PORT PLANNING

Nautical Access Recommendations

2023

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EDITION

PRATICAGEM DO BRASIL

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TABLE OF CONTENTS

PREFACE

The Brazilian maritime nature is indisputable,furthermore the sea importance for the continuity and development of the country whether in terms of maritime trading or the exploration of the existing wealth at sea and seabed. The Brazilian territorial waters, including the Blue Amazon, are essential for the economy, national defense, and the Brazilian energy matrix. In this context, the combination of ships and ports is fundamental for the survival of a country that is oriented towards the sea. The dependence of Brazil on the sea is undeniable.

When analyzing the supply chain of basic necessities for people's daily lives, it becomes evident that, in addition to ships, ports also play a crucial role. They serve as gateways for the flow of goods and wealth to and from our continental country, reaching even the most remote destinations.

Overtime, we observed an interesting trend: for different reasons, especially in economy and preservation of the environment, the dimensions of the ships in terms of length, beam and draught have increased extraordinarily. The ships are increasing. What about the ports? Those built more recently were able to adjust their projects, adapting their characteristics to modern times, but older ports find themselves forced to adapt or adjust operational parameters, at the risk of losing merchandise, in terms of regional competitiveness.

Port facilities are essential components of the logistics supply chain via sea and river routes. In order to accommodate modern and larger ships, ports require constant modernization and appropriate infrastructure for the loading and offloading of the most varied types of goods transported by the vessels that dock there.

Thus, to plan new port facilities and their access or with the aim of improving the assess risks for a ship of larger dimensions than those initially planned to enter a existing port, an academic study that clearly addresses the current international references on port planning, especially publications from Pianc (The World Association for Waterborne Transport Infrastructure).

I was very pleased to receive the invitation to preface the work "Port Planning - Recommendations on Nautical Accesses". This book is the result of the collective effort of several academics with extensive knowledge of various areas related to the subject, all with the common goal of providing the maritime community with a national academic reference, in the language Portuguese, which is based on knowledge extracted from the international best practices manuals regarding aspects related to the compatibility of the waterways with the type of ships that will sail in them. In addition, the information presented in this book can also contribute to studies and simulations aiming at setting up or modifying operational parameters of existing fairways to accommodate larger ships, which comes happening more frequently due to the increase in port activities in our country.

When navigating through the lines of this book, we come across all the components that must be considered in the planning and implementation of a port facility, characteristics of the port entrance ways and the numerous variables that must be mathematically evaluated such as depth, channel dimensions and maneuvering basin areas, berths and anchorages. Hydrodynamic and meteorological effects are also studied, and their potential risks o ships.

It is important to emphasize that the authors have used an extremely technical approach, focusing on the number of variables related to the maneuverability of the type of ship, such as turning circles, acceleration, deceleration, the influence of currents, wind and waves, in addition to the hydrodynamic effects of navigation in restricted waters and the performance of tugboats. Fluid mud navigation is also addressed, as well as very important concepts such as the squat effect, nautical bottom, and dynamic draught.

The approach to the general classification of merchant ships is highly beneficial, as it is crucial for planners and those involved in the port's operational parameters to be knowledgeable about the characteristics of type of ships and their evolution over time. Another important point is the part of this book that deals with risk analysis, an inexorable requirement in the process of port planning, from its preliminary design phase, continuing during the preparation of the project, an occasion in which the safety aspects of operations in the port are focused, allowing the proposition of risk mitigation or contingency actions.

The book presents methods and techniques for simulating ship maneuvers, presenting technical support for an adequate simulation of different scenarios, which, at present, is fundamental, as it virtually creates a similar environment to that of the port facility under analysis, as well as the characteristics of the ships that will operate in that port, making it possible to assess risks and subsidize decisions.

In conclusion, I express my gratitude to the distinguished authors and organizers for this invaluable piece that thoroughly covers all the requirements related to the planning and safety of navigation resulting from the ship x port interaction in the maritime area. The approach, despite prioritizing technique, does not divert attention from practice, as it covers relevant topics to the navigator, such as dimensions of the channel, buoyage, pilotage, tugboats port and port facilities, among other aspects already mentioned

I would like to emphasize that this publication is not a regulatory document and is not exhaustive in its coverage of the subject. However, it is a significant technical-academic contribution that can inspire and serve as a reference for professionals involved in port planning and channel management, as it is based on internationally recognized good safety practices.

May the progress of maritimity, the growth of Brazil and safety navigation be the north of all those dedicated to planning port facilities in our country. Enjoy the reading!

Vice Admiral (VAlte RM1) Wilson Pereira de Lima Filho

President of the Maritime Tribunal

LIST OF FIGURES

* Figures taken from the books *A manobrabilidade do navio no século 21* and *Princípios de hidrodinâmica e a ação das ondas sobre o movimento do navio*, kindly provided by the author, Edson Mesquita dos Santos.

LIST OF TABLES

CHAPTER 1
Introduction

Waterborne transport is the most economical way of transporting goods and raw materials in large quantities from one place to another. More than 80 percent of internationally traded products are like this transported, and, in the case of raw materials, this value exceeds 90 percent. When observing the location of Brazil and the countries with which it maintains extensive trade, the significant importance of the waterborne transport for imports and exports is evident.

Port facilities are fundamental parts of the waterborne transport chain, and ports require constant modernization to accommodate new types of ships, larger ones, increased vessel traffic, as well as for the construction of facilities suitable for different types of goods transported. Furthermore, new port facilities are being planned for the future, primarily driven by Law No. 12.815/2016 (Law of Ports), which offers greater flexibility for private sector investments in port development.

In recent decades, there has been a strong advance in scientific and technological knowledge, which was crucial for the accelerated advance of waterborne transport : traffic simulators; simulators maneuvers; more advanced methods of designing and building ships and port facilities; equipped ships of advanced steering, propulsion, control, loading systems; port facilities also equipped with advanced loading and unloading systems; etc., all of them contributed to the development of the sector.

It is worth noting that various international publications and recommendations from the International Maritime Organization (IMO) suggest that not only new projects, but also any physical or operational changes to ports that may affect ship maneuverability and create new practices must undergo analysis and decisions involving maritime and port authorities, users, simulation centers and engineering offices.

In view of this, a multidisciplinary group consisting of designers, researchers, engineers, seafarers, shipowners, ports, and terminals was created to prepare clear recommendations for port projects. These recommendations are based on consolidated technological knowledge and the guidelines of international entities. However, it is crucial to establish the phases of the project on which these recommendations are focused. To do this, Decision 106 of CONFEA – Conselho Federal de Engenharia e Agronomia *(Federal Council of Engineering and Agronomy)*, Law No. 8.666 of June 21, 1993, and Resolution No. 361 of CONFEA, which define the terms "project", "basic project", and "executive project", will be observed. This book adopts the definitions and attributions established in these regulations.

The initial phase of a basic project involves political and planning decisions made by the competent port authorities, administrations, users, project offices and construction companies. Following this decision-making phase, the project moves into a more detailed stage. The scope of a basic project is outlined in the regulations of the Federal Council of Engineering and Agronomy (CONFEA). This book provides recommendations for the design of port construction to support the development of a future basic project. However, the recommendations presented here do not cover the entire scope of port construction design. The contents covered are strongly related to those addressed in documents such as the 2014-PIANC Harbour Approach Channels, Recommendaciones para Obras Marítimas, and the United States Army Corps of Engineers (USACE). As such, we adopt the division established by PIANC, presenting the recommendations in two phases: the Concept Project phase and the Detailed Project phase.

It can be challenging to differentiate the phase of political decisions and initial planning from the concept phase of the basic project, since the initial phase of the project requires establishing parameters that enable a preliminary evaluation of its technical, economic, environmental and social feasibility. In this phase, nautical operation ideas begin to take shape, allowing for the development of technical analyses. Initially, these ideas are mere expectations that are not yet precisely consolidated into a *stricto sensu* project. Thus, the phase in which these decisions are made and preliminary evaluations of the project's main parameters are carried out is often referred to as a preliminary project.

It is essential to highlight that the purpose of this book is to provide recommendations and best practices to engineers responsible for formulating the basic project, in order to establish clear and well-defined parameters to be achieved in the executive project, as this stage is crucial for the success of the undertaking.

These recommendations cover both the geometric aspects of channels, pilot points, ports, terminals, and waterways, as well as the dynamics of navigation. They are based on the premise that navigation should be carried out in the safest possible manner.

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CHAPTER 2
Port Fairways

2.1. Introduction

The objective of this chapter is to explore navigation on entrance channels to port facilities. It complies recommendations presented by international entities to be considered in projects of port facilities, channel projects, proposals for accommodating new types of ships and all other design changes that may affect the operation of ships, resulting in new maneuvers or practices.

These recommendations cover both, the geometric aspects of the channels and the evolution, along with the dynamics of navigation, aiming to carry it out efficiently and as safely as possible. Safety is influenced by the size and maneuverability of the ships that will use the fairway, the channel dimensions, the type of navigational aid, environmental conditions (currents, winds and waves) and the experience of users, captains, harbour masters and pilots. Safety and efficiency must be considered before optimizing the project in relation to costs, as they are strongly associated with the human factor, which is very difficult to measure, and it is also recommended the mitigation of potentially dangerous conditions as much as possible (ASCE Manuals and Reports on Engineering Practice No. 94, 1998, p. 4).

The ideal design of a port requires an assessment of the physical environment, currents, and climatic conditions. Additionally, it is crucial to understand the safety factors that depend on pilots' responses and other users who are exempt from pilotage. When pilots are not required, special attention should be given to traffic coordination.

As mentioned in the Introduction of this book, following the normative decision 106 (Law No. 8.666, of June 21, 1993) and Resolution No. 361, both by CONFEA, and the division established by PIANC, the recommendations contained in this chapter focus on the basic design, divided into two phases: the Concept Design and the Detailed Design.

International publications and recommendations by the International Maritime Organization (IMO) suggest that any changes in port operations that may impact ship maneuvering, creating new practices, must undergo several analyses and decisions involving Maritime and Port Authorities, users, simulation centers and engineers. The 2014 PIANC Report-121 provides a flowchart (Figure 2.1) that gives an idea of the suggested process.

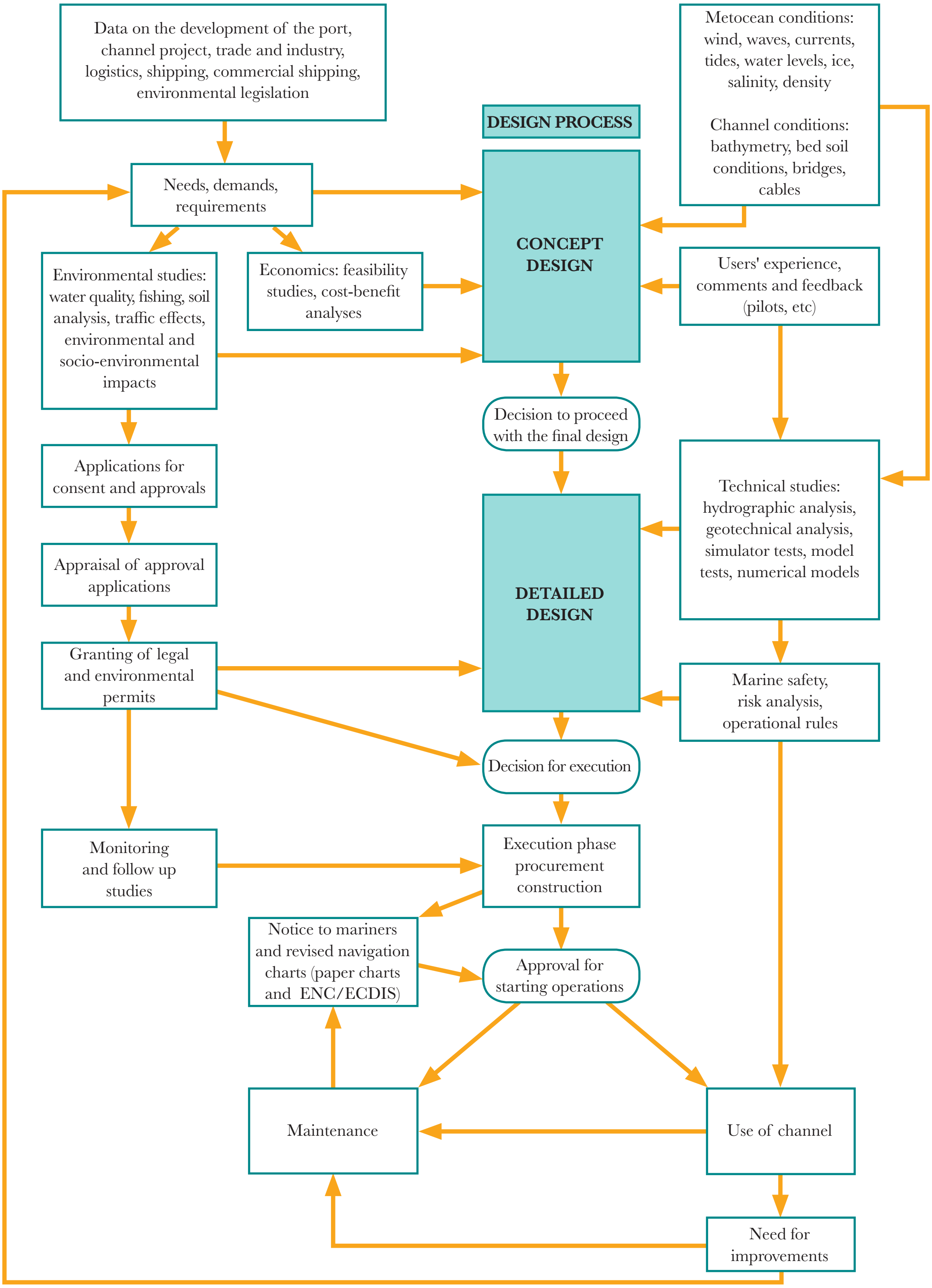


Figure 2.1. Flowchart (Pianc 121, 2014, p. 16)

2.2. Definitions of Concept Design and Detailed Design

Concept Design

The Concept Design defines the main geometrical dimensions of channels, inner channels, maneuvering basins and port facilities. Although the depth, width and alignment of a channel are closely related, they are considered separately. The objective is to minimize the number of alternative solutions for the dimensions (width, depth, and alignment) of the channel, maneuvering basin, inner channel, and other port facility details, identifying one or more viable proposals for the Detailed Design.

