, especially when determining the probability of the random motion process exceeding a certain threshold. Such performance has been widely and successfully applied to the analysis of urban traffic flow and economics (Stathopoulos & Karlaftis, 2001; Granger & Engle, 1982), but unfortunately it has not been found in the literature relating to the study of maritime engineering and transport. A contribution of the present study to this research area is the introduction of the spectral method to the integration of the grounding risk for entire waterways, as presented in Chapter 4. It is assumed that the trajectories of a ship track and swept path are seen as the response ensemble of either a stationary or a non-stationary random process. The study then concentrates on estimating the response characteristics by analyzing their power spectrum density. The probability of a ship exceeding the channel limits within a certain period of time (duration of ship passage throughout the entire waterway) can be determined using the Poisson description. The method could also be useful for evaluating the extent to which mariner competence can be adapted to navigational conditions by exploring the behavior of the power spectrum density function of ship tracks estimated along the waterway.

7.1.3 Risk assessment with regard to optimal designs of waterway depths

In this thesis the assessment of navigation risk in relation to waterway depths is expressed in terms of the probability of a ship touching the bottom.

For the channels that are exposed to the open sea, the determining of channel depth and the making of allowances for underkeel clearance in order to prevent accidents due to grounding is something that is very dependent on wave condition and sailing speed. However, as pointed out in Chapter 2, the present design guidelines for underkeel clearance allowances in coastal entrance channels and shallow waterways, which are very much based on a deterministic approach, are not comprehensive or even conservative (Demirbilek & Frank, 1999). There has therefore been a growing tendency to apply the probabilistic approach to the risk-based optimization of waterway depths, both in design and navigational operation. Apparently this approach depends on the reliable estimation of ship vertical motion response due to wave effects and transit conditions.

Because of the dependence only on wave actions (other external factors including pilot's control effort have little effect so they can be neglected) vertical motion responses can be accurately computed either from numerical models or from tank towing experiments (Cramer & Hansen, 1994). However, these approaches are only applicable to a particular transit condition and a specified sea state which does not satisfy risk- and simulation-based optimization and the operation of channel depths in the long-term. A significant part of this thesis is related to the development of a new model of ship motion response, of how transit conditions and waves affect ship motion. The new model allows us to study ship behavior in all possible ranges of sea state and ship transit parameters. Moreover, all the uncertainties inherent in those parameters can be taken into consideration. The calculated results of the ship motion from the new model compare very well with those of the numerical model, as has been explained and presented in Chapter 5.

The limitations of the existing guidelines (PIANC, 1997; USACE, 1998) for the determination of minimum safe underkeel clearance allowance have been investigated using this new model. It may be concluded that the wave period and ship speed, which are not considered in the above-mentioned guidelines, have a great effect on the ship grounding risk. These results, as revealed in Figures 5.7, 5.8 and 5.9, could be useful when improving guidelines on safe transit before the ship enters the channel. The accessibility policy for ship entrance as well as for the long-term optimal design of channel depths will therefore be more accurately and practically established.

The new parametric model has been successfully applied to developing an appropriate simulation model for the investigation of channel performance as well as for the optimal design of channel depths at the Cam Pha Coal Port. The simulation was executed for a bulk carrier of 65,000 DWT. This simulation model included four main components: (1) an exponential probability law for a number of ship arrivals (departures); (2) the parametric model of wave-induced motion response; (3) the modeling effects of tidal variations on channel performance; and (4) a Poisson probability law for a grounding model in a single random ship arrival. The most advanced part of this simulation model in comparison with former models is the accurately calculated minimum underkeel clearance allowance with possible navigational conditions for safe transit.

7.2 Recommendations

In this section recommendations are given for further simulation experimental work, for more advanced modeling of ship motion response, and for the optimal design of an entire port.

7.2.1 Improvement of the developed models in the present study

The application of the ARMAX and semi-Markov models, as presented in Chapter 3, to generalize the real time simulation data used in the long-term prediction of navigation risk is restricted to the context once the trajectories of ship tracks become stationary random processes. This restriction generates issues that will be used to improve our models more comprehensively. First, the transition matrix as expressed in Equations (3.8) and (3.9) should be a time-dependent conditional probability. This means that the next state of the rudder is not only dependent on the present state but also on the space (position) given that state. The calculation procedure is the same as that described in Chapter 3, but far more complex because more than one transition matrix is being estimated. Secondly, much more effort should also be put into the investigation of dependence regarding ship speed, rudder motion, and other factors affecting ship control. To do that, more real time simulation trials should be conducted and collected.

Sailing speed is an important factor which is strongly interactive with ship maneuvering and steering behavior. As indicated, a required navigational depth can be reduced if the ship is navigated at low speed. However, in many situations, the lower the sailing speed, the wider the channel width requires due to the effect of cross winds and currents. Further effort needs to be made to incorporate an optimal study of the channel width, so that the whole channel can be optimized in an integrated manner.

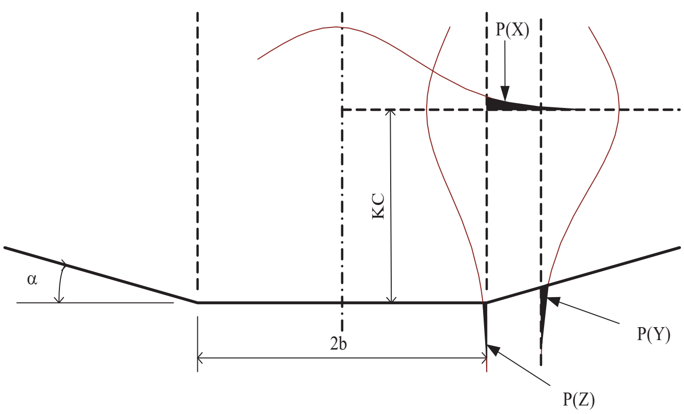

Figure 7.1: Probability calculation of ship grounding and excursion indicated black zones

Suppose that a ship is considered as to be aground, as described in Equation (3.1), when exceeding the channel border somewhat unrealistically. She would be likely to survive a grounding in one of the following cases:

- The water depth is sufficient to allow the pilot to steer her back to the right track.
- There is uncertainty concerning channel depth and width where some parts of the channel are deeper or wider than the designed parameters.

So the total probability that a ship is actually touching the bottom both inside and offside the channel borders, as illustrated in Figure 7.1, is given as (Quy et al., 2005):

$$P_g = P(Z) + P(X)\,P(Y|X) - P(Z)\,P(X)\,P(Y|X) \tag{7.1}$$

Where $P(Z)$ is the probability of ship grounding inside the channel; $P(X)$ is the probability of ship excursion (offside) the channel borders, as determined in Equation (3.1); $P(Y)$ is the probability of ship grounding during excursion; $P(Y|X)$ is the conditional probability of ship grounding during excursion.

There is no easy solution to the above equation because of the following problems:

- The behavior of a ship during excursion from the safe channel boundaries can only be investigated using real time simulation experiments; however, the modeling of ship maneuverability in such cases has not been fully completed.
- Regarding the first problem, before it can be decided whether the ship has had an accident or will survive; the mariners find themselves in a "dangerous situation" for a short period of time. The responses of the mariners during such simulated experimental situations are different from those displayed in reality; neither category of cases has yet been properly understood.
- Uncertainties concerning the channel bed, including the dredged bank slope and siltation, cannot be easily taken into account in the model.