The Concept Design process begins with the preliminary design phase, where the width, depth, and alignment of the channel are determined using simplified data and formulas that are relevant to the ships and environmental characteristics.

Once the preliminary design is established, the channel dimensions are re-evaluated with more accurate data on environmental characteristics, which may require field surveys, and the maneuvering of the project ship. During this stage, risk analyses and simplified simulations may be conducted. The final result must be the most reliable hypothesis of geometry and dimensions of nautical access, ensuring its safety, maneuverability and navigability.

Detailed Design

The Detailed Design is a process assigned to validate, develop and improve the initial Concept Design, according to the realistic environmental and operational data, including the movement and maneuverability of the project ship, risk analyses, implementation and maintenance costs, and other possible impacts.

The methods used in the Detailed Design may vary, but they often rely on both numerical and physical models, and therefore need a greater amount of information, technical assessment, and experience to interpret results accurately as well as. The depth, width and alignment of the channel shall be analyzed in conjunction with the maneuverability of the design ship under local environmental conditions. Operational rules which refer to constraints due to environmental conditions, the design ship particularities, (proppultion system, rudder type, etc), towing assistance, including (bollard pull, type and positioning of tugs) etc.

2.3. Concept Design

Components

The Concept Design components are the following:

a. Channels
b. Maneuvering area
c. Inner or approach channels
d. Maneuvering basins
e. Anchorages
f. Port facilities
g. Tugboat bollard pull and push-pull forces
h. Air draught and air draught clearance
i. Risk management and analysis
j. Floating terminals

2.3.1. Channels

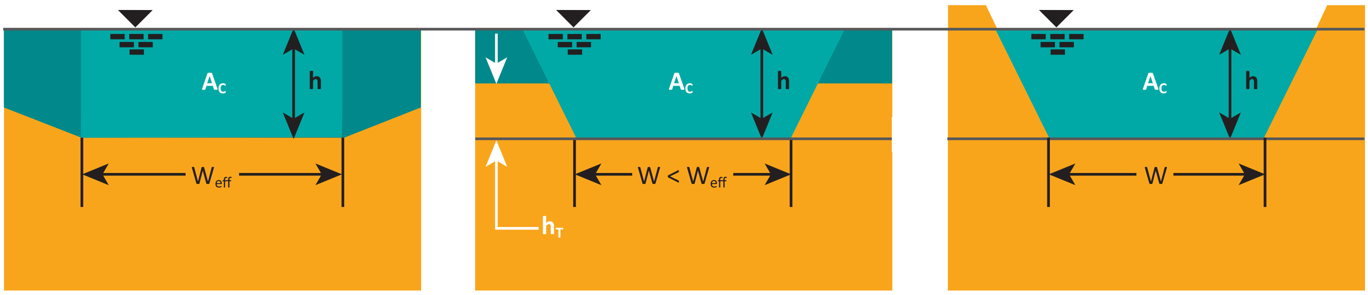
2.3.1.1. Types

Channels are classified in two categories based on their ability to protect ships from sea waves:

a. Outer channels: These channels are directly exposed to sea waves, which can cause vertical motion (heaving) on the ship, with significant wave periods above six (6) seconds.
b. Inner channels: These channels are situated in an environment relatively shielded from sea waves, with significant wave periods under six (6) seconds.

Concerning geometry, channels are classified as shown in Figure 2.2:

a. Open or unrestricted channels, symbolized by the letter U
b. Laterally restricted channels with underwater trench (dredged channels), symbolized by the letter R
c. Canal channels with a high trench, which are the narrow stretches of rivers and waterways, symbolized by the letter C.



Unrestricted channel - U   Restricted channel - R   Canal - C

Figure 2.2. Types of channels (PIANC 121, 2014, p. 28)

Open or unrestricted channels (symbolized by U) are relatively large and have either no banks or banks with a slope of less than 1:10, and are generally found at the ends of port facilities. River stretches can be classified as laterally unrestricted channels if they are wide enough (i.e. section width is greater than eight times the beam of the ship for a depth/draught ratio of 1.2)

Restricted channels (R) with immersed slopes are typical in dredged channels. This type of channel is an intermediate between the open type and the one with emersed banks.

The canal channel with side walls (C) is a special case of this type, in which the height of the sides extends above the water surface.

Channels may be characterized by one or more of these types, and the cross sections may have different configurations along the channel. They can also be a combination of these three types, with an open and unrestricted channel on one side and restricted with side walls on the other.

An unrestricted channel can be created from a restricted channel if it is wide enough. Studies with reduced physical models or numerical models can be used to define how wide the restricted channel should be, depending on the beam of the ship and the depth to avoid being affected by the bank effect.

The parameters that define the geometry of channels will be presented in Chapter 5, item 5.2.

2.3.1.2. Channel depth (PIANC 121, 2014, section 2.1.)

The required depth at each location shall be determined taking the following into account:

a. The water levels in question and the factors that affect their variability, determining the reference plane for the vertical position of the ship, which includes reduction levels on nautical charts, astronomical tides, elevation of water levels due to meteorological conditions, variations in the flow rate of rivers, etc.;
b. ship-related factors that may cause any part of the hull to reach a level lower than the keel level under static or dynamic conditions; and
c. the seabed and aspects that affect its variability, which include bathymetric inaccuracies, tolerance to sedimentation and dredging.

During the first phase of the Concept Design, can be used as an initial estimate of the depth, depending on the speed of the ship, the waves and the conditions of the channel bottom, the values listed in the Table 2.1. Additionally, this table provides a recommended air draught clearance (ADC), which will be further discussed later (PIANC 121, 2014, p. 37).

If the design ship in the preliminary design phase is a container ship, a passenger ship, a Ro-Ro vessel or a ship that acquires dynamic transverse heel when turning or when under the action of transverse environmental forces, a separate estimate for dynamic heel shall be included, which should be added to the ship-related factors.

2.3.1.2.1. Factors associated with channel depth

When designing a channel, the following recommendations shall be taken into account in relation to the three factors associated with the mentioned vertical dimensions. These factors are interrelated with each others.

Table 2.1. Channel depth component and air draught estimates for the preliminary design (PIANC, 121, 2014, p. 38, Table 2.2)

<table>
<tr><th>Description</th><th>Vessel Speed</th><th>Wave Conditions</th><th>Channel Bottom</th><th>Inner Channel</th><th>Outer Channel</th></tr>
<tr><td colspan="6">Ship Related Factors Fs</td></tr>
<tr><td rowspan="10">Depth h</td><td>$\leq$ 10 knots</td><td rowspan="3">None</td><td></td><td>1.10T</td><td></td></tr>
<tr><td>10-15 knots</td><td></td><td>1.12T</td><td></td></tr>
<tr><td>$>$ 15 knots</td><td></td><td>1.15T</td><td></td></tr>
<tr><td rowspan="3">All</td><td>Low Swell
$(H_s) < 1m)$</td><td></td><td></td><td>1.15T to 1.2T</td></tr>
<tr><td>Moderate Swell
$(1m < H_s < 2m)$</td><td></td><td></td><td>1.2T to 1.3T</td></tr>
<tr><td>Heavy Swell
$(H_s > 2m)$</td><td></td><td></td><td>1.3T to 1.4T</td></tr>
<tr><td colspan="5">Add for Channel Bottom Type</td></tr>
<tr><td rowspan="3">All</td><td rowspan="3">All</td><td>Mud</td><td>None</td><td>None</td></tr>
<tr><td>Sand/clay</td><td>0.4m</td><td>0.5m</td></tr>
<tr><td>Rocks/coral</td><td>0.5m</td><td>1m</td></tr>
<tr><td colspan="6">Air Draught Clearance (ADC)</td></tr>
<tr><td>ADC</td><td>All</td><td>All</td><td></td><td>$0.05H_{st}$</td><td>$0.05H_{st} + 0.4T$</td></tr>
</table>

Note 1: For Ship Related Factors: Assumes T > 10 m. If T < 10 m, use value for T = 10m.

Note 2: Swell means waves with peak periods T_p greater than 10s.

Note 3: For Outer Channel swell values, use lower value for smaller swell wave periods and higher value for larger swell periods.

Note 4: Value of significant wave height H_s is dependent on required operation, design ship type, level of accessibility, wave period and relative wave direction

Note 5: H_{st} is the distance from the surface of the sea to the top of the ship.

Note 6: Seawater density assumed for T. Additional adjustments required if fresh water.

2.3.1.2.2. Factors associated with the water level

These factors include the reference level (datum) of a selected design water level, astronomical and meteorological tidal effects and possible unfavorable conditions, as described below.

a. Design water level

– The design water level is the first step for determining the appropriate depth for a channel. It is influenced not only by astronomical and meteorological factors, but also by the draughts of the design ships, local operating conditions, ecological considerations and currents. The optimal or ideal depth condition of a channel is therefore an iterative process involving trial selection of different design water levels. (PIANC 121, 2014, p. 24).

b. Tidal variation during transit

– The water level in a channel is influenced by both astronomical tides and meteorological effects. The tide varies over time and space. The tide varies in time and space, and this variation can be obtained by data collection, analysis and interpretation of water level records or can be predicted using tide charts or mathematical models;

– In cases of appreciable tidal elevations or long channels influenced by the tide, the decision to use the channel should be based on the observation of the tidal cycle. For port facilities accessed by ships of different draughts, it is recommended to use an adequate tidal window (time period). Tidal windows associated with high water can be used to allow vessels with deep draughts to navigate the channel.

c. Adverse conditions

– In some port facilities, the flow of a river or long-term weather effects associated with tidal stages can result in strong currents, making it unsafe for a design ship to navigate. As a result, arrivals and departures may be restricted to certain windows, causing downtime and making the channel unavailable for certain types of ships.

– Another factor to consider is the seasonal oscillation of the water level, which is affected by flood and dry seasons, such as in the Amazon region.

All the factors associated with the water level of a channel must be in the same reference level (*datum*). The reference level is the navigation chart *datum*.

2.3.1.2.3. Factors related to the design ship

These include the static draught and underkeel clearance (UKC).

The draught and the static trim of the design ship, including the possible List are the starting points to define the underkeel clearance.

Six safety factors are recommended to calculate UKC:

a. Allowance for uncertainties in the static draught;
b. Changes in water density;
c. The squat effect, including the dynamic trim;
d. Dynamic heel due to windage and turning;
e. Wave response allowance; and
f. Net UKC.

These factors and their subdivisions are presented in figure 2.3 (PIANC 121, 2014, p. 23).

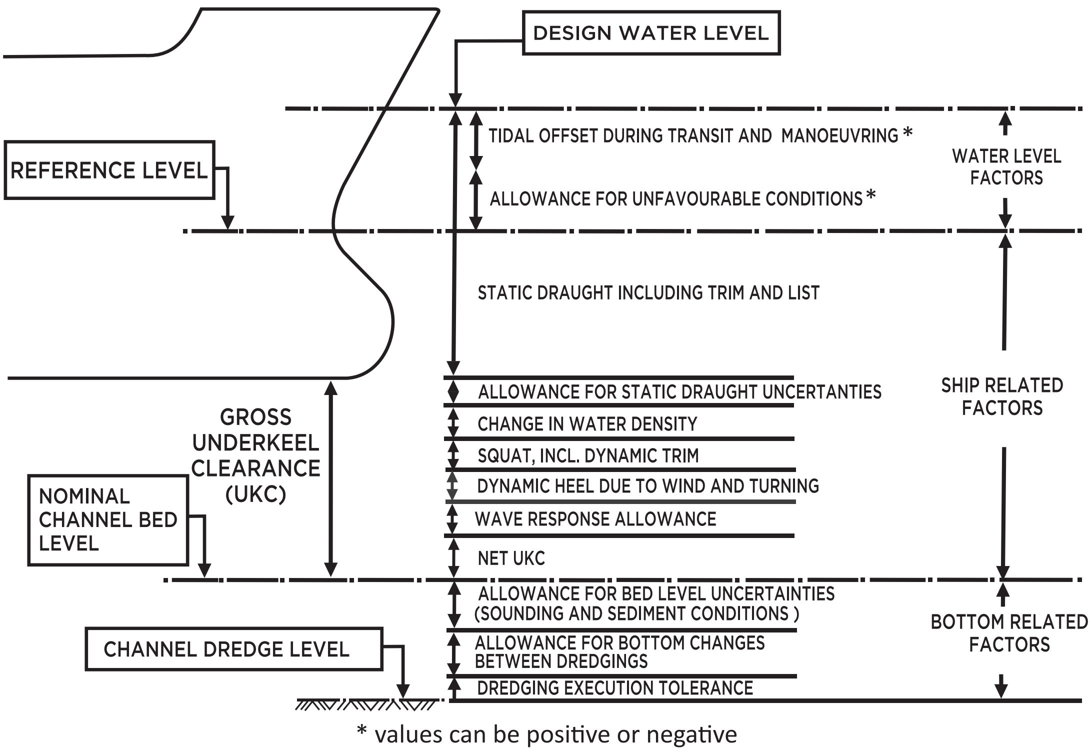


Figure 2.3. Factors associated with the depth of a channel
(taken from PIANC 121, 2014, figure 2.1, p. 23)

2.3.1.2.3.1. Allowance for static draught uncertainties

The maximum draught, as well as the static trim, may vary during the ship travel (depending on fuel consumption, water and provisions, ballast adjustment, etc.). If the ship is not in even keel conditions, the maximum forward or aft draught should be used.

The static draught of a ship is often uncertain and difficult to measure accurately. It is generally not measured accurately at the arrival port, where the density may be different from that at the departure port, or where sea conditions make an accurate reading of the draft difficult. Another cause of uncertainty can be a static inclination to one side caused by unbalanced cargo load, ballast or damage (Permanent List). A safety margin should be considered to account for the uncertainties in the static draught. It is recommended that empirical squat and vertical wave motion formulas listed in Chapters 5 and 3, respectively, are used during the Concept Design to incorporate this uncertainty factor. These formulas are conservative and can provide a reasonable safety margin. Continuous monitoring by the competent authority can help reduce this uncertainty factor.

2.3.1.2.3.2. Changes in water density

Differences in water density between open sea and internal waters at a port facility can cause variations in draught and trim of a ship. If the design vessel moves into waters with lower density, the draught increases in proportion to the decrease in density, depending also on the hull's verticality relative to the waterplane (waterplane gradient). When leaving seawater and entering fresh water, the draught of the design ship typically increases by approximately 2% to 3%, as the ship's displacement volume is inversely proportional to the water density.

The relationship between the draught of the design ship and waters with higher or lower density is a function of the C_B block coefficient and the C_{WP} flotation area coefficient and can be calculated, for ships in even waters, using this formula:

$$T_{\delta lower} = \left(1 + (\rho_{higher} - \rho_{lower}) \frac{C_B}{C_{WP}} \right) T_{\delta higher}$$

where

$T_{\rho higher}$ is the ship's draught in water with higher density, given in meters (m),

$T_{\rho lower}$ is the ship's draught in water with a lower density, given in meters (m),

C_B is the block coefficient, and

C_{WP} is the flotation coefficient.

For example, to calculate the draught of the ship in fresh water (density equal to 1) knowing the draught of the ship in seawater (density equal to 1.025), one has: (PIANC 121, 2014, Appendix C/ eq. C-2)

$$T_{freshwater} = \left(1 + (0.025)\frac{C_B}{C_{WP}}\right) T_{seawater}$$

the water plane coefficient being

$$C_{WP} = \frac{A_{WP}}{L_{pp} B}$$

where

A_{WP} is the ship's waterplane cross-sectional area, given in square meters (m^2),

L_{pp} is the ship's length between perpendiculars, given in meters (m), and

B is the ship's beam, breadth moulded, given in meters (m).

To estimate the the water plane coefficient (PIANC 121, 2014, expression D-2), the following approximation can be used:

$$C_{WP} \approx \frac{1}{3}(2C_B + 1)$$

that is, the ship's draught in fresh water for a conventional ship is equal to 1.02 to 1.025 multiplied by its draught in salt water.

2.3.1.2.3.3. The squat effect, including dynamic trim

The squat effect is the tendency of a ship to sink and trim while in motion, thus reducing the water under its keel. The squat is highly dependent on the speed of the ship and is pronounced in shallow waters and can become critical.

The empirical equations recommended in the Concept Design are presented in Chapter 5.

2.3.1.2.3.4. Dynamic heel due to windage and turning

The sinkage of the bilge keel is a function of the dynamic transverse heeling angle, $\emptyset_{WR}$, and is applicable to design ships due to the effects of dynamic heeling (such as large containers, passenger ships, and Ro-Ro vessels). The safety margin angle must be 2°.

The sinkage of the ship bilge keel, S_K, should be calculated using the formula (based on PIANC 121, 2014, eq. 2-8)

$$S_K = 0.9\frac{B}{2}\,\text{Sin}\varnothing_{WR}$$

where

S_K is the vertical sinkage level of the ship bilge keel, given in meters (m).

B is the ship's beam, breadth moulde, given in meters (m).

$\varnothing_{WR}$ relative wind direction angle.

This value should be included in the calculation if it represents at least 5% of the tolerance given for the sum of vertical wave motion and squat.

2.3.1.2.3.5. Wave response allowance

The magnitude of vertical movements of the design ship due to waves in a channel depends on many factors, among which stand out: (USACE-EM 1110-2-1613-2006)

a. Sea conditions, including swell;
b. Height, period, direction, and speed of wave propagation;
c. Speed, course and heading of the ship;
d. Ship's natural period in roll, pitch and heave, and encounter frequency;
e. Channel depth, width and underkeel clearance;
f. Current conditions: ebb or flood;
g. Wind speed and direction;
h. Proximity of banks and siltation areas; and
i. Navigation strategy employed for movement in waves.

The response of large sized design ships to waves is negligible in cases where the wavelengths are short and when the ship-wave encounter frequency is high and the waves are of low height.

The effect of waves on design ships tends to increase with increasing wave height and decreases with increasing length of the design ship. The maximum response occurs when the wavelengths are equal to or nearly equal to the length of the design ship. Waves with periods less than 6s produce small responses from design ships because the natural periods of the design ship movements are longer (in deep waters, the natural response period of the design ship is between 10s and 17s), except in the case of small vessels.

The movement of the design ship in waves differs in shallow waters and deep waters due to several reasons, among which the following stand out:

a. For a given wave period, the wavelength in shallow waters is shorter than in deep waters. This alters the force of wave excitation in relation to the length of the design ship;

b. For a given wave period, the wave celerity is lower in shallow waters than in deep waters. This changes the encounter frequency and shifts the peak response of the design ship to a different period from that in deep waters;
c. The added mass in heave and the moment of added inertia in pitch are usually much higher in shallow waters than in deep waters, increasing the natural periods of the vessel and tending to reduce the vertical movements of the design ship.

When combined, these effects generally tend to reduce the wave response of the ship in shallow waters compared to deep waters.

In naval architecture, the transfer function that represents the ratio between the amplitude of response of the ship and the amplitude of the monochromatic wave that excites the movement is known as RAO (response amplitude operator). This transfer function has an amplitude and a phase angle. The vertical motions of the design ship are determined by the RAO, which is also called the amplification factor and depends on the period, direction, and frequency of the wave and the speed of the ship. Normally, the amplification of the responses of the design ship tends to be smaller for higher waves due to nonlinear effects in the dynamics of the vessel, making RAO calculations of movement conservative even for high waves.

The RAO can be obtained through tank tests with reduced scale models or by using pertinent numerical codes.

During the Concept Design phase, it is recommended to use the Japanese or Spanish trigonometric methods described in Chapter 3.

2.3.1.2.3.6. Net UKC (PIANC 121, 2014, item 2.1.2.7., p. 33)

The safety margin for the net UKC, which is the safety margin resulting from the type of bottom, in a inner channel, must follow the recommendations listed below (refer to Table 2.1):

a. 0.4m for sand or clay bottoms;
b. 0.5m for coral or rocky bottoms.

Note: A wrecked hull or underwater construction in the channel is considered a rocky bottom for the purpose of determining the safety margin.

In open channels, for the safety margin arising from the type of bottom it is recommended to use (refer to Table 2.1):

a. 0.5m for sand or clay bottoms;
b. 1m for coral or rocky bottoms.

Note: A wrecked hull or underwater construction located within the channel is considered a rocky bottom for the purpose of determining the safety margin.

The safety margin for mud bottoms may be disregarded if other factors associated with the design ship have been adequately calculated.

2.3.1.2.4. Safety margin based on the maneuverability of the design ship (PIANC 121, 2014, p. 33)

Once the UKC has been calculated, it must be compared with the vertical safety margin due to the maneuverability of the design ship, which is a safety factor that ensures it can transit the channel with its own resources. The maneuverability margin (MM) is independent of the UKC and represents the minimum clearance below the design ship (between the nominal depth level and the position corresponding to the vessel's greatest draught) and seeks to ensure the minimum controllability of the design vessel. The UKC must not be less than the vertical maneuverability margin of the design vessel.

The MM value limit depends on type of design ship, channel dimensions and alignment, as well as the traffic of design ships (including themselves in one or two maneuvering lanes). A suitable MM value for most design ships, types, and channels is a minimum of 5% of the draught or 0.6m, whichever is greater.

In inland port areas with minimal or no wave action, the MM value can be reduced to 0.5m for tug-assisted operations, regardless of the draught of the design vessel.

The safety margin for vertical clearance is defined by the maximum value calculated between the UKC and the MM.

2.3.1.2.5. Bottom-related factors (PIANC 121, 2014, p. 34)

a. Allowance for Bed Level Uncertainties (bathymetry and sediment conditions)

– All sensors have a built-in tolerance or uncertainty that must be taken into account. Additionally, there are uncertainties in the actual depth due to tolerances in the measured bathymetric survey data.

b. Allowance for bottom changes between dredging

– Sedimentation or silting may occur after dredging, or between successive dredging operations. This value is sometimes known as advanced maintenance. The dredging depth can be purposely deeper than the required nominal depth in order to provide some allowance for anticipated sedimentation and increase the time needed for the next dredging cycle. A similar estimate is required for the silting of natural channels that are typically not dredged.

c. Dredging Execution Tolerance

– After dredging or de-rocking work is completed, the dredged or de-rocked bottom will not be perfectly flat, so it is necessary to include an additional depth value (over-dredge depth) to ensure that the dredging depth is effectively achieved;

– The over-dredge depth differs from others because it is a subsidy for the inaccuracies of the dredging activity itself that cannot be characterized by a general formula. This measurement is difficult for the designer to determine precisely, as it is beyond their control, regardless of the level of development of the design (Concept or Detailed). This complexity is due to the fact that over-dredge depth is related to aspects of very different natures, such as type and size of dredging equipment to be used, type of soil to be dredged and its hardness, dredger positioning control and whether the dredging to be carried out is deepening (capital dredge) or maintenance (maintenance dredge), and may also be strongly influenced by local conditions, such as, for example, tides, currents and, mainly, waves;

– Although the over-dredge depth depends on interactions with dredge operators for proper implementation, the typical values presented in Table 2.2. can be used as a reference for developing the engineering design.

Table 2.2. Typical values for dredging or rock demolition tolerances related to various local conditions (in meters) (based on Table 12 - British Standards 6349 5 1991)

Local conditions	**Trailing hopper dredge**	**Suction dredge**	**Bucket dredge**	**Clamshell dredge**	**Backhoe dredge**	**Front-end loader**
Seabed material	m	m	**m**	**m**	m	m
Loose silt	0.20	0.20	0.20	0.20	0.15	0.20
Cohesive silt	0.30	0.15	0.15	0.25	0.15	0.15
Fine sand	0.20	0.15	0.15	0.20	0.15	0.15
Medium sand	0.20	0.15	0.15	0.20	0.15	0.15
Gravel	0.20	0.15	0.15	0.20	0.15	0.15
Soft clay	0.25	0.15	0.15	0.25	0.15	0.15
Medium clay	0.30	0.15	0.15	0.30	0.15	0.15
Hard clay	0.25	0.15	0.15	0.25	0.15	0.20
Very weak rock	0.30	0.30	0.25	n/a	0.35	0.30
Weak rock	n/a	0.30	0.25	n/a	0.35	0.30
Moderately weak rock	n/a	0.30	n/a	n/a	0.35	0.35
Pre-worked rock	0.35	0.35	0.35	0.35	0.35	0.375

Local condition adjustments - Sea conditions						
Inner waters						
Small dredger	0.125	0.15	0.15	0.175	0.10	0.10
Medium-sized dredger	0.10	0.125	0.125	0.15	0.10	0.10
Large dredger	0.075	0.10	0.15	0.15	0.075	0.075
Open waters						
Small dredger	0.30	n/a	n/a	0.50	n/a	n/a
Medium-sized dredger	0.25	0.35	0.35	0.40	0.35	0.35
Large dredger	0.20	0.30	0.30	0.35	0.30	0.30
Currents						
Moderate (0.5m/s)	0	0	0	0.10	0	0
Strong (1m/s)	0.10	0.05	0	0.20	0.10	0.10
The values shown for adjustments of local conditions must be added to the values shown for the bottom material.						
Note 1: The values shown are a reference for the development of the project and are not exempt from validation when contracting of the dredging work. **Note 2:** None of the data presented is an absolute value. Difficulties in ensuring the dredging depth may arise when low values are specified.						

2.3.1.3. Channel width

This section outlines the procedures for calculating the appropriate width for a channel. Initially, we will consider the width values to be used in the preliminary design stage based on the beam of the design ship, number of maneuvering lanes and bank. Following this, we will present the recommended procedure for the Concept Design phase, which takes into account several factors that influence navigation in the channel. These factors are detailed below in the calculation process.

2.3.1.3.1. Preliminary design for straight sections of a channel (ABNT-NBR 13246-1995)

For single-lane traffic, the minimum width (W) should be calculated based on the ship's beam (B), as follows:

a. Sloping bank: W > 3.6B;
b. Vertical bank: W > 4.2B.

For two-lane traffic, the minimum width (W) should be calculated based on the ship's beam (B):

a. Slopping bank: W > 6.8B;
b. Vertical bank: W > 7.4B.

In extensive channels with strong currents or cross winds, the minimum width should be determined as follows:

a. One navigable lane: W > 1.0L;
b. Two navigable lanes: W > 1.5L.

2.3.1.3.2. Concept Design Methods for Straight Channels (PIANC 121, 2014, item 3.1.5.)

When designing Straight Channels during the Concept Design phase, it is important to consider 13 factors related to their width, as per Figure 2.4.

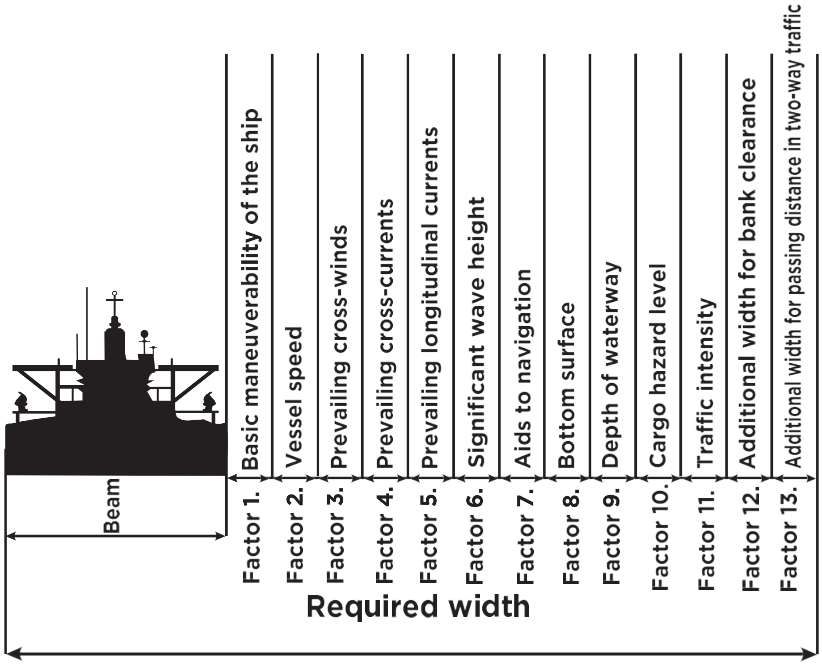


Figure 2.4. Factors associated with additional width for Straight Channels

The minimum recommended width (W) for straight stretches of a channel should be determined as a function of the beam (B) of the largest design ship, meeting the following recommended minimum criteria.

For a single maneuvering lane

$$W = W_{BM} + \Sigma W_i + W_{BR} + W_{BG}$$

For two maneuvering lanes

$$W = 2W_{BM} + 2\Sigma W_i + W_{BR} + W_{BG} + W_P$$

where

W_{BM} represents the basic maneuverability range of the ship (factor 1), given in meters (m);

W_i represents the safety margin due to environmental and local factors (factors 2 to 10), given in meters (m);

W_{BR} and W_{BG} are the factors associated with channel bank clearances (factor 12), given in meters (m);

W_P represents the safety margin that includes passing distance and traffic intensity (factors 11 and 13), also given in meters (m).