The above-mentioned problems will constitute the further work of this research.

7.2.2 Integrated model of entire port performance evaluation and risk assessment

A seaport can be seen as a complex system of various underwater constructions and facilities such as the entrance channel, breakwater, navigation aids, water basin, anchorage area, berthing and mooring facilities, all of which are exposed to dynamically changing environments. So the safety assessment of a ship during its stay and operation in the port is a very difficult task involving technological, human and organizational factors. A ship may be at risk anywhere in the port at different levels and in different ways that may change dynamically from time to time. There is no general model of overall risk assessment of ship accident in association with the economic optimum for the whole port. It is predicted that in the future a larger-scale model of risk will incorporate the results of entire port performance while introducing more local factors, such as the specifics of channel operation, navigational aid configuration, berthing and mooring procedures and unloading/loading operations. Ultimately a comprehensive model of all the economic and risk factors combined will provide more accurate estimates of the economic loss associated with the risk evaluation of ship accident for the entire port or any given place in the port. This is a challenging issue for researchers.

References

Amrozowicz, M. D., Brown, A., & Golay, M. (1997). A probabilistic analysis of tanker groundings. In 7^{th} *International Offshore and Polar Engineering Conference.* Honolulu, Hawaii.

Andrew, L. S., & John, F. D. (1998). Risk-based decisions for entrance channel operation and design. *International Journal of Offshore and Polar Engineering*, *8*(3), 2000–2006.

Ankudinov, V., & Filippov, I. (2006). Modeling of ship motions in restricted channels on marine simulators. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'06).* Terschelling, Netherlands: Maritime Institute Willem Barentsz (MIWB), Terschelling.

Ankudinov V., J. B. K., Kaplan P. (1993). Assessment and principal structure of the modular mathematical model for ship manoeuverability prediction and real-time simulations. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'93).* Newfoundland, Canada.

Baker, C. W., & McCafferty, D. B. (2005). *Accident database review of human-element concerns* (Tech. Rep.). The Royal Institute of Naval Architects.

Bendat, J. S., & Piersol, A. G. (1986). *Random data: analysis and measurement procedures.* Washington, DC: John Wiley & Sons.

Blendermann. (1994). Parameter identification of wind load on ships. *Journal of Wind Engineering and Industrial Aerodynamics*, *51*(3), 339-351.

Bouw, R. (2005). *Admittance policy tidal bound ships.* Msc. thesis, Delft University of Technologies, Delft, Netherlands.

Briggs, M. J., Borgman, L. E., & Bratteland, E. (2003). Probability assessment for deep-draft navigation channel design. *Coastal Engineering*, *48*, 29–50.

Bruzzone, A. G., Mosca, R., Revetria, R., & Rapallo, S. (2000). Risk analysis in harbor environments using simulation. *Safety Science*, *35*, 75-86.

Burgers, A., & Kok, M. (1989). The statistical analysis of ship maneuvering simulator results for fairway design based on the interdependency of fairway cross-section transits. In 9^{th} *International Harbour Congress.* Antwerp, Belgium.

Burnay, S., & Ankudinov, V. (2003). The prediction of hydrodynamic forces acting on the hull of maneuvering ship based upon a database of prediction methods. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Chun, K. L., & Kijima, K. (2003). On the safe navigation considering the interaction forces between ships in confined water. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Corotis, R. B., Vanmarcke, E. H., & Cornell, C. A. (1972). First passage of non-stationary random processes. *Journal of Engineering Mechanics Division*, *98*(2), 401-415.

Cramer, E. H., & Hansen, P. F. (1994). Stochastic modeling of long term wave induced response of ship structure. *Marine Structure*, *7*, 537-566.

Daggett, L. L., Hewlett, J. C., Ankudinov, V., & Webb, D. (2003). Validation of ship motion models in shallow/restricted waters. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Dand, I. (2003). Low speed maneuvering criteria: some considerations. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Dand, I. W., & Colwill, R. D. (2003). Simulation of traffic flows using dynamic ship modeling. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Da-Qing, L., Ottosson, P., & Tragardh, P. (2003). Prediction of bank effects by model tests and mathematical models. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Demirbilek, Z., & Frank, S. (1999). *Deep-draft coastal navigation entrance channel practice* (Tech. Rep.). Washington, DC: US Army Corp of Engineers.

DMA. (2007). *http://www.sofartsstyrelsen.dk/sw228.asp* (Tech. Rep.). 38 C, Vermundsgade, DK-2100 Copenhagen.

ECO. (2005). *Maritime safety* (Tech. Rep.). Luxembourg: Official Publications of the European Communities.

Eide, M. S., Soma, T., Endresen, O., & Brett, P. O. (2006). *Risk based ship prioritisation* (Tech. Rep.). Hovik, Norway: Det Norske Veritas.

Eloot, K. (2006b). *Selection experimental determination and evaluation of a mathematical model for ship maneuvering in shallow water.* PhD thesis, Universiteit Gent.

Eloot, K., & Vantorre, M. (2004). Prediction of low speed maneuvering based on captive model tests: opportunities and limitations. In 31^{st} *Annual General Meeting of IMSF.* Antwerp, Belgium: Ghent University.

Emrullah, D. (2003). Simulation modelling and analysis of a port investment. *SIMULATION*, *79*(2), 94-105.

Fossen, T. I. (1994). *Guidance and control of ocean vehicles.* John Wiley & Sons.

Fowler, T. G., & Sorgard, E. (2000). Modeling ship transport risk. *Risk Analysis*, *20*(2).

Giang, H. H. (2003). *Probabilistic design of approach channel widths.* Prepared for: WL|Delft Hydraulics and Dutch institute MARIN, International Institute for Infrastructural, Hydraulic and Environmental Engineering, Delft, Netherlands.

Granger, C. W. J., & Engle, R. (1982). *Applications of spectral analysis econometrics* (Vol. 3). Handbook of Statistics.

Gucma, L. (2000). The method of average navigation risk assessment with consideration of inequality of ships accident probability along the waterway. In *Risk Analysis II.* Southampton-Boston: Wit Press.

Gucma, L. (2005). Methods of probability assessment of ships accidents on restricted water areas. In

K. Kolowrocki (Ed.), *Advances in Safety and Reliability* (Vol. 2, p. 717-735). Gdansk, Poland: Taylor & Francis Group, London.

Gucma, L. (2006). The method of navigational risk assessment on waterways based on generalised real time simulation data. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'06).* Terschelling, Netherlands: Maritime Institute Willem Barentsz (MIWB), Terschelling.

Gucma, L., & Pietrzykowski, Z. (2006). Ship maneuvering in restricted areas: an attempt to quantify dangerous situations using a probabilistic-fuzzy method. *The Journal of Navigation*, *59*, 251-262.

Hanekamp, H. B., & Vries, W. A. (1998). Development in safety management for the North Sea and the approaches to Rotterdam. In 29^{th} *International Navigation Congress* (p. 39-53). The Hague, Netherlands.

Haskoning, R. (2004). *Master plan report* (Tech. Rep.). Mombasa Port, Kenya: Kenya Port Authority.

HELCOM. (2006). *Maritime transport in the Baltic Sea* (Tech. Rep.). Helsinki, Finland: Baltic Marine Environment Protection Commission.