2.3.1.3.2.1. The W_{BM} factor associated with basic ship maneuverability (PIANC 121, 2014, item 3.1.5.1)

The following horizontal safety margin values are recommended based on the ship's beam (B):

a. 1.3B for ships with good maneuverability;
b. 1.5B for ships with moderate maneuverability;
c. 1.8B for ships with poor maneuverability.

Maneuverability can be classified as good, moderate or poor, as specified below:

a. Good, when the ship has the ability to maintain its course in the channel using up to 5° rudder;
b. Moderate, when the ship has the ability to maintain its course in the channel using up to 25° rudder
c. Poor, when the ship needs to use up to hard-over rudder angle to maintain its coursed in the channel.

Note 1: The ability can be measured by performing the maneuverability test known as VSZZ (Very Small Zig Zag).

Note 2: If information about a ship's maneuverability is not available, the basic maneuverability margin of the ship in the horizontal plane is considered moderate or poor.

2.3.1.3.2.2. Factor W_1 associated with ship speed

As an important part of the design process, the ship's speed should be the first item to be defined. It cannot be too low (to the point of affecting maneuverability) nor too high (to the point of compromising safety). Ship speed is measured relative to the water and can be referenced from Table 2.3. (PIANC 121, 2014, p. 87, table 3.5)

Table 2.3. Width W_1 factor as a function of Vessel Speed V_S

Vessel Speed (Knots,with respect to the water)	**Vessel Speed**	**Inner and Outer Channels**
$V_s > 12$	Fast	$0.1B$
$8 < V_s < 12$	Moderate	0
$5 < V_s < 8$	Slow	0

2.3.1.3.2.3. The W_2 factor associated with prevailing crosswind speed V_{CW}

Also called transverse winds, the prevailing crosswinds VCW affect the ships at any speed, but their greatest impact occurs at low speeds, where they can cause the ship to drift laterally and acquire a drift angle. For both situations, it is recommended to increase the necessary maneuvering width.

The effects of crosswinds depend on the following factors

a. Ship's windage;
b. Depth to draught ratio (because a ship's resistance to lateral motion changes as the depth to draught ratio approaches unity. Wind causes less drift with thinner sheets of water below the keel);
c. Wind speed and its relative direction.

To account for crosswind effects, it is necessary to leave a wider margin than necessary for basic maneuvering, as outlined in Table 2.4 (PIANC 121, 2014, Table 3.5 on p. 87).

Table 2.4. W_2 factor for consideration of V_{CW} crosswind effects in knots

Crosswinds (in knots)	Vessel Speed	Inner and Outer Channels
$V_{cw} \leq 15$ (mild) ($V_{cw} \leq$ Beaufort 4)	Fast Moderate Slow	0.1*B* 0.2*B* 0.3*B*
$15 < V_{cw} < 33$ (moderate) (Beaufort 4 to Beaufort 7)	Fast Moderate Slow	0.3*B* 0.4*B* 0.6*B*
$33 < V_{cw} < 48$ (strong) (Beaufort 7 < V_{cw} < Beaufort 9)	Fast Moderate Slow	0.5*B* 0.7*B* 1.1*B*

The additional widths specified in Table 2.4 apply to all design ships with a balanced ratio between windage surfaces and the lateral underwater area.

These vessels include (a) tankers and bulk carriers/OBOs (Ore/Bulk/Oil) in full load or ballast conditions, as well as (b) container ships, cargo vessels (freighters), car carriers, and LNG/LPG vessels. For high-sided ships such as loaded container ships, cruise liners and Ro-Ro ships, it is necessary to add 0.2B to the values given in Table 2.4.

2.3.1.3.2.4. The W_3 factor associated with the speed of prevailing cross-currents (V_{CC})

Prevailing cross-currents, or V_{CC} cross-currents, can significantly impact a ship's maneuverability and ability to maintain its course and heading.

To account for these effects, a recommended safety margin is provided in Table 2.5 (PIANC 121, 2014, p. 87, Table 3.5).

Table 2.5. W_3 factor safety margin for effects of cross-currents V_{CC}

Cross-currents (knots)	Vessel Speed	Outer Channel	Inner Channel
$V_{CC} < 0.2$ (negligible)	All	0	0
$0.2 < V_{CC} < 0.5$ (low)	Fast Moderate Slow	0.2*B* 0.25*B* 0.3*B*	0.1*B* 0.2*B* 0.3*B*
$0.5 < V_{CC} < 1.5$ (moderate)	Fast Moderate Slow	0.5*B* 0.7*B* 1*B*	0.4*B* 0.6*B* 0.8*B*
$1.5 < V_{CC} < 2$ (strong)	Fast Moderate Slow	1.0*B* 1.2*B* 1.6*B*	a a a
[a] The use of maneuvering simulators is recommended to define the appropriate safety factor to be employed in the case of strong cross-currents in an inner protected channel.			

2.3.1.3.2.5. The W_4 factor associated with the effect of prevailing longitudinal currents V_{LC}

Longitudinal currents can affect the ship's maneuverability and affect its ability to stop.

Table 2.6 shows the recommended safety margin for the effects of longitudinal currents.

Table 2.6. Safety margin for longitudinal current effects
(PIANC 121, 2014, p. 87, Table 3.5.)

Longitudinal currents (knots)	**Vessel Speed**	**Inner and Outer Channels**
$V_{LC} \leq 1.5$ (low)	All	0
$1.5 < V_{LC} < 3$ (moderate)	Fast Moderate Slow	0 0.1*B* 0.2*B*
$V_{LC} > 3$ (strong)	Fast Moderate Slow	0.1*B* 0.2*B* 0.4*B*

2.3.1.3.2.6. The W_5 factor representing the effects of significant wave height, H_S (m)

When a ship encounters beam and quartering seas, it can experience drift angles and sideways drift due to second-order drift forces. These effects can occur in both deep and shallow waters, and may require widening of the channel.

Table 2.7 provides the recommended W_5 factor amounts for channel widening as a function of the beam and quartering sea wave heights.

Table 2.7. W_5 factor as a function of beam, bow or stern quartering wave heights
(Pianc 121, 2014, p. 87, Table 3.5.)

H_s of the port/starboard bows and quarters or beam wave heights	**Vessel Speed**	**Inner Channel**	**Outer Channel**
$Hs \leq 1m$	All	0	0
$1m < Hs < 3m$	All	0.5*B*	0
$Hs \geq 3m$	All	1*B*	0

2.3.1.3.2.7. The W_6 factor representing aids to navigation

Aids to navigation for the channel are classified into three categories:

a. Excellent: when they possess the following characteristics:
1. The channel has
– Paired lighted buoys with radar reflectors
– Lighted leading lines

– Vessel Traffic Service (VTS) - Note: VTS is not necessary in port facilities with low traffic, but it is necessary to rely on a monitoring system.

2. The use of

– Pilots

– Differential global navigation satellite positioning systems (DGPS)

– Electronic Chart Display and Information System (ECDIS)

b. Good: when they possess the following characteristics:

1. The channel has

– Paired lighted buoys with radar reflectors

– Lighted leading lines

2. The use of

– Pilots

– Differential global navigation satellite positioning systems (DGPS)

c. Moderate: when they lack at least one of the components listed in the characteristics of aids classified as good.

The recommended values for aids to navigation are given in Table 2.8.

Table 2.8. Recommended values for W_6 representative of available aids to navigation

Aids to navigation	Vessel Speed	Inner and Outer Channels
Excellent with shore-based traffic management	All	0
Good	All	0.2*B*
Moderate	All	0.4*B*
Note: This safety margin is not the one applied for the definition of "floating navigation aid out of position" for the purpose of inspection by the competent authority.		

2.3.1.3.2.8. The W_7 factor associated with bottom surface effects (PIANC 121, 2014, p. 87, Table 3.5.)

The bottom surface effect is relevant only in shallow waters, and it can be ignored if the water depth is greater than 1.5 times the draught.

Table 2.9. displays the recommended values for the bottom surface effect.

Table 2.9. Recommended W_7 values associated with bottom surface effect

Bottom surface	Inner and Outer Channels
If depth ≥ 1.5T	0
If depth < 1.5T, then:	
If smooth and soft	0.1B
If rough and hard	0.2B

2.3.1.3.2.9. The W_8 factor associated with bottom surface effects (PIANC 121, 2014, p. 87, Table 3.5.)

The maneuverability of a ship is affected as its depth-to-draught ratio approaches one.

Table 2.10. shows the recommended values for depth effects.

Table 2.10. Recommended W_8 values for h depth effects

Depth of channel	Outer Channel	Depth of Channel	Inner Channel
$h \geq 1.5T$	0	$h \geq 1.5T$	0
$1.5T > h > 1.25T$	0.1B	$1.5T > h > 1.15T$	0.2B
$1.25T > h$	0.2B	$1.15T > h$	0.4B

2.3.1.3.2.10. Cargo hazard level (W_9)

According to the International Maritime Organization (IMO) (MSC.122(75) - 2002), hazardous cargoes are classified based on the following factors:

a. Toxicity;
b. Explosive potential;
c. Pollution potential;
d. Combustion potential;
e. Corrosive potential.

Examples of cargoes with a high hazard level include LNG, LPG, and certain classes of chemicals.

Generally, no additional width is required in the presence of hazardous cargo. However, additional safety margins, such as speed reduction in combination with VTS assistance or support tugs, should be applied.

The risk assessment involved must be specified in the Detailed Design.

2.3.1.3.2.11. Traffic Intensity (W_{10})

An additional safety margin is necessary to account for traffic intensity. The recommended values are displayed in Table 2.11.

Table 2.11. Traffic intensity values

Traffic intensity	Vessel Speed	Inner and Outer Channels
Low	All	0
Medium	All	0
High	All	0.5*B*
Note: Traffic intensity is divided into: low: 0 to 1 ship/h; medium: 1 to 3 ships/h; high: more than 3 ships/h.		

2.3.1.3.2.12. Distance from banks, or bank clearance (W_{BR} and/or W_{BG})

When a design ship navigates in the vicinity of a bank, the flow along the hull is altered and becomes asymmetrical with respect to the ship's center line plane. This generates hydrodynamic forces that may lead to situations not controllable by the design ship's steering system. To avoid them, an additional safety width margin is required. The safety clearance for the left bank is symbolized by W_{BR} and for the right bank by W_{BG}.

Some important factors to consider are:

a. Speed of the design ship;
b. Bank or structure slope;
c. Symmetry of the cross-section of the channel;
d. Depth to draught ratio (h/T ratio);
e. Under-keel clearance; and
f. Distance between the ship and the bank.

Figure 2.5. shows the distance to the bank or bank clearance (W_{BR} and/or W_{BG}).

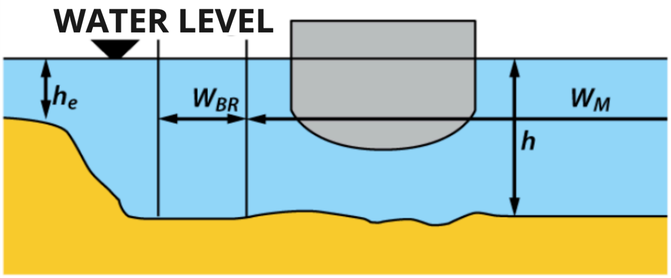


Figure 2.5. Distance to left bank in a channel (W_{BR})
(taken from PIANC 121, 2014, Figure 3.6)

Table 2.12 presents the recommended values for additional width required for bank clearance. It is worth noting that these values are conservative since they assume that the bank immersion level (he) is 75% of the channel depth.

Table 2.12 Additional width for bank clearance (PIANC 121, 2014, p 89)

Width for bank clearance	Vessel Speed	Outer Channel or Inner Channel
Gentle underwater channel slope (1:10 or less steep)	Fast Moderate Slow	0.2*B* 0.1*B* 0
Sloping channel edges and shoals (steeper than 1:10)	Fast Moderate Slow	0.7*B* 0.5*B* 0.3*B*
Steep and hard embankments, structures	Fast Moderate Slow	1.3*B* 1*B* 0.5*B*

2.3.1.3.2.13. Channel width for double way manoeuvring lanes (W_P)

To determine the additional width required for passing distance in double way manoeuvring lanes (as shown in Figure 2.6), the beam (B) of the largest passing ship should be considered, regardless of whether or not it is the design ship. The passing distance refers to the distance between lanes in a double way manoeuvring channel, and not the distance between the hulls.

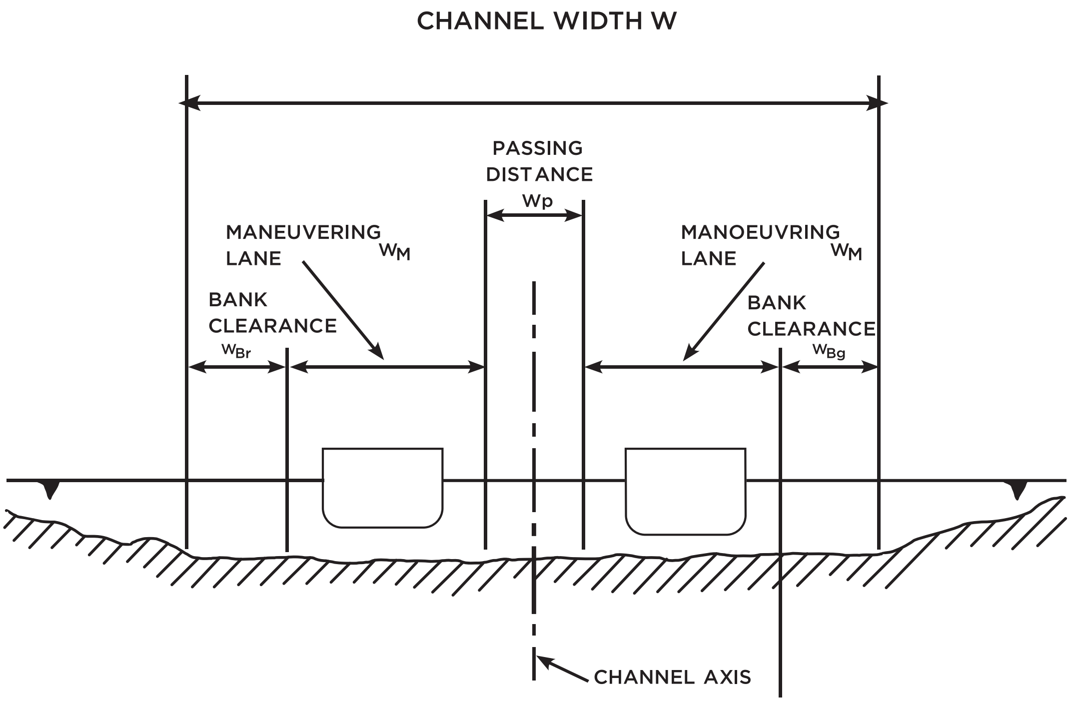


Figure 2.6
Double way manoeuvring lanes width (taken from PIANC 121, 2014, Figure 3.2)

Table 2.13 presents the recommended values for double way manoeuvring channels where overtaking is not permitted. If overtaking is allowed, the values provided should be increased and specified by a Detailed Design.

Table 2.13 Additional width for two-way traffic (taken from PIANC 121, 2014, p. 90)

Width for passing distance	Outer Channel (open water)	Inner Channel (protected water)
Vs > 12 (fast)	2*B*	1.8*B*
8 < Vs < 12 (moderate)	1.6*B*	1.4*B*
5 < Vs < (slow)	1.2*B*	1*B*

2.3.1.3.3. Additional width for large tidal range (PIANC 121, 2014, p.90)

If there is a large tidal range (say in excess of 4 m) combined with strong currents and steep underwater banks on both sides of the channel, consideration should be given to the possibility of a design ship blocking the channel. This can happen if a ship runs aground on one side of the channel, and is turned by changes in the tidal current direction ending up across the channel. In such conditions, based on a proper risk assessment, the channel width should be wider than the design ship's total length.

2.3.1.4. Channel bends (PIANC 121, 2014, item 3.1.2.)

2.3.1.4.1. Bend configuration

A bend in a channel is described by its radius, R, and the angle of the bend, α.

Figure 2.7 shows a channel bend configuration.

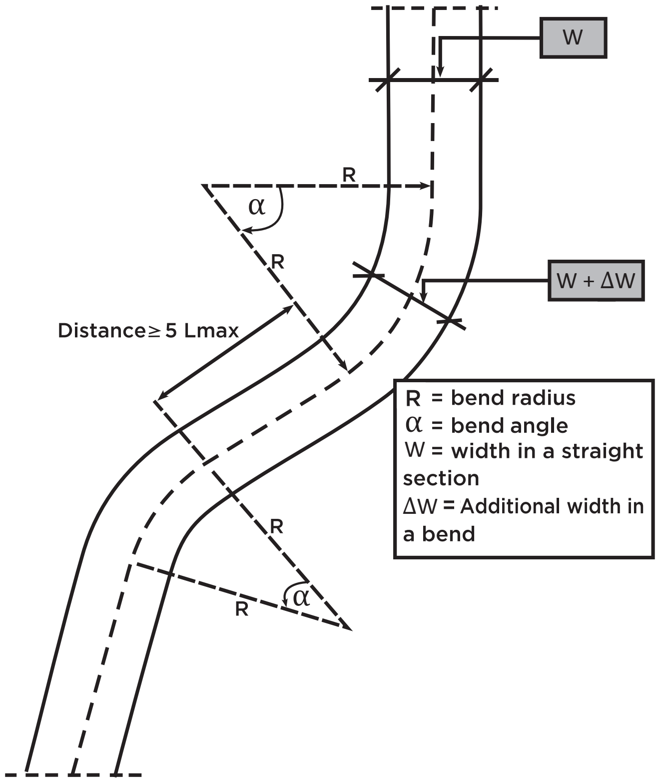


Figure 2.7 Channel bend configuration (taken from PIANC 121, 2014, Figure 3.3)

A bend in a channel typically connects two straight channels. However, two bends could also occur in a sequence, although such feature should be avoided.

The distance between two successive bends should be more than five ship lengths of the largest design vessel. Transitions shorter than this length should be examined using a maneuvering simulation study. When two bends turn in the same direction, the distance between them should be greater than three ship lengths of the largest design vessel, as depicted in Figure 2.8.

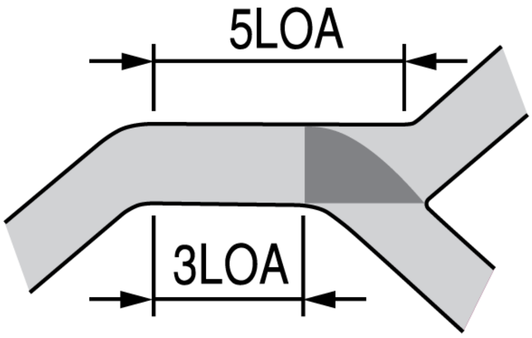


Figure 2.8 Distance between successive bends

A bend may or may not have banks. Where banks are present, the channel may resemble an artificial canal with low water levels, and where they are not present, it may simply indicate a turning maneuver from one channel section to another. Ship behavior and, as a result, bend marking, will differ for each type. Bends with banks could affect the ship's behavior due to interaction effects, so their presence should be indicated.

Any curve connecting straight sections of a channel must take into account the ship's ability to turn. This section features values of additional width, ΔW, relative to straight sections of an entrance channel.

2.3.1.4.2. Additional widths in bends (PIANC 121, 2014, item 3.1.6.1.)

The additional width required in bends, ΔW, is determined by the ship's drift angle and the time it takes for the ship to return to the channel axis, and can be calculated using the following equation:

$$\Delta W = \Delta W_{DA} + \Delta W_{RT}$$

The additional width due to the drift angle can be calculated using the following equation:

$$\Delta W_{DA} = \frac{L_{OA}^{2}}{\alpha R_C}$$

where

ΔW_{DA} is the additional width of a vessel's swept path due to drift angle in a curved channel section. It is given in meters (m);

L_{OA} refers to the length overall, and is given in meters (m);

α is a factor that depends on the type of ship. For conventional ships, $\alpha = 8$, while for large displacement ships or those with $C_B \geq 0.8$ (such as oil tankers and bulk carriers), $\alpha = 4.5$;

R_C is the bend radius, which can be found in Table 2.14.

Table 2.14 Bend radius R_C (taken from PIANC 121, 2014, table 3.8)

No.	Ship Type	R_C
1	Cargo ship	5 Loa
2	Small cargo ship	6 Loa
3	Container ship (over Panamax)	7 Loa
4	Container ship (Panamax)	6 Loa
5	Very Large Bulk Carrier	6 Loa
6	Large Bulk Carrier (Panamax)	6 Loa
7	Small Bulk Carrier	5 Loa
8	VLCC	5 Loa
9	Small Tanker	5 Loa
10	LNG ship	4 Loa
11	Refrigerated Cargo Carrier	5 Loa
12	Passenger Ship	4 Loa
13	Ferry Boat	5 Loa

An additional width ΔW_{RT} is required in bends to compensate for response time delay, given by the following equation:

$$\Delta W_{RT} = 0.4B$$

2.3.1.4.3. Bend radius length

The restriction on the length of the ship (L) is determined by the alignment of the channel and the deflection angle α of its bends.

The following criteria are recommended:

$$\alpha \leq 25° \rightarrow R_C > 3L$$

For $\alpha > 25°$, the bend radius R_C, as a function of the design ship type should exceed the values provided in Table 2.14.

2.3.2. Maneuvering areas

Maneuvering areas may be necessary for large vessels (over 50,000DWT) in the following locations:

a. End section of the outer channel;
b. Harbor entrance;
c. Initial section of the inner or approach channel;

d. Entrance of the turning basin;
e. Pilot boarding or landing areas.

The maneuvering area should be analyzed from the upstream point where the design ship begins to reduce speed to the downstream point of the turning area.

2.3.2.1. Factors associated with the stopping distance of the design ship (PIANC 121, 2014, p. 96)

When operating in relatively protected waters, the slowing down and stopping maneuvers of the design ship within port boundaries are determined by the following factors (see Figure 2.9.)

a. Entry speed of the design ship;
b. Time required for attaching tugs and maneuvering; and
c. Actual stopping distance.

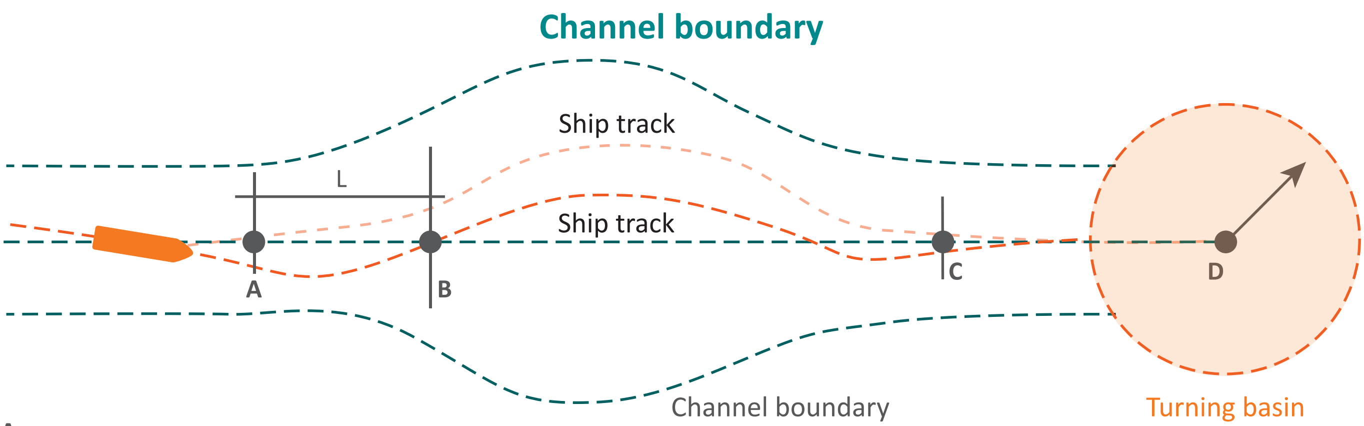


Figure 2.9 Stopping procedures and channel dimensions
(based on PIANC 121, 2014, Figure 3.10)

2.3.2.2. Time required for connecting tugs and maneuvering into position (PIANC 121, 2014, p. 96)

The time required for attaching tugs and maneuver them into position (B-C, in Figure 2.9.) depends on the crew skill and environmental conditions.

On average, this process can take from five to twenty minutes. The design ship speed limit should be low, as specified in Table 2.3, and the limiting wave height should be between 1.5m and 3m, depending on the type of tug, towing equipment and the crew expertise.

2.3.2.3. Stopping distance with assistance of tugs (PIANC 121, 2014, p. 97)

The actual stopping distance (as shown in Figure 2.9) is relatively short. Large ships use hull resistance combined with astern power, and at the same time, with the assistance of tugs to control the course, stopping at a distance that varies between 1.5 L_{OA} to 2 L_{OA}, from slow speed.

For example, if a ship is required to perform a stopping maneuver under the protection of breakwaters, and enters the harbour at 6 knots,the stopping length to the turning basin centre will be the combination of the following distances:

a. The ship slows down to 4 knots over a period of up to 15 minutes while tugs maneuver into position, covering a distance of up to about 2,300m (see B-C in Figure 2.9.);

b. The distance of L_{OA} is added immediately upon passing the entrance of the port facility, before tugs can come near (see A-B in figure 2.9);

c. The actual stopping distance of 2 L_{OA} is added (see C-D in Figure 2.9.);

d. The total stopping distance, if L_{OA} = 300m, is: 900m + 2,300m = 3.2km

2.3.2.4. Stopping distance without tug assistance

The stopping distance for design ships with a moderate initial speed, using astern power and traveling in a straight line from their initial heading, can be calculated by: (ROM 3.1-99, p. 163)

$$S = \frac{1}{2}\frac{\Delta}{g} C_m V_0^2 \left[1 - 0.32\frac{R_T}{T}\right]\frac{1}{T} + \frac{t_{ri} V_0}{2}$$

This equation can only be used for

$$T \geq R_T$$

$$\frac{R_T\, g\, t_{ri}}{\Delta\, C_m V_0} \leq 0.6$$

where

S is the stopping distance in a straight line, given in meters;

Δ is the displacement of the ship, given in tons;

g is the acceleration of gravity;

C_m is the virtual mass coefficient of the ship (mass + added mass), C_m =1.08;

V_0 is the initial speed of the ship, expressed in meters per second (s);

R_T is the forward resistance at the ship's initial speed, expressed in ton-force (TF);

T is the thrust force of the propeller when astern, expressed in ton-force (TF);

t_{ri} is the time to reverse the engine (in case of lack of data, use 20s), expressed in seconds (s).

Methods for calculating the forward resistance and thrust can be found in *Principles of Naval Architecture* and other publications on ship hydrodynamics.

2.3.2.5. Pilot boarding and landing areas

The pilot boarding point should be situated at a sufficient distance from the limit of the compulsory pilotage area to allow safe boarding conditions.

The area should allow sufficient time and space for the master-pilot information exchange.

It should be large enough to enable the design ship to maneuver safely and provide a suitable lee for the transfer, taking into account all probable headings and the prevailing local meteorological conditions.

Note: Unless the design ship is at anchor or at berth, it is likely to be underway at a relative speed of around 6 to 12 knots and may need to maintain its course, heading and speed for up to 20 minutes while waiting for the pilot to board, depending on the vessel and prevailing conditions.

2.3.3. Inner or approach channel to the port facility

2.3.3.1. Inner channel depth

The depth of the inner channel should be determined by considering the same factors as those used for the channel. Water level should be assessed using tidal windows, meteorological tides and vertical dimensions associated with river flood or ebb, including the current window. Ship-related factors such as the squat effect is null, wave action may also be null, but immersion due to water density variation must be considered. Additionally, siltation-related bottom factors should be taken into account when there is no maintenance dredging.

It is recommended to ensure a minimum maneuverability margin value of 5% of the draught or 0.6m (whichever value is larger) when tugboat assistance is not available (PIANC 121, 2014, p. 33).

For tug-assisted maneuvers, a minimum value of 0.5m of maneuverability margin should be guaranteed, regardless of the ship's draught.

2.3.3.2. Inner channel width

The width of the inner channel in a harbor will depend on whether tug assistance is being used.

2.3.3.2.1. Inner channel width without tug assistance

When tug assistance is not being used, the width of the inner channel should be equal to or greater than the design ship's length overall (L_{OA}). This is to prevent incidents where a ship runs aground across the harbor entrance.