Howell, R. (2002). Predicted under keel clearance. In *PIANC* 30^{th} *International Navigation Congress* (Vol. S7D P110, p. 1334-1346). Sydney.

Hu, S., Fang, Q., Xia, H., & Xi, Y. (2007). Formal safety assessment based on relative risks model in ship navigation. *Reliability Engineering and System Safety*, *92*, 369-377.

Huchison, B. (2003). Maneuvering simulation: An application to waterway navigability. In *World Maritime Technology Conference.* San Francisco.

Hwang, W. Y. (2004). *Guidelines for documenting math models for ship-handling simulator users not majored in hydrodynamics and math modeling* (Tech. Rep.). 31^{st} IMSF Annual General Meeting: U.S. Merchant Marine Academy.

IMO. (2007). *http://www.imo.org* (Tech. Rep.). 4 Albert Embankment, London SE1 7SR, UK.

Iribarren, J. R. (1998). *Determining the horizontal dimensions of ship maneuvering areas* (Tech. Rep.). PIANC Bulletin 100.

Isherwood, R. M. (1972). Wind resistance of merchant ships. *Trans. RINA*, *15*, 327-338.

Itoh, K., Yamaguchi, T., Hansen, J. P., & Nielsen, F. R. (2001). Risk analysis of ship navigation by use of cognitive simulation. *Cognition, Technology and Work*, *3*, 4-21.

Janssen, J., & Manca, R. (2006). *Applied semi-markov processes.* Springer Science, Inc.

Jiang, T., & Henn, R. (2003). Numerical prediction of ship squat and trim in shallow water. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Jones, D. L. (2005). *Prony's method* (Tech. Rep.). Connexions Project. http://cnx.org/content/m12762/latest.

Journee, J. M. J. (2001). *User manual of SEAWAY.* Technology University of Delft.

Journee, J. M. J. (2002). *Introduction in ship hydro-mechanics.* Delft University of Technology.

Kite-Powell, Hauke, L., & Jin, D. (1999). Investigation of potential risk factors for groundings of commercial vessels in U.S. ports. *International Journal of Offshore and Polar Engineering*, *9*(1).

Kristiansen, S. (2005). *Maritime transport: Safety management and risk analysis.* London: Elsevier Butterworth-Heinemann.

Lan, J. (2003). *Probabilistic design of channel widths.* Prepared for: WL|Delft Hydraulics and Dutch institute MARIN, International Institute for Infrastructural, Hydraulic and Environmental Engineering, Delft, Netherlands.

Lee, S., Kijima, Y., K. Furukawa, & Nakiri, Y. (2006). Ship maneuvering characteristics as function of ship form in shallow water. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'06).* Terschelling, Netherlands: Maritime Institute Willem Barentsz (MIWB), Terschelling.

Lin, S., Kite-Powell, H. L., & Patrikalakis, N. M. (1998). Physical risk analysis of ship grounding. In *Massachusetts Institute of Technology.* Massachusetts, USA.

Lin, Y. K. (1967). *Probabilistic theory of structure dynamics.* McGRAW-HILL, Inc.

Literingen, H. (2000). *Ports and terminals.* Netherlands: Delft University of Technology.

Liu, C. P., Chu, C. W., Liang, G. S., & Su, Y. (2005). Establishing marine accident classification: A case study in Taiwan. *Journal of the Eastern Asia Society for Transportation Studies*, *6*, 952-967.

Magnus, S. E., Endresen, Q., Breivik, Q., Brude, O. W., & Ellingen, H. I. (2007). Prevention of oil spill from shipping by modeling of dynamic risk. *Marine Pollution Bulletin*, *54*, 1619-1633.

Matlab. (2005). *System idetification toolbox, version 7.0.4.365* [CD-ROM, License 58666]. The MathWork, Inc.

McDuff, T. (1974). *The probability of vessels collision* (Tech. Rep.). Washington, DC: Ocean Industry.

Mecklenbrauker, W., & Hlawatsch, F. (Eds.). (1997). *The Wigner distribution: theory and applications in signal processing.* ELSEVIER Science B.V.

Memos, D., & Tzanis, K. (2000). Joint distribution of wave heights and periods in waters of any depth. *Journal of Waterway, port, Coastal, and Ocean Engineering*, *126*(3), 162-172.

Merrick, R. W., Dorp, J. R., Blackford, J. P., Shaw, G. L., Harrald, J., & Mazzuchi, T. (2003). A traffic density analysis of proposed ferry service expansion in San Francisco bay using a maritime simulation model. *Reliability Engineering and System Safety*, *81*, 119-132.

Merrick, R. W., Dorp, J. R. v., Mazzuchi, T. A., & Harrald, J. R. (2001). Modeling risk in the dynamic environment of maritime transportation. In *Proceedings of the 2001 Winter Simulation Conference.* Arlington, VA, USA.

Meyer, S. (2005). *Anual report 2005: Marine accident investigation branch* (Tech. Rep.).

Michele, V., Roberta, D., Luca, S., & Carlo, P. (2003). Alternative methods for identification of hydrodynamic coefficients from manoeuvers. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Moes, J., Rossouw, M., Brophy, M., & Loon, F. V. (2002). Minimum safe underkeel clearance in port entrance channels. In *PIANC* 30^{th} *International navigation congress* (Vol. S10B P153, p. 1828-1835). Sydney.

Murata, S., & Kobayashi, H. (2003). Quantitative estimation of safety degree on ship's operations. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Nakamura, S. (2005). *Ship-handling simulation study for Cai Mep-Thi Vai International Terminals* (Tech. Rep.). Japan Marine Science Inc.

Ninness, B., Wills, A., & Gibson, S. (2005). *Identification toolbox UNIT-EE05031* (Tech. Rep.). The University of Newcastle.

O'brien, T. (2002). Experience using dynamic underkeel clearance systems: selected case studies and recent developments. In *PIANC* 30^{th} *International Navigational Congress* (Vol. S10B P150, p. 1793-1804). Sydney.

Ochi, M. K. (1990). *Applied probability and stochastic processes in engineering and physical sciences.* New York: John Wiley & Sons.

OCIMF. (1977). *Prediction of wind and current loads on VLCCs* (Tech. Rep.). London, England: Oil Companies International Marine Forum.

Otto, S., Pedersen, P. T., Samuelides, M., & Sames, P. C. (2002). Elements of risk analysis for collision and grounding of a Ro-Ro passenger ferry. *Marine Structures*, *15*, 461-474.

Pawlowski, J. S. (1996). Hydrodynamic modeling for ship maneuvering simulation. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'96).* Denmark.

PIANC. (1992). *Capacity of ship maneuvering simulation models for approach channels and fairways in harbors* (Tech. Rep.). Brussels, Belgium: Supplement to Bulletin No.77.

PIANC. (1997). *Approach channels - a guide for design* (Tech. Rep.). Brussels, Belgium: Final report of the joint PIANC-IAPH.

Price, W. G., & Bishop, R. E. D. (1974). *Probabilistic theory of ship dynamics.* New York: John Wiley & Sons.

Priestley, M. B. (1994). *Spectral analysis and time series: Probability and mathematical statistics* (Vol. 1 & 2). London: Academic Press Limited.

Quy, N. M. (2001). *Feasibility study project of expansion of Cam Pha Coal Port* (Tech. Rep.). Vietnamese Coal Incorporation, in Vietnamese.

Quy, N. M., Vrijling, J. K., & Gelder, P. (2008). Risk- and simulation-based optimization of channel depths: Entrance channel of Cam Pha Coal Port. *SIMULATION*, *84*(1), 41-55.

Quy, N. M., Vrijling, J. K., Gelder, P., & Groenveld, R. (2005). Methods to assess safety criteria of approach channels with respect to the acceptability of ship grounding risks. In 6^{th} *International Symposium on Navigation* (p. 69-76). Gydnia, Poland: Gdynia Maritime University.

Quy, N. M., Vrijling, J. K., Gelder, P., & Groenveld, R. (2006). On the assessment of ship grounding risk in restricted channels. In 8^{th} *International Conference on Marine Sciences and Technologies* (Vol. 1, p. 294-299). Festival and Congress Center - Varna, Bulgaria.

Quy, N. M., Vrijling, J. K., Gelder, P., & Groenveld, R. (2007a). Identification and estimation of ship navigational limits for waterway designs using simulation. In 4^{th} *International Conference on Collision and Grounding of Ships* (p. 79-85). Hamburg, Germany.

Quy, N. M., Vrijling, J. K., Gelder, P., & Groenveld, R. (2007b). Long-term prediction of navigational risk for maritime engineering design using simulation. In *Asian and Pacific Coast Conference* (p. 1605-1611). Nanjing, China Ocean Press.

Quy, N. M., Vrijling, J. K., Gelder, P., & Groenveld, R. (2007c). Modeling of ship motion responses and its application to risk-based design and operation of entrance channel. *Journal of Maritime Research*, *4*(2), 47-62.

Quy, N. M., Vrijling, J. K., Gelder, P., & Groenveld, R. (2007d). Parametric modeling of ship motion responses for risk-based optimization of entrance channel depths. In 11^{th} *World Conference on Transport Research* (p. ID-212). University of California, Berkeley, USA.

Quy, N. M., Vrijling, J. K., Gelder, P., & Groenveld, R. (2007e). Simulation-based optimization of navigational depths: A case study at the entrance channel of Cam Pha Coal Port. In *Asian Conference on Modeling and Simulation* (p. 192-198). Bejing, ACTA Press.

Quy, N. M., Vrijling, J. K., Gelder, P., Groenveld, R., & Gucma, L. (2006a). On the probabilistic analysis of non-stationary ship maneuvering results for waterway design. In 31^{st} *PIANC Congress* (p. 1-4). Estoril, Portugal.

Quy, N. M., Vrijling, J. K., Gelder, P., Groenveld, R., & Gucma, L. (2006b). On the statistical analysis and probabilistic modelling of ship maneuvering results for waterway design. In J. O. Puig, R. M. Barbe, & V. G. Carcelle (Eds.), 3^{th} *International Conference on Maritime Transport* (p. 189-198). Barcelona, Spain.

Quy, N. M., Vrijling, J. K., Gelder, P., Gucma, L., & Nakamura, S. (2008). Generalization of ship performance for long-term prediction of navigation risk. *Submitted to Journal of Marine Science and Technology*.

Rosqvist, T., & Tuominen, R. (2004). Qualification of formal safety assessment: An exploration study. *Safety Science*, *42*, 99-120.

Sarioz, K., & Narli, E. (2003). Assessment of maneuvering performance of large tankers in restricted waterways: A real time simulation approach. *Ocean Engineering*, *30*.

Savenije, R. P. A. C. (1995). *Probabilistic admittance policy deep draught vessels* (Tech. Rep.). Rotterdam, Netherlands: Ministry of Transport, Public Works and Water Management, Transport Research Centre.

Savenije, R. P. A. C. (1998). *Safety criteria for approach channels* (Tech. Rep.). Rotterdam, Netherlands: Ministry of Transport, Public Works and Water Management, Transport Research Centre.

Sii, H. S., Wang, J., Liang, G. S., & Ruxton, T. (2001). Novel risk assessment techniques for maritime safety management system. *International Journal of Quality and Reliability Management*, *18*(9), 982-1000.

Simonsen, B. C. (1997). *Mechanics of ship grounding.* PhD thesis, Technical University of Denmark.

Simonsen, B. C., & Hansen, P. F. (2000). Theoretical and statistical analysis of ship grounding accidents. *Journal of Offshore Mechanics and Arctic Engineering*, *122*, 200-207.

Simonsen, B. C., & Hansen, P. F. (2002). GRACAT: Software for grounding and collision risk analysis. *Marine Structure*, *15*, 383-401.

Simonsen, C. D., Stern, F., & Agdrup, K. (2006). CFD with PHH test validation for maneuvering VLCC2 tanker in deep and shallow water. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'06).* Terschelling, Netherlands: Maritime Institute Willem Barentsz (MIWB), Terschelling.

Stathopoulos, A., & Karlaftis, M. G. (2001). Spectral and cross-spectral analysis of urban traffic flows. In *IEEE Intelligent Systems Conference Proceedings.* Oakland, USA.

Strating, J., Schilperoort, T., & Blaauw, H. G. (1982). *Optimization of depths of channels* (Tech. Rep.). Netherlands: Delft Hydraulics.

Teng, C. C., & Liu, P. C. (2000). Estimating wave height distributions from wind speed distributions. *Coastal Engineering*, *1*, 310-319.

Thompson-Clarke. (2007). *Assistance with the implementation of an underkeel clearance system for torres strait* (Tech. Rep.). Australian Maritime Safety Authority, Australian: Australian Maritime Safety Authority.

Thoresen, C. (2005). *Port designer's handbook: Recommendations and guidelines.* London: Thomas Telford Ltd.

Thuy, N. N., Hoi, N. T., & Loc, D. Q. (1998). *Regioning study of wind and wave characteristics of Vietnam Coasts* (Tech. Rep.). Hanoi, Vietnam: Vietnam Meteorologic and Ocean Hydraulic Center in Vietnamese.

Trucco, P., Cagno, E., Ruggeri, F., & Grande, O. (2007). A Bayesian belief network modeling of organisational factors in risk analysis: A case study in maritime transportation. *Reliability Engineering and System Safety*, *in press*.

USACE. (1998). *Hydraulic design of deep-draft navigation projects.* Washington, DC: USA Army Corps of Engineers.

USACE. (2006). *Hydraulic design of deep-draft navigation projects.* Washington, DC: USA Army Corps of Engineers.

Vantorre, M., Delefortrie, G., Eloot, K., & Laforce, E. (2003). Experimental investigation on ship-bank interaction forces. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Vantorre, M., & Johan, J. (2003). Validation of strip theory code seaway by model test in very shallow water. In *Flander Hydraulics Research, Antwerp, Belgium.*

Vantorre, M., & Laforce, E. (2002). Development of a probabilistic admittance policy for the Flemish harbours. In *PIANC* 30^{th} *International Navigation Congress* (Vol. S7D P107, p. 1299-1314). Sydney.

Vrijling, J. K. (1995). *Probability of obstruction of the entrance channel* (Tech. Rep.). Delft University of Technology.

Vrijling, J. K. (2004). Audit *HARAP* (Tech. Rep.). Delft, Netherlands: Delft University of Technology.