2.3.3.2.2. Channel width with tug assistance

The width of the channel depends on the method of tug assistance, which can be European or American*

a. European assistance method: when using this method, the width of the inner channel is given by the greater result of the two expressions below (ROM 3.1-99, Part VIII: Layout Requirements, p. 286)

$$W_{ci} = 2B_{max} + L_r + 20m$$

$$W_{ci} = 3B_{max} + L_r$$

where

W_{ci} is the width of the inner channel, given in meters (m);

L_r refers to the length of the tow rope and tug set, given in meters (m), regardless whether the ropes are attached, as per table 2.15.

Table 2.15. Tugboat and tow rope related factor (ROM 3.1-99, p. 286)

Vessel displacement (tons)	L_r **(m)**
Up to 5,000	45
between 5,000 and 10,000	46-50
between 10,000 and 20,000	51-60
between 30,000 and 60,000	61-70
More than 60,000	71-85

* *For a description of American and European assistance methods, see Chapter 3 of* Tug use in Port

b. American Assistance Method: When using this method, it is recommended to determine the width of the internal channel (W_{ci}) according to the following formula:

$$W_{ci} = 2B_{max} + 2.5\ L_{OAR}$$

where

L_{OAR} refers to the length overall of the tug, expressed in meters (m).

2.3.4. Turning basin

2.3.4.1. Turning basin diameter

When the design ship is assisted by tugs, the nominal diameter of the turning basin should be $\geq 2\ L_{OA}$ and when it is maneuvering on its own, $\geq 3\ L_{OA}$.

2.3.4.2. Turning basin depth

The same depth-related factors that are considered for the channel should also be applied to the turning basin's depth. Concerning water level, tidal windows, meteorological tides and vertical dimensions related to river floods or ebbs can be considered. Ship-related factors such as the squat effect is null, wave action may also be null, but the immersion due to water density variation should be taken into account. When maintenance dredging is not performed, the bottom factor associated with siltation should be considered.

In the turning basin, the underkeel clearance should never be less than 0.6m or 5% of the draught, whichever value is greater, when the design ship is not assisted by tugs. When tug assistance is used, the underkeel clearance should never be less than 0.5m, and it is independent of the design ship's draught. These limits are applicable for muddy bottoms; for other bottom types, the additional clearance for the specific bottom type must be considered (see PIANC 121, 2014, item 2.1.2.8).

2.3.4.3. Turning basins and design ships

The depth of the turning basin depends on the design ship's draught. If the design ship will always maneuver in the turning basin in the light load condition, the reference draught should be that of the light loadline.

For turning basins shared by several ships, there may be multiple basins within the same turning area, or some within other basins. For example, a longer vessel may rotate, in the light or medium draught condition, in a given turning area in a basin with a larger diameter and shallower depth. The same turning basin may contain a deeper basin that allows a ship of shorter length and greater draught to turn.

2.3.5. Anchorage (PIANC 121, 2014, p. 100, item 3.1.9.)

Anchorage refers to the area where vessels drop anchor while awaiting entry into a port or for undertaking cargo handling, passenger transfer, bunkering or other cargo operations associated with that port. Anchorages are typically located in an outer harbor area. However, under certain circumstances, an anchorage area may be required within the working port area, such as when the port lies along the banks of a river.

2.3.5.1. Design factors

When designing an anchorage, the following factors should be considered (PIANC 121, 2014, p. 100):

a. Size, dimensions and characteristics of the design vessel(s);
b. Type of operations that will be undertaken;
c. Duration for which the vessel(s) will stay at anchor;
d. Site's general configuration and availability of space for maneuvering;
e. Arrangement as a general anchorage area or have defined anchorage positions;
f. Number of defined anchoring points to be provided at the site;
g. Marine environment in the area and operational limiting conditions;
h. Site's physical characteristics and, in particular, depth and shape of the seabed and the ability of the bed material for anchor holding.

2.3.5.2. Anchorage Capacity (PIANC 121, 2014, p. 100)

The size of an anchorage must be sufficient to allow vessels to move freely, with a reasonable margin of safety. To determine the necessary size, several factors should be considered, including the expected stay of the ships at the anchorage, the length of the design ship, the length of the anchor chain and clearance from nearby hazards or ships. In general, ships must pay out an anchor chain length of at least five times the water depth to ensure a horizontal pull at the anchor. Assuming a dragging of the anchor of 30 meters, the required minimum radius of a free weather-vaning anchorage can be calculated using the following formula:

$$R_A = L_{OA} + 5h + 30m$$

where

R_A is the anchorage radius, given in meters (m);

L_{OA} is the design ship's length overall, given in meters (m);

h is the local depth.

2.3.5.3. Depth

The bottom surface of an anchorage should be relatively flat and free from obstructions that could foul an anchor. Because vessels weather-vane around their anchor, this may experience less severe vertical wave-induced motions than in a channel. However, there may be some squat caused by a strong current.

Anchorage areas may be protected from waves, so wave motions can be relatively small. As a result, the underkeel clearance at an anchorage does not need to be greater than that required in an all-weather and tide navigation channel, which is typically 1.1 times the vessel's draught (1.1T).

2.3.5.4. Quality of the holding ground

The anchorage area and, therefore, the nature of the seabed holding ground in the anchorage is generally determined by the geographical location of the port.

2.3.5.5. Protection from wind and waves

Whenever possible, the anchorage should be chosen based on prevailing winds and currents to provide the greatest natural shelter possible while also ensuring sufficient protection from wave effects.

2.3.5.6. Maritime traffic in the area

To minimize the risk of collision, anchorages should not be located near busy shipping lanes, especially considering the effects of fog and other phenomena that can reduce visibility.

2.3.5.7. Nautical facilities for anchoring

Anchorage areas should have suitable natural or artificial markings that enable ships to be accurately and safely positioned when approaching and while remaining at anchor.

2.3.5.8. Anchorage design for a ship with one anchor ahead

The swinging radius measured at the design ship's deck level can be calculated deterministically by adding up the following lengths (see Figure 2.10):

a. Vessel's length overall (L_{OA});

b. Length of chain it is expected to pay out at the anchorage. It is advisable to consider the total amount of chain available for the calculation to account for the possibility of having to pay it fully out because of heavy winds, waves or currents;

c. An additional safety distance to cover anchoring inaccuracies, which is intended for errors caused by inaccuracy of the method used for locating the position of the vessel to be anchored or the vessel's run during the time elapsed between the moment the order to drop anchor is given and the time when the anchor holds in the seabed. Chart accuracy and the crew's skill level are also important factors to consider. This safety distance depends on various factors and a value between 25% and 50% of the L_{OA} of the vessel may be acceptable;

d. A suitable margin for the event whereby the anchor drags. This can be evaluated with the following criteria, determined as a function of the wind velocity

1. Good anchoring resistance seabed:

- Anchoring with wind velocity ≤ 10m/sec = 0m;
- Anchoring with wind velocity of 20m/sec = 60m;
- Anchoring with wind velocity of 30m/sec = 120m;
- Anchoring with wind velocity ≥ 30m/sec = 180m;

2. Bad anchoring resistance seabed:

- Anchoring with wind velocity ≤ 10m/sec = 30m;
- Anchoring with wind velocity of 20m/sec = 90m;
- Anchoring with wind velocity of 30m/sec = 150m;
- Anchoring with wind velocity ≥ 30m/sec = 210m.

Note: Similar criteria could be established for combined or separate winds, waves, and currents, considering the resultant of longitudinal forces acting on the ship.

A safety clearance which may be 10% of the L_{OA}, with a minimum 20m (except for fishing and pleasure crafts, which may be reduced to 5m).

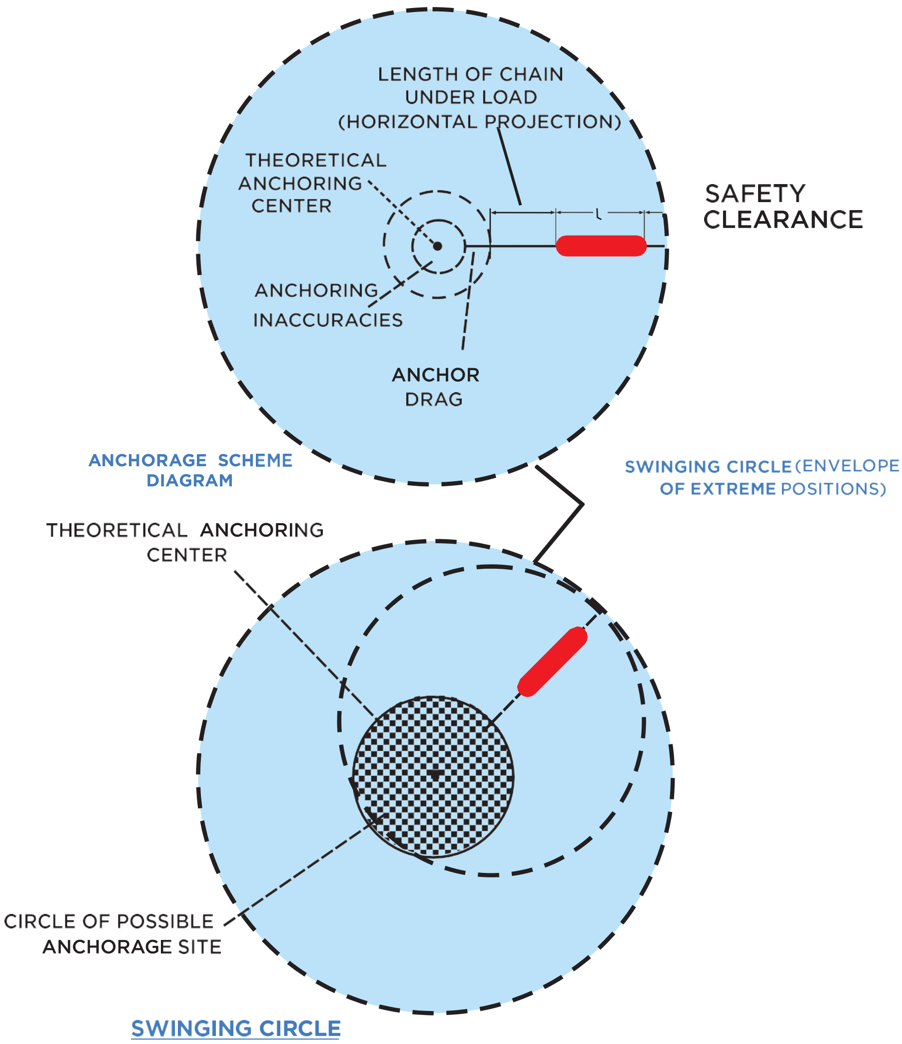


Figure 2.10 Swinging radius of a vessel with one anchor ahead
(taken from PIANC 121, 2014, p.103; ROM and others)

2.3.6. Port facilities

2.3.6.1. Passing speed of design ship where moored vessels are present

To ensure that a passing design ship does not cause significant disturbance to a moored ship, the speed of the passing design ship and the separation distance between the two ships should be considered. The following guidelines can be used:

a. Passing ship speed of 4 knots or less for a separation distance (hull side to hull side) of at least 2B;
b. Passing ship speed should be 6 knots or less for a separation distance (hull side to hull side) of at least 4B.

2.3.6.2. Clearance from ships provisionally positioned in the vicinity of the banks of a channel

To ensure that a passing design ship can keep a safe speed when vessels are provisionally positioned at the banks of a channel, a minimum clearance distance of 2.5B should be maintained between the design ship and the channel edge (see Figure 2.11).

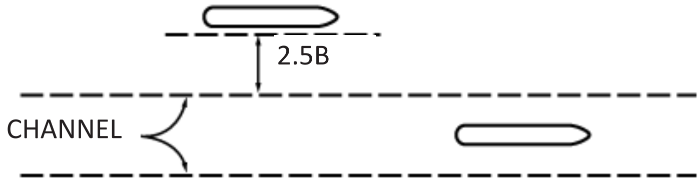
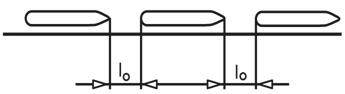
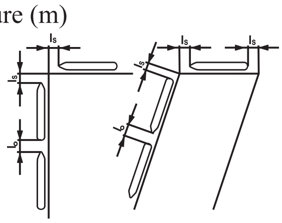
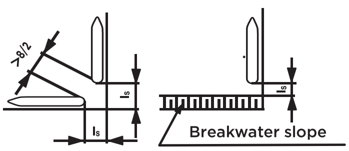


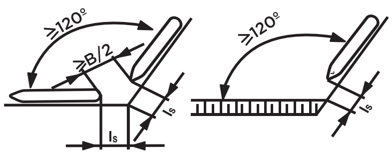
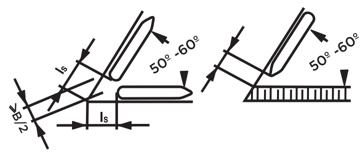
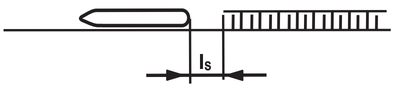
Figure 2.11 Clearance between ships positioned near the banks

2.3.6.3. Minimum distance between design ships at berth

The clearance between berthed design ships depends on the type of berth configuration and the length overall of the design ship. Table 2.16. shows the recommended minimum distances.

Table 2.16. Minimum distance between design ships at berth
(taken from ROM 3.1-99, Figure 8.48)

Representative scheme of the quay	**Values of the variable *Lo* as a function of the length overall (*L*) of the largest vessel at berth (inm)**				
	Over 300	**300-201**	**200-151**	**150-100**	**Less than 100[(1)]**
Distance << *Lo* >> between vessels berthed in the same alignment (m) 	30	25	20	15	10
Separation << *Lo* >> between vessels and changes in alignment or type of structure (m) 	30	25	20	10	5
	45/40	30	25	20	15

Representative scheme of the quay	Values of the variable *Lo* as a function of the length overall (*L*) of the largest vessel at berth (inm)				
	Over 300	**300-201**	**200-151**	**150-100**	**Less than 100[(1)]**
	30/25	20	15	15	10
	-/60	50	45	30	20
	20	15	15	10	10

Note 1 - 20% of << *L* >> will be taken as the value of << *Lo* >> for vessels with length overall less than 12 m ans the remaining values will be proportionately adjusted.
B - ***Beam*** of the largest vessel affecting the calculation of the dimension being analyzed.