Vrijling, J. K., & Gelder, P. (2004). *Probabilistic design.* Netherlands: Technology University of Delft.

Wang, G., Spencer, J., & Yongjun, C. (2002). Assessment of ships performance in accidents. *Marine Structures*, *15*, 313-333.

Wang, J. (2001). The current status and future aspects in formal ship safety assessment. *Safety Science*, *38*, 19-30.

Wang, J. (2004). Use of advances in technology for maritime risk assessment. *Risk Analysis*, *24*(4), 1041-1063.

Wang, J. (2006). Maritime risk assessment and its current status. *Quality and Reliability Engineering International*, *22*, 3-19.

Webster, C. (1992). *Shiphandling simulation application to waterway design.* New York: National Academy of Sciences, United States of America.

Wei-Yuan, H., Jakobsen, B. K., Barr, R. A., Ankudinov, V. K., & Fuller, N. R. (2003). An exploratory study to characteristize ship maneuvering performance at slow speed. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Welvaarts, W. (2001). *Risk analysis of vessels exceeding horizontal boundaries in a channel.* Prepared for: WL|Delft Hydraulics and Dutch institute MARIN, Delft University of Technologies, Delft, Netherlands.

Wendy, L. M., & Angel, R. M. (2002). *Computational statistics handbook with MATLAB* (Tech. Rep.). Printed in the United States of America: Chapman & Hall/CRC.

Yasukawa, H. (2003). Simulation of ship collision caused by hydrodynamic interaction between ships. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'03).* Kanazawa, Japan.

Yasukawa, H., & Kobayashi, E. (1995). Shallow water model experiments on ship turning performance. In *Mini Symposium on Ship Manoeuverability.* Fukuoka, Japan.

Yeon, S. M., Yeo, D. J., & Rhee, K. P. (2006). Optimal input design for the identification of low speed maneuvering mathematical model. In *International Conference on Marine Simulation and Ship Maneuverability, (MARSIM'06).* Terschelling, Netherlands: Maritime Institute Willem Barentsz (MIWB), Terschelling.

Appendix A

Definition of widths and extra depth for approach channel design

A.1 Basic and additional widths by PIANC

The values of the basic maneuvering width (W_{BM}), additional widths (W_i) and widths for bank clearance (W_{br} and W_{bg}) as mentioned in Eq. 2.1 are given in Tables A.1, A.2 and A.3.

Table A.1: Basic maneuvering lane

Ship maneuverability	good	moderate	poor
Basic maneuvering lane, W_{BM}	1.3B	1.5B	1.8B

Table A.2: Additional widths for bank clearance (W_{br} and W_{bg})

Width for bank clearance	Ship speed	Outer channel exposed to open water	Inner channel protected water
Sloping channel and shoals	fast	0.7B	-
	moderate	0.5B	0.5B
	slow	0.3B	0.3B
Steep and hard embankment	fast	1.3B	-
	moderate	1.0B	1.0B
	slow	0.5B	0.5B

A.2 Allowances to the underkeel clearance by Vietnamese practice

This section presents Vietnamese practice for definition of the allowances to the underkeel clearance as mentioned in Eq. 2.5

Allowances for sailing and steering possibility, Z_1

Allowances for sailing and steering possibility are defined as a multiple of the draft T of the design ship and depend on the type of surface soil with thickness of at least 0.5 m, as shown in Table A.4 and A.5.

Table A.3: Additional widths for straight channel section

Width W_i	Ship speed	Outer channel	Inner channel
1. Ship speed (knots)			
fast > 12		0.1B	0.1B
moderate > 8-12		0.0	0.0
slow 5-8		0.0	0.0
2. Prevailing cross wind (knots)			
mild $\leq$ 15 ($\leq$ Beaufort 4)	all	0.0	0.0
moderate > 15-33 (> B4 - B7)	fast	0.3B	-
	mod	0.4B	0.4B
	slow	0.5B	0.5B
sever > 33-48 (> B7 - B9)	fast	0.6B	-
	mod	0.8B	0.8B
	slow	1.0B	1.0B
3. Prevailing cross current (knots)			
negligible < 0.2	all	0.0	0.0
low 0.2-0.5	fast	0.1B	-
	mod	0.2B	0.1B
	slow	0.3B	0.2B
moderate > 0.5-1.5	fast	0.5B	-
	mod	0.7B	0.5B
	slow	1.0B	0.8B
strong > 1.5-2	fast	0.7B	-
	mod	1.0B	-
	slow	1.3B	-
4. Prevailing longitudinal current (knots)			
low $\leq$ 1.5	all	0.0	0.0
moderate > 1.5-3	fast	0.0	-
	mod	0.1B	0.1B
	slow	0.2B	0.2B
strong > 3	fast	0.1B	-
	mod	0.2B	0.2B
	slow	0.4B	0.4B
5. Significant wave H_s & length λ (m)			
$H_s \leq 1$ and $\lambda \leq L$	all	0.0	0.0
$3 > H_s > 1$ and $\lambda = L$	fast	2.0B	
	mod	1.0B	
	slow	0.5B	
$H_s > 3$ and $\lambda > L$	fast	3.0B	
	mod	2.2B	
	slow	1.5B	
6. Aids to navigation			
excellent with shore traffic control		0.0	0.0
good		0.1B	0.1B
moderate with infrequent poor visibility		0.2B	0.2B
moderate with frequent poor visibility		$\geq$ 0.5B	$\geq$ 0.5B
7. Bottom surface			
depth $\geq$ 1.5T		0.0	0.0
depth < 1.5T then			
- smooth and soft		0.1B	0.1B
- smooth or sloping and hard		0.1B	0.1B
- rough and hard		0.2B	0.2B
8. Depth of waterway			
$\leq$1.5T		0.0	0.0 ($\geq$ 1.5T)
1.5T - 1.25T		0.1B	0.2B (< 1.5-1.15T)
< 1.25T		0.2B	0.4B (< 1.15T)
9. Cargo hazard level			
low		0.0	0.0
medium		0.5B	0.4B
high		1.0B	0.8B

Table A.4: Allowances for sailing and steering possibility

The type of bottom surface soil with thickness at least 0,5m	Z_1 (m)
Mud or very soft soil	$0.04T$
Deposit soil mixed with mud	$0.05T$
Hard soil or rock	$0.06T$

Allowances for waves, Z_2

For following and heading waves, the wave allowances can be defined from wave height, $H_{3\%}$ (the wave height with occurrence frequency of 3% in all waves recorded), as given in the following table.

Table A.5: Wave allowances, Z_2 (m)

Overal length	$H_{3\%}$									
of ship (m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
75	0	0.05	0.20	0.35	0.55	0.75	1.05	1.30	1.60	1.90
100	0	0.05	0.15	0.25	0.40	0.60	0.80	1.05	1.30	1.60
150	0	0	0.05	0.15	0.25	0.35	0.50	0.65	0.85	1.10
200	0	0	0.05	0.05	0.15	0.25	0.50	0.60	0.60	0.80
250	0	0	0	0.05	0.10	0.15	0.25	0.35	0.45	0.60
300	0	0	0	0.00	0.05	0.10	0.20	0.25	0.35	0.50

For other wave directions ($\phi \neq 180^o$ & 0^o) these values should be reduced by dividing to the factor K_2 as defined follows: for $0^o \leq \phi < 15^o$, $K_2 = 1.0$; for $15^o \leq \phi < 35^o$, $K_2 = 1.4$; for $35^o \leq \phi < 90^o$, $K_2 = 1.7$.

Allowances for squat, Z_3

The values in Table A.6 defined for squat allowances, which can be applied to all ship types with the water depth is not less than 7.0m.

Allowances for siltation, Z_4

The allowance for siltation depends on the annual siltation rate, which is defined by measuring the thicknesses of siltation in the dredged holds laying along the proposed waterway. Maximum siltation allowances should not be larger 1.2m. The value of 0.4m is commonly adopted in many cases.

Allowances for unbalanced loading, Z_o

Allowances for unbalanced loading, Z_o, can be determined from the following formula:

$$Z_o = \frac{B}{2}\sin\alpha - Z_1 \tag{A.1}$$

where B is the beam of ship; $\alpha = 2^o$ for tanker ship and $=4^o$ for general cargo ship with dead weight tonage (DWT) $\geq$ 6,000 ton, and $= 8^o$ for DWT $<$ 6,000 ton.

Table A.6: Squat allowances, Z_3 (m)

Ship speed	Allowances for squat, Z_3 (m)	
	Dredged-type channel	Canal-type channel
2	0.05-0.1	0.10
3	0.10	0.15
4	0.10-0.15	0.20
5	0.15-0.20	0.25
6	0.20-0.25	0.35
7	0.25-0.35	0.45
8	0.35-0.50	0.60
9	0.45-0.65	0.80
10	0.60-0.90	1.10
11	0.80-1.20	-
12	> 1.00	-

Appendix B

Linear programming solution of environmental combinations

Environmental conditions of the approach channel at IJmuiden port

Table B.1: Occurrence frequencies of current speeds

Direction	Current speeds (m/s)												Total
(degree)	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	
15	0.000	0.000	0.083	0.083	0.000	0.000	0.083	0.000	0.083	0.083	0.000	0.000	0.415
190	0.083	0.000	0.083	0.000	0.000	0.000	0.083	0.083	0.083	0.083	0.000	0.083	0.581

Table B.2: Occurrence frequencies of wind speeds

Wind speed	Wind direction (degree)											
(m/s)	15	45	75	105	135	165	195	225	255	285	315	345
2.5	0.00365	0.00376	0.00328	0.01001	0.01181	0.0074	0.00624	0.00583	0.00503	0.00463	0.00457	0.00418
5.0	0.01549	0.01541	0.01945	0.0308	0.02917	0.03026	0.01362	0.01679	0.0187	0.01803	0.01498	0.01721
7.5	0.01484	0.01491	0.0345	0.01647	0.01105	0.03213	0.02575	0.03552	0.02856	0.02151	0.01723	0.02326
10.0	0.00795	0.00729	0.02181	0.00328	0.00129	0.01011	0.0244	0.05042	0.02865	0.01723	0.01385	0.01384
12.5	0.00187	0.00238	0.00671	0.00102	0.00003	0.00243	0.01785	0.04477	0.01842	0.01186	0.00981	0.00625
15.0	0.00044	0.00009	0.00158	0.00028	0	0.00053	0.00908	0.02175	0.00888	0.00671	0.00587	0.00248
17.5	0.00004	0	0.00005	0	0	0.00015	0.0043	0.00805	0.00395	0.00474	0.00218	0.0008
20.0	0	0	0	0	0	0	0.00094	0.00249	0.00196	0.00156	0.00046	0.00006
22.5	0	0	0	0	0	0	0.00011	0.00023	0.00044	0.00004	0.00002	0
25.0	0	0	0	0	0	0	0	0.00005	0.00008	0	0	0
Total	0.04428	0.04384	0.08738	0.06186	0.05335	0.08301	0.10229	0.1859	0.11467	0.08631	0.06897	0.06808

Table B.3: Occurrence frequencies of significant wave heights

Sig. wave	Wave direction (degree)											
height (m)	15	45	75	105	135	165	195	225	255	285	315	345
0.2	0.05742	0.01264	0.00410	0.00290	0.00265	0.00230	0.00610	0.02049	0.02543	0.03323	0.11743	0.33645
0.4	0.00899	0.00085	0.00005	0.00000	0.00000	0.00005	0.00005	0.00760	0.01174	0.00740	0.03043	0.16400
0.6	0.00190	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00275	0.00385	0.00235	0.00755	0.05477
0.8	0.00050	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00070	0.00180	0.00060	0.00395	0.02109
1.0	0.00015	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00025	0.00070	0.00040	0.00220	0.00939
1.2	0.00025	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00025	0.00010	0.00025	0.00110	0.00575
1.4	0.00015	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00015	0.00045	0.00005	0.00060	0.00420
1.6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00015	0.00035	0.00000	0.00075	0.00240
1.8	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00010	0.00015	0.00010	0.00040	0.00200
2.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00010	0.00015	0.00010	0.00020	0.00190
2.2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00015	0.00000	0.00035	0.00165
2.4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00010	0.00005	0.00020	0.00150
2.6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00005	0.00010	0.00005	0.00015	0.00080
2.8	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00005	0.00000	0.00010	0.00060
3.0	0.00005	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00010	0.00020	0.00065
3.5	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00015	0.00010	0.00010	0.00055	0.00030
Total	0.06942	0.01349	0.00415	0.00290	0.00265	0.00235	0.00615	0.03274	0.04522	0.04478	0.16616	0.60745

Linear programming solution

This section describes the procedure of a linear programming solution of environmental combinations as developed by Briggs et al. (2003).

Let the mixture of environmental conditions occurring at the harbor entrance channel at any particular time be classified into one of the following three categories:

- A = extreme conditions during which ship passage would be attempted;
- B = normal conditions, which would always allow attempted passage; and
- C = gentle (no problems with environmental conditions).

These criteria are then set up so that the mix of environmental conditions of wind, wave, and current at any particular time can always be classified into one, and only one, of these categories. This criterion was based on an evaluation of the contribution from each of the environmental conditions of wind, wave, and current to navigation safety. Winds (w), waves (H_s), and currents (v) were separately divided into severe (A), normal (B), and gentle (C) categories.