2.3.6.4. Criteria for minimum distance between design ships berthed at a quay (see Tsinger, 1996 and Thoresen, 2014)

The determination of quay dimensions for berthing design ships follows criteria that can be divided into two groups:

- Projects in which ships will berth without tug assistance, where ships are less than 100 meters in length;
- Projects in which ships will require tugboat assistance.

In general, some distances must be respected, including:

- The longitudinal distance between ships berthed at a quay should be greater than $0.1L_{OA}$ of the largest ship at berth;
- The distance from the extreme end of the berthed ship to the end of the quay should be between 0.1 and $0.15L_{OA}$ of the berthed ship;
- If the quay has a slope at the end of its bottom, the distance from the end of the ship to the end of this slope should be $0.15L_{OA}$ or more.

2.3.6.4.1. Design ships berthed in a basin with a single quay on each side, without tug assistance (Thoresen, 2014)

Design ships of less than 100m in length can berth without tug assistance.

If the project involves berthing of two ships, one on each side as seen in figure 2.12, the basin width B_{nd} should be equal to

$$B_{nd} = 2B_{max} + 30m$$

If the project involves working with ships berthed ship-to-ship, two on each side of the dock, as seen in Figure 2.12, the basin width B_{nd} should be calculated as follows

$$B_{nd} = 4B_{max} + 50m$$

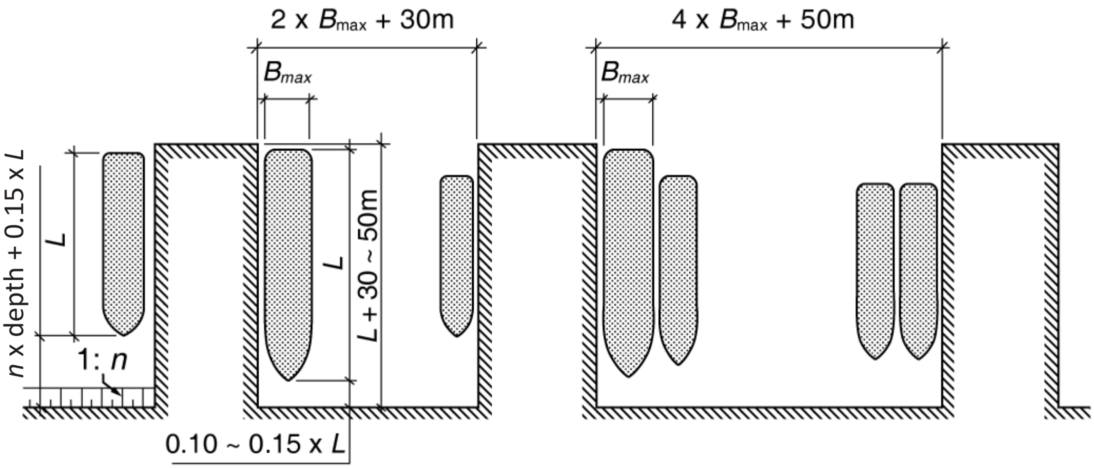


Figure 2.12. Minimum width for a basin with a single quay on each side (Thoresen, 2014, p.86)

If a project allows two ships to berth at each lateral quay of the basin, as represented in Figure 2.13, the basin width B_{nd} should be equal to

$$B_{nd} = 2B_{max} + 50m$$

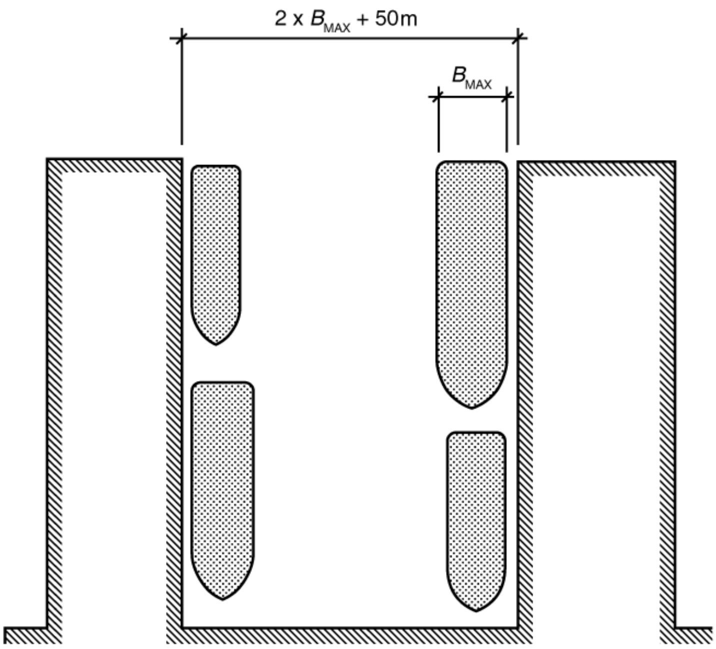


Figure 2.13 Minimum width for a basin with more than one ship berthed at each side (Thoresen, 2014, p.86)

If the project establishes different lengths for each quay, where one quay accommodates only one ship and the other accommodates two ships, the basin width should be calculated using the following formula:

$$B_{nd} = 2B_{max} + 50m$$

Figure 2.14. shows a sketch of an area set up with three different basins accommodating two, three and four ships and the recommended openings (see Tsinger, 1996).

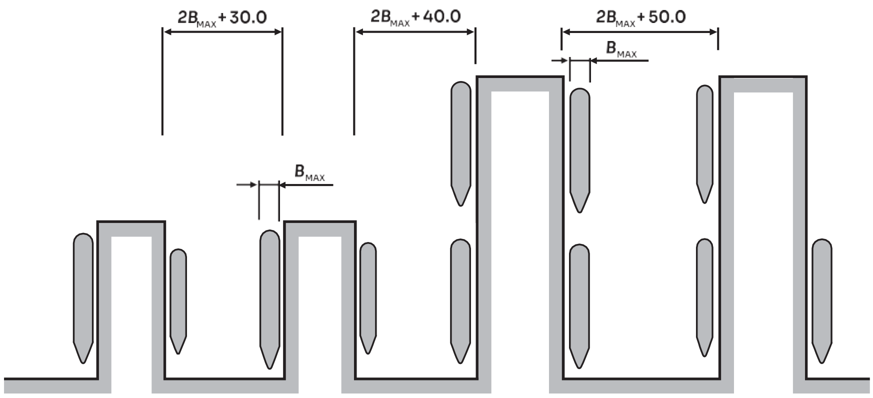


Figure 2.14. Minimum width for three different basins (Tsinger, 1996, p. 155)

2.3.6.4.2. Design ships moored with assistance of tugs (ROM 3.1-99)

For basins with berths on both sides where only one ship can berth at each side (as shown in Figure 2.14.), the recommended minimum width of the basin is determined by the greater of the following values: (as recommended by ROM 3.1-99)

$$B_{nd} = 2B_{max} + L_R + 20m$$

$$B_{nd} = 3B_{max} + L_R$$

where

B_{nd} is the minimum recommended width, given in meters (m);

B_{max} is the maximum beam of the design ship, given in meters (m);

L_R is the length of the tow rope and tug set, given in meters (m), as seen in Table 2.17.

Table 2.17. L_R values (ROM 3.1-99, p. 285)

Vessel displacement (tons)	L_R (m)
Up to 5,000	45
between 5,000 and 10,000	46-50
between 10,000 and 20,000	51-60
between 30,000 and 60,000	61-70
More than 60,000	71-85

B_{nd} minimum width is represented in figure 2.15.

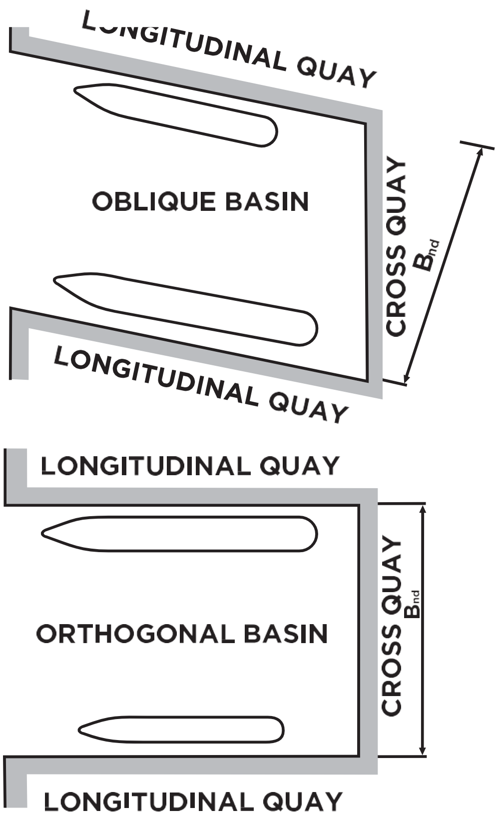


Figure 2.15 B_{nd} minimum width (figure 8.51, taken from ROM 3.1-99)

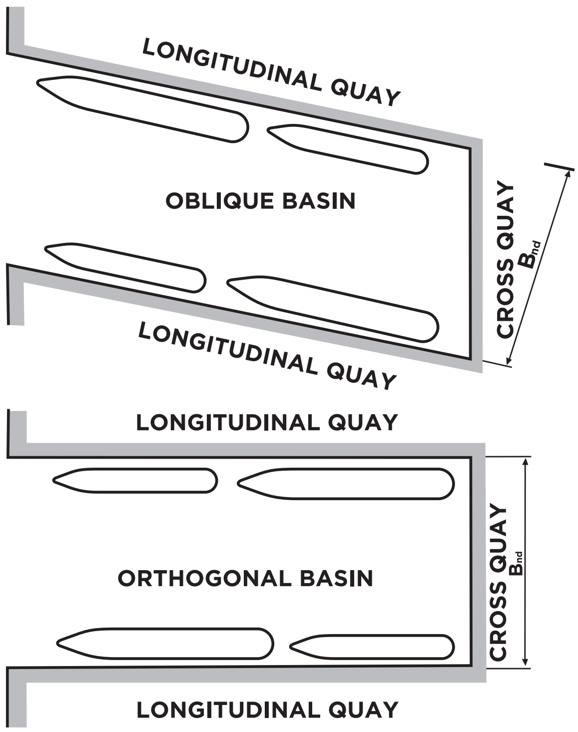


Figure 2.16. B_{nd} minimum width (figure 8.50, taken from ROM 3.1-99)

In the scenario of basis with berths on both sides, each one capable of accommodating two ships and not allowing ships to berth ship-to-ship or maneuver simultaneously, the minimum width of the basin will be the greater of the following values:

$$B_{nd} = 3B_{max} + L_R + 20m$$

$$B_{nd} = 5B_{max} + L_R$$

2.3.6.4.3. Design ships moored ship-to-ship with assistance of tugs

When performing transhipment operations between design ships that are both over 100m in length, ROM 3.1-99 recommends calculating the minimum width of the basin using the values obtained from the formulas in 2.2.6.4.2. added to:

$$B_{ndp} = nb\ (B_{max} + 2)$$

where

B_{ndp} is the increase in the basin's width, given in meters (m);

B_{max} is the maximum beam of the design ship, given in meters (m);

nb is the maximum number of ships moored ship-to-ship in any cross-section of the basin, without counting those directly moored to the quay;

Value 2, given in meters (m), is the minimum space required for fenders inserted between ships moored ship-to-ship.

Figure 2.17. shows the minimum width for basin for design ships over 100m in length moored ship-to-ship.

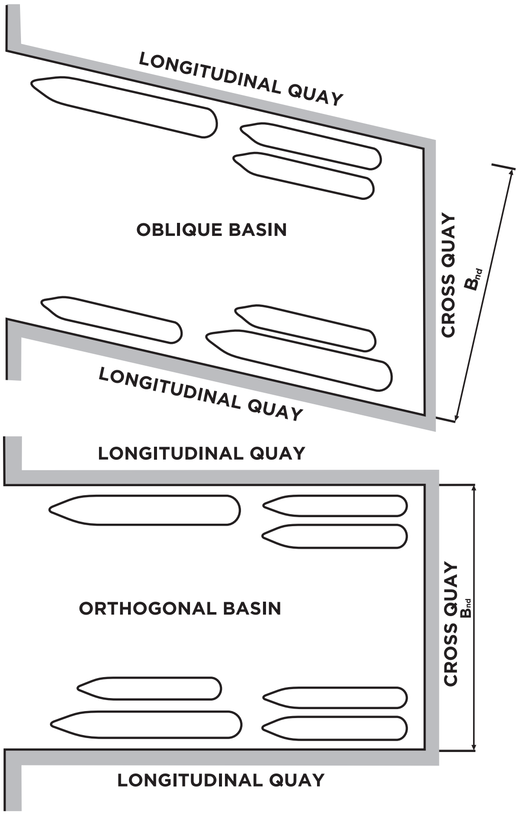


Figure 2.17 Minimum width for basin for design ships over 100m in length moored ship-to-ship (figure 8.52, taken from ROM 3.1-99)

2.3.6.4.4. Minimum distance between a ship moored at the rear part of a basin and the quay

The minimum distances must meet the minimum limit of l_S, as represented in Figure 2.18.

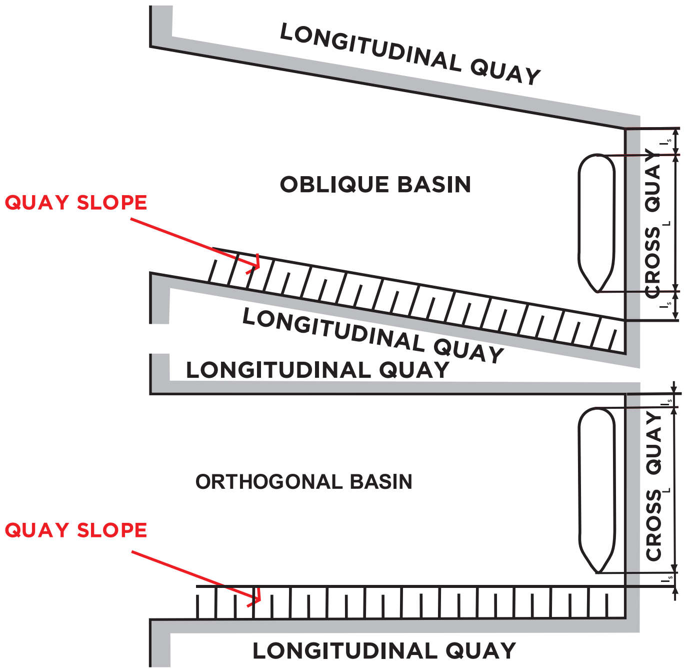


Figure 2.18. Minimum limit l_S (Figure 8.49. taken from ROM 3.1-99)

The minimum value of distance l_S is given on table 2.18.