Table B.4: Individual environmental probabilities

Categories	Wind	Wave	Current	Criteria
A	0.03270	0.01696	0.083	w >15m/s; H_s ≥1.5m; v ≥0.6m/s
B	0.38127	0.10374	0.581	7.5< w ≤15m/s; 0.5m≤ H_s <1.5m; 0.2m/s< v <0.6m/s
C	0.58603	0.85230	0.336	w ≤ 7.5m/s; H_s <0.5m; v ≤0.2m/s

Table B lists individual probabilities for winds $P(w_i)$, waves $P(Hs_i)$, and currents $P(v_i)$ in each category, where subscript $i = A, B$, or C. These probabilities were calculated from the measured wind, wave, and current data as presented in Tables B.1, B.2 and B.3. These individual probabilities are then combined in the paragraphs below to arrive at the final overall environmental probability $P[Env = j]$ for each of the three categories. Let each possible logical combination of the interdependent wind, wave, and current conditions be represented by three alphabetic letters or triples. The first letter is the wind category, the second is the wave category, and the third is the current category. Thus, AAC would be Category A winds, Category A waves, and Category C currents. The set of all (logically) possible combinations are listed in Table B:

Table B.5: possible combinations of environmental conditions

	Win			Wave			Current		
Category A	AAA	ABA	ACA	AAA	BAA	CAA	AAA	ABA	ACA
	AAB	ABB	ACB	AAB	BAB	CAB	BAA	BBA	BCA
	AAC	ABC	ACC	AAC	BAC	CAC	CAA	CBA	CCA
Category B	BAA	BBA	BCA	ABA	BBA	CBA	AAB	ABB	ACB
	BAB	BBB	BCB	ABB	BBB	CBB	BAB	BBB	BCB
	BAC	BBC	BCC	ABC	BBC	CBC	CAB	CBB	CCB
Category C	CAA	CBA	CCA	ACA	BCA	CCA	AAC	ABC	ACC
	CAB	CBB	CCB	ACB	BCB	CCB	BAC	BBC	BCC
	CAC	CBC	CCC	ACC	BCC	CCC	CAC	CBC	CCC

Some of these combinations are physically very unlikely or impossible. Thus, ACC (high winds, but low waves and currents) is quite unlikely.

From two these tables we have 27 joint probabilities of combinations in each category, they are constrained to satisfy nine equations as presenting in following tables:

Table B.6: Probabilities of wind occurrence in the categories

Wind					Probabilities of the combination, $P_{i,j,k}$					Row sums
Wind in category A	AAA	AAB	AAC	ABA	ABB	ABC	ACA	ACB	ACC	0.03270
Wind in category B	BAA	BAB	BAC	BBA	BBB	BBC	BCA	BCB	BCC	0.38127
Wind in category C	CAA	CAB	CAC	CBA	CBB	CBC	CCA	CCB	CCC	0.58603

Table B.7: Probabilities of wave occurrence in the categories

Wave					Probabilities of the combination, $P_{i,j,k}$					Row sums
Wave in category A	AAA	AAB	AAC	BAA	BAB	BAC	CAA	CAB	CAC	0.01696
Wind in category B	ABA	ABB	ABC	BBA	BBB	BBC	CBA	CBB	CBC	0.10374
Wind in category C	ACA	ACB	ACC	BCA	BCB	BCC	CCA	CCB	CCC	0.85230

Table B.8: Probabilities of current occurrence in the categories

Current					Probabilities of the combination, $P_{i,j,k}$					Row sums
Current in category A	AAA	ABA	ACA	BAA	BBA	BCA	CAA	CBA	CCA	0.083
Current in category B	AAB	ABB	ACB	BAB	BBB	BCB	CAB	CBB	CCB	0.581
Current in category C	AAC	ABC	ACC	BAC	BBC	BCC	CAC	CBC	CCC	0.336

The first row of Table B, for an example, can be rewritten in the equation form for wind in category A as:

$$P[\text{Env} = \text{extreme}] = P_{\text{AAA}}+P_{\text{AAB}}+P_{AAC}+P_{\text{ABA}}+P_{\text{ABB}}+P_{\text{ABC}}+P_{\text{ACA}}+P_{\text{ACB}}+P_{\text{ACC}} = 0.01 \quad \text{(B.1)}$$

and so on, these nine equations can be expressed in the matrix equation

$$Ax = b \quad \text{(B.2)}$$

where A is the matrix of once and zero with size of (27 $\times$ 9); and x and b are defined as:

$$\begin{aligned} x = [&P_{\text{AAA}} + P_{\text{AAB}}+P_{AAC} + P_{\text{ABA}} + P_{\text{ABB}} + P_{\text{ABC}} + P_{\text{ACA}} + P_{\text{ACB}} + P_{\text{ACC}} \\ &+P_{\text{BAA}} + P_{\text{BAB}} + P_{\text{BAC}} + P_{\text{BBA}} + P_{\text{BBB}} + P_{\text{BBC}} + P_{\text{BCA}} + P_{\text{BCB}} + P_{\text{BCC}} \\ &+P_{\text{CAA}} + P_{\text{CAB}} + P_{\text{CAC}} + P_{\text{CBA}} + P_{\text{CBB}} + P_{\text{CBC}} + P_{\text{CCA}} + P_{\text{CCB}} + P_{\text{CCC}}]^T \end{aligned} \quad \text{(B.3)}$$

$$b = [1, 0, 0, 0, 0, 0, 0, 0, 0, 0]^T \tag{B.4}$$

Whatever the joint probabilities are, they must satisfy $Ax = b$ structurally. Furthermore, each of the nine joint probabilities must be non-negative and less than or equal to one, if there are to be probabilities. A reasonable, somewhat conservative approach would be to choose values for the joint probabilities which maximize P[Env=normal]. This leads to the following condition for possible solution of linear programming method:

- $Ax = b$;
- $0 \leq$ (All components of x) ≤ 1; and
- P[Env=normal] is maximized.

This general structure is the set of conditions for a linear programming problem. Various software packages are available for the solution (e.g., "linprog" in the Matlab Optimization Toolbox). The Matlab program was used for the currently stated problem to obtain x.

Appendix C

The reverse arrangement test for stationarity

Let it be hypothesized that the sequence of sample mean square values $(\bar{x}_1^2, \bar{x}_2^2, \ldots, \bar{x}_N^2)$ represents independent sample measurements of a stationary random variable with mean square value of ψ_x^2. If this hypothesis is true, the variations in the sequence of sample values will be random and display no trend, the hypothesis of stationarity is accepted. Otherwise, this is rejected. Meaning that any non-stationarity of interest will be revealed by trends in the mean square value of the data. For detecting trends in the sequence, the reverse arrangement test (RAT) is the most effective and powerful tool. The RAT is applied as a test for stationarity as follows (Bendat & Piersol, 1986):

- Divide the assemble record into N equal time intervals where the data in each interval may be considered independent;
- Compute a mean square value for each interval and align these values in time sequence;
- Count the number of times that $x_i > x_j$ for $i < j$, each such inequality is called a reverse arrangement. The total number of reverse arrangement, denoted by A, is determined as follows:

$$h_{ij} = \begin{cases} 1 & \text{if } x_i > x_j \\ 0 & \text{otherwise,} \quad \text{then} \end{cases} \tag{C.1}$$

$$A = \sum_{i=1}^{N-1} A_i \qquad \text{where} \tag{C.2}$$

$$A_i = \sum_{j=1}^{N} h_{ij} \tag{C.3}$$

Since the sequence of N values are independent, then the total number of reverse arrangements is a random variable, with a mean and variance values as:

$$\mu_A = N(N-1)/4 \tag{C.4}$$

$$\sigma_A^2 = (2N^3 + 3N^2 - 5N)/72 \tag{C.5}$$

Tabulation of percentage points for the distribution function of A presented in the following:

Table C.1: Percentage points of reverse arrangement distribution

N	σ					
	0.990	0.975	0.950	0.050	0.025	0.010
40	290	305	319	460	474	489
50	473	495	514	710	729	751
60	702	731	756	1013	1038	1067
70	977	1014	1045	1369	1400	1437
80	1299	1344	1382	1777	1815	1860
90	1668	1721	1766	2238	2283	2236

Now, let it be hypothesized that the sequence of N values belong to stationary random process, where there is no trend. The acceptable region for this hypothesis is:

$$[A_{N,1-\sigma/2} < A \leq A_{N,\sigma/2}] \tag{C.6}$$

where σ is the level of significant of the test; and the value of $A_{N,\sigma/2}$ such that Prob$[A_N > A_{N,\sigma/2} = \sigma/2]$.

Appendix D

Estimation of the Fourier transform

The analytic signal, $s(t)$, is defined by (Mecklenbrauker & Hlawatsch, 1997):

$$s(t) = x(t) + j\tilde{x}(t) \tag{D.1}$$

Where $\tilde{x}(t)$ is the Hilbert transform of $x(t)$. Once can also write $s(t)$ in another form as:

$$s(t) = A(t)e^{j\theta(t)} \tag{D.2}$$

Where $A(t)$ is called the envelop signal of $x(t)$ and $\theta(t)$ is called instantaneous phase signal of $x(t)$, which are expressed as (Bendat & Piersol, 1986):

$$A(t) = \left[x^2(t) + \tilde{x}^2(t)\right]^{1/2} \tag{D.3}$$

$$\theta(t) = tan^{-1}\left[\frac{\tilde{x}^2(t)}{x(t)}\right] = 2\pi f_0 t \tag{D.4}$$

The instantaneous frequency f_o is given by:

$$f_0 = \left(\frac{1}{2\pi}\right)\frac{d\theta(t)}{dt} \tag{D.5}$$

It is a very simple transform to obtain $Z(f)$ from $X(f)$. One should compute $X(f)$ for all f and then define $Z(f)$ by $Z(0) = X(0)$ and

$$Z(f) = \begin{cases} 2X(f) & \text{for } f > 0 \\ 0 & \text{for } f < 0 \end{cases} \tag{D.6}$$

The inverse Fourier transform of $Z(f)$ give $s(t)$ with:

$$\tilde{x}(t) = \mathrm{Im}[s(t)] \quad \text{and} \quad x(t) = \mathrm{Re}[s(t)] \tag{D.7}$$

For digital computations of the response assemble $\{x_i(n\Delta t)\}$ under study, here $n = 0, 1, \ldots, N-1$; $i = 1, 2, \ldots, n_s$, Eq. (D.7) can be rewritten as:

$$x(n\Delta t) = 2\Delta f \mathrm{Re}\left[\sum_{k=0}^{N/2} X_i(k\Delta f) exp\left(\frac{j2\pi kn}{N}\right)\right] \tag{D.8}$$

$$\tilde{x}(n\Delta t) = 2\Delta f \mathrm{Im}\left[\sum_{k=0}^{N/2} X_i(k\Delta f) exp\left(\frac{j2\pi kn}{N}\right)\right] \tag{D.9}$$

Here, the factor $\Delta f = 1/(N\Delta t)$ with:

$$X_i(k\Delta t) = \Delta t \sum_{n=0}^{N-1} x_i(n\Delta t) exp\left(\frac{-j2\pi kn}{N}\right) \tag{D.10}$$

Note that the values of $X_i(k\Delta t)$ are needed only from $k = 0$ up to $k = N/2$, where $Nyquist$ frequency occurs, to obtain the digitized values of $x(n\Delta t)$ and its the Hilbert transform $\tilde{x}(n\Delta t)$. The envelop signal of $x(n\Delta t)$ in Eq. (D.4) in discrete form is:

$$A(n\Delta t) = \left[x^2(n\Delta t) + \tilde{x}^2(n\Delta t)\right]^{1/2} \tag{D.11}$$

The analytic signal $s(t)$ is then estimated from Eq. (D.1)

Acknowledgements

After four years of doing this research I feel like a captain driving a *ship* and trying to accommodate safely at the final destination, the Aula Centrum. I did a lot of calculations on the risk of ship accidents as presented herein; but I have not tried to estimate the failure probability of my voyager. However, I am sure that it would not be finished without the help of the people around me.

First of all, I would like to express my sincere appreciation to Han Vrijling, my promotor, for allowing me great freedom in formulating my new ideas. From him I have learned to work with efficiency and effectiveness, as he always has the goal in mind. Not only did he show me how to do good research but he also generated great motivation and encouragement in developing my research.

The second person I would like to mention is Pieter van Gelder, my co-promoter and daily supervisor. Can you imagine how hard he was to be a daily supervisor of a PhD student. I went to him every day, asking questions, discussing probabilistic design and even disturbing him. I would like to thank him for sharing his expertise, for his patient and his kind support.

I am greatly indebted to Lars Frydkaer who I have been working with during past ten years in the field of port construction. He helped me all the way and all the time in not only reviewing my English writing but also commenting my research works and papers. It was amazing that he answered my emails from anywhere at anytime, even two o'clock in the morning. He is more than my friend, he is like a brother.

I would like to express my gratitude to Rink Groenveld, my second daily supervisor and lecturer of port and waterway design, which is of great concern with my research subject. Thank you for your ideas and for showing me the gaps in the maritime research that formed my research topics during all phases of my research. I also want to thank Kohei Nagai, who unexpectedly became my "third supervisor". He was always available whenever I need his help. His criticisms were strict but undoubtedly helpful and substantial. I wish to express my appreciation to J.M.J. Journee and the people in Faculty of 3mE, Section of Ship Hydromechanics and Structures, for giving me the valuable comments and the numerical model of ship motion (SEAWAY), which was used in this study.

I am very honored to have such an international committee with well-known experts in the field of my research. Thank them for giving me valuable comments, data and your co-operation in writing the papers by which my research activities were progressed.

I am very thankful to the Ministry of Vietnam Education through all the staff members of the Project 322 for sponsoring of my project. I also grateful to all CICAT staffs, especially Paul Althuis and Veronique Van der Vast, for their administration and financial supports.

Cheers and many thanks to all my colleagues and friends in Delft who offered ideas, thoughts, games and humor that helped me to release all of tremendous workload and to refresh myself.

All the members of my family contributed to this thesis in many ways more than they could realize. I want to thank my parents in law for their continual supports and always back me from distance. I am deeply indebted to my parents for their unconditional credit and supports that have sustained me throughout my life.

Being alone for a long time with very heavy works to take care of my big family has been great sacrifice of my wife, Ngo Thu Thuy; special thanks for all her supports and patience during hard time. Finally, I thank my two sons, Minh Anh and Minh Duc, for their great contribution to make my desire come true. Their angel faces with smiles are indispensably inspiring source to all my successes.

Nguyen Minh Quy

Delft, June 2008

About the Author

The author was born in Hanoi, Vietnam on the 22^{nd} of October 1970. In 1989 he started studying Port and Waterway Engineering at Hanoi University of Civil Engineering, where he obtained his BSc degree in port engineering in 2001.

Since 1994, he has worked for the Transport Engineering Design Incorporation, the largest consulting company in Vietnam, as Port and Waterway Engineer. During his professional career, he has been the consultant and project manager responsible for more than 50 different port and harbor projects in Vietnam and abroad, including Japan, Kenya and Indonesia.

In August 2004, he started his PhD research at the Section of Hydraulic Engineering, Delft University of Technology under the supervision of Prof. J.K. Vrijling and Dr. P.H.A.J.M. van Gelder. The research has been sponsored by Ministry of Education, Vietnam via Project 322 with financial assistance from CICAT, Delft University of Technology.