Table 2.18. Minimum value of distance l_S

Quay schematic	Values of the variable l_s as a function of the length overall (L) in meters (m) of the longest ship at berth				
	Over 300	**300-201**	**200-151**	**150-100**	**Under 100**
Separation <<l_s>> between ships and changes in alignment or type of structure expressed in meters (m) 	**30**	**25**	**20**	**10**	**5**

2.3.6.5. Turning area for a design ship entering a basin

To allow for entry into a basin with assistance of tugs, the diameter of the turning area should be $1.5L_{OA}$. This distance should be measured from the cross quay when it is free or from the maximum beam of the design ship (B_{max}) at berth, as shown in Figure 2.19.

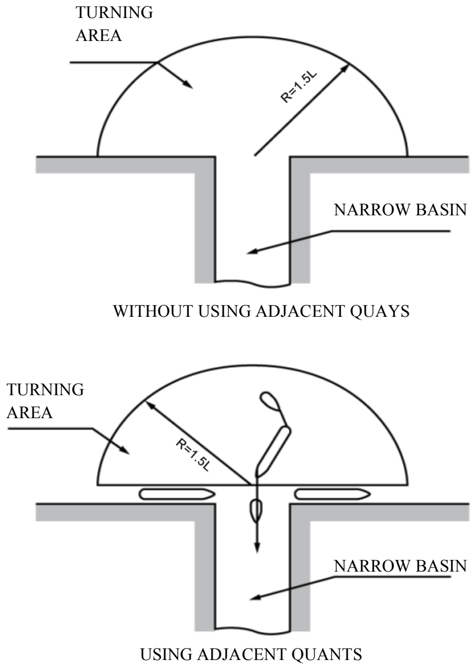


Figure 2.19. Turning area (taken from ROM 3.1-99 figure 8.47)

2.3.6.6. Pier angle relative to the direction of environmental forces

For optimal performance, the angle formed by the pier and the prevailing wind direction should be 30 degrees. Additionally, longitudinal currents in relation to the pier should be less than 3 knots, while cross-currents should be less than 0.75 knots.

2.3.6.7. Mooring berth area (see ABNT 1995)

The dimensions of the mooring berth area should be determined based on the minimum dimensions and verification criteria recommended in sections 2.2.6.7.1. and 2.2.6.7.2., as well as any clearances or restrictions that may be required due to:

a. The location and nature of the berth construction;
b. The purpose of the berth use;
c. Recommended safety measures for berthing and unberthing maneuvers;
d. The conditions of use of the bordering area.

2.3.6.7.1. Area dimensioning

When dimensioning the berth area in a protected area without currents, the following criteria and parameters should be considered:

a. For berthing or unberthing maneuvers, regardless of use of tugs:
– Length: 1.2L;
– Width: 1.2B.

2.3.6.7.2. Depth dimensioning

The minimum depth of the berth basin should be equal to the maximum draught of the largest design ship, considering the function of the port facility, and taking into account the following factors:

a. Ship-related
1. Influence of the static trim;
2. Water density;
3. Response allowance;
4. Additional clearance, which varies according to the nature of the channel bed:
   - Muddy: –
   - Sandy: a minimum of 0.40 m;
   - Rocky: a minimum of 0.5 m.

b. Water level-related, while the project ship remains in port
1. Tide (meteorological and astronomical);
2. Tolerance to favorable and unfavorable conditions.

c. Bottom-related: the same used for channels.

If applicable, the vertical motion of vessels due to wave action should also be considered due to the specifics of the local environment.

2.3.7. Bollard pull and pull-push force of tugs

The total force to be provided by tugs should be the sum of the bollard pull and the pull-push force of each tug. With the static force of tugs, it is possible to maintain static balance with the transverse environmental forces acting on the design ship. With the pull-push force, the hull's transverse hydrodynamic resistance to acceleration/deceleration can be overcome.

2.3.7.1. Bollard pull for ensuring maneuverability

Calculating the total force required for tugs to assist a ship depends on several factors. To determine the necessary bollard pull, refer to Chapter 5 of Henk Hensen's book "Tug Use in Port."

The main factors influencing calculations are:

• **Port characteristics**
Fairway restrictions, harbor entrances, route to quays, turning basin, maneuvering space at a pier or in its turning basin, available stopping distance, locks, bridges, moored ships, water depth, speed restrictions, etc.

• **Types of quay construction**
Types of quays: open, e.g. hollow or solid extending out to sea.

• **Types of ships**
Type, size, draught, underkeel clearance, trim, windage and factors as engine power ahead/astern, propeller type, maneuvering performance and existence of thrusters and specific rudders.

• **Environmental conditions**
Winds, currents, waves, visibility.

• **Tug assistance method**
Towage with long ropes, operation on ship's side or a combination of methods.

2.3.7.2. Force due to the added mass for the pull-push condition

When a ship is accelerated or decelerated, the fluid exerts a lateral resistance force associated with the added mass. This force is not static, but rather a dynamic contributing factor that must be added to the static bollard pull of the tugs.

For hollow piers, the resistance effect associated with the added mass is greater than that for solid piers. Therefore, the following safety factors should be adopted: (*Tug use in port*, Chapter 5)

a. F Force due to added mass for hollow piers - force to compensate for the additional mass in ton-force

$$F = \frac{0.09\ \Delta\ V_y^2}{30}$$

b. F Force due to added mass for solid piers - force to compensate for the added mass in ton-force

$$F = \frac{0.07\ \Delta\ V_y^2}{30}$$

where

Δ is the displacement of the ship, expressed in tons (ton);

V_y is the lateral approach speed to the pier, with average speeds of 0.15m/s to 0.25m/s for a distance of 30m from the pier.

2.3.8. Air draught (PIANC 121, 2014, p. 236)

2.3.8.1. Design ship height and air draught

Two measurements are used to determine the height of a design ship: the height H_{kt}, which is the distance from the keel to the highest point, and the air draught H_{st}, which is the distance from the water surface to the top of the ship. Figure 2.20. illustrates these measurements.

To accurately calculate the air draught, the water surface should include the highest probable navigable level, such as astronomical high tide or tidal waves, taking into account tidal and meteorological effects. The ship's draught is denoted by T.

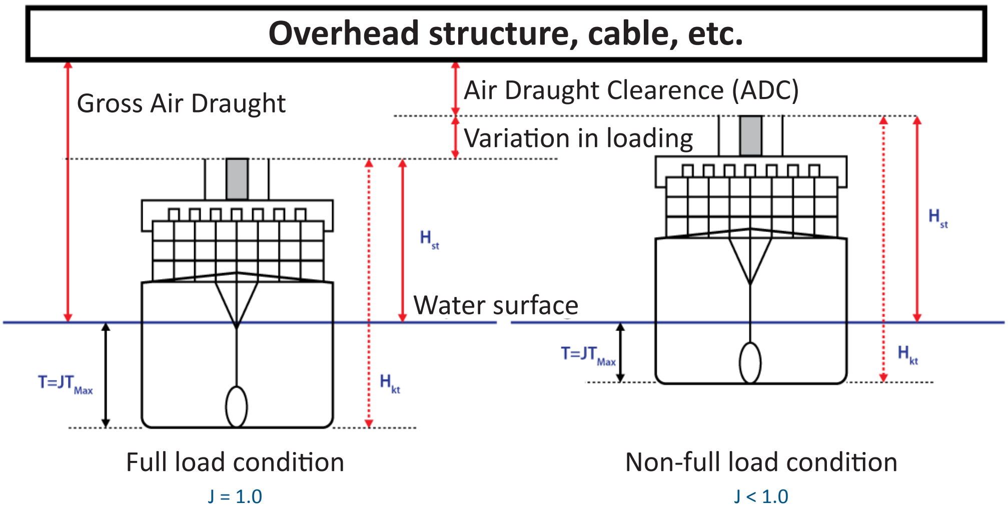


Figure 2.20. How the air draught clearance of a ship varies as a function of its loading condition. (PIANC 121, 2014, p. 236)

The relationship between these variables is expressed by: (PIANC 121, 2014, p. 236):

$$H_{st} = H_{kt} - T = H_{kt} - J\,T_{max}$$

where

H_{kt} is the height from the design ship's keel to its top, given in meters (m);

H_{st} is the height from the sea or water surface to the top of the ship, given in meters (m);

T is the draught of the ship in full-load condition, given in meters (m);

J is the draught factor, which varies from 0.5 to 1.0 according to the draught;

T_{max} is the draught in full-load condition, given in meters (m).

The values of H_{kt} and T_{max} are generally fixed for a given design ship. However, the actual draught T (= J T_{max}) of a ship changes depending on its loading condition and other factors.

The draught factor J is used to account for changes in loading, with a maximum value of 1 when the ship is fully loaded and less than 1 when not fully loaded. For ballast conditions, values range from 0.5 for weight carriers to 0.8 for volume carriers. The H_{st} increases as J decreases, in such a way that, as the ship's draught becomes less, the clearance between the top of the ship and overhead structures such as bridges become smaller and may pose dangers. As a result, the H_{st} will also vary from full load to lighter load conditions.

Finally, the gross air draught is the vertical distance from the water surface to the bottom (or lowest part) of the overhead structures. The air draught clearance (ADC) is what is left for clearance after the H_{st} and variation in ship loading is subtracted from the gross air draught.

2.3.8.2. Air Draught Clearance (ADC) (PIANC 121, 2014, p. 236)

To ensure safety, there must always be a positive clearance or ADC between the top of a ship and the bottom of any overhead structure.

An estimate of the ADC during the Concept Design phase can be calculated as:

$$ADC = 0.05\ H_{st} \geq 2m$$

where

H_{st} is the height from the sea or water surface to the top of the ship, given in meters (m).

For outer channels where wave conditions can be significant, an additional allowance of 0.4 T (40% of the static draught of the design ship) should be added to the ADC. Additionally, the ADC calculation must consider power line sagging.

2.3.9. Floating Terminals

The same requirements for maneuvering spaces, ship spacing, tugboats and risk analysis that apply to fixed piers in the Concept and Detailed Designs also apply to floating terminals. We cannot simply estimate the stress that a floating terminal will experience based on the number of ships berthed there. It is necessary to calculate the aerodynamic and hydrodynamic forces acting on the ships moored at the terminal in order to determine the forces to which the terminal will be subjected.

2.4. Detailed Design

Before discussing design considerations, it is crucial to emphasize the importance of identifying port facilities as unique entities. Each port facility has its own distinct characteristics, which are akin to a "fingerprint" of the port. Factors such as water depth, width in straight stretches or curves, turning basin geometry and internal channel layout, which have been studied and validated for one port, cannot be applied to another port, even if it is in close proximity.

In 1983, the U.S. federal government funded a series of advanced studies to determine whether a single standard for port facilities could be established using only one variable, the dredging depth in channels. Unfortunately, the group's conclusion was that the physical and environmental characteristics of each port are unique, and dredging depths must be specified for each location, which was a discouraging result for the US Department of Transportation. However, general criteria can still provide a useful first approximation for design and practice, along with basic standards of adequacy. The following quote is taken from the original document "Criteria for the Depths of Dredged Navigational Channels," Marine Board of National Research Council, Final Report, 1983

"In light of its reviews and appraisals, the panel concludes that the physical environment and characteristics of each port are unique *and the* criteria for channel *depth, as well as the specification of overdredge depth,* must be site-specific. *Nevertheless,* general criteria provide a useful first approximation for design *and practice, and basic standards of adequacy."*

After this brief introduction, the following items present recommendations to follow in the Detailed Design:

a. Simulation of the environment and ship's maneuverability;
b. Channels including the air draught;
c. Maneuvering spaces;
d. Inner or approach channels;
e. Turning basins;
f. Anchorages;
g. Port facilities;
h. Bollard pull and tug pull-push force;
i. Risk analysis.

2.4.1. Simulation of the environment and ship's maneuverability

2.4.1.1. Simulation of the environment

Simulation of the environment can be accomplished using numerical models to solve problems of fluid mechanics that represent the local physical environment. It must meet verification and validation requirements. Technical documentation should be produced that details the results obtained and the corresponding verification and validation processes. For an environment simulator to be used in a port project, its numerical model must represent the physical aspects relevant to navigation in a given area.

When physical models are used, their physical similarity to the prototype must be justified, including any restrictions and how the validation process was conducted. The results obtained, as well as the respective validation processes and limitations of the model, should also be documented.

The results of environmental simulations should be realistic because a good ship maneuver simulation is of no use if the environmental data does not correspond to reality. Changes due to dredging, for example, can significantly alter the environment and should be taken into consideration. Generally speaking, deepening resulting from dredging changes the tide and increases siltation rates.

2.4.1.2. Simulation of the maneuverability of the design ship (see NORMAM 11)

Ship maneuverability simulation models for the design ship can be divided into two major groups: physical models, (scaled-down versions of the ship), and mathematical (numerical) models.

Physical models can be either interactive, when under human control, or non-interactive, with automated control. Interactive models can be manually controlled or controlled remotely.

Numerical maneuverability models for the design ship can also be interactive or non-interactive, and can be conducted in real-time or fast-time. Non-interactive models can be controlled by an autopilot or programmed navigation driving routines.

Maneuver simulation models should utilize data from the model that accurately represents the local environment.

To demonstrate the feasibility of using the ship model for producing analyses in the Detailed Design phase, a vessel maneuvering booklet should be presented and its recommendations are listed in Chapter 4.

2.4.2. Channels

2.4.2.1. Detailed vertical design of the channel

In this section, we will discuss the various factors that should be considered while designing the vertical layout of channels, specifically the factors that affect the channel depth.

2.4.2.1.1. Factors associated with water depth

The tide varies in time and space. In long channels influenced by tides, numerical models that represent the local physical environment must be used to solve the fluid mechanics problem, or physical models should be used to define the critical times and places for the passage of design ships in full-load condition. The models should include the astronomical and meteorological tides, if any, and the seasonal oscillation of the water depth when subject to flood and dry seasons. The analysis must be done considering the average lifetime of the design ship.

If numerical models are employed, technical documentation should be submitted listing the maximum draught, tidal windows and current windows estimated for the design ship's lifetime.

2.4.2.1.2. Ship related factors

2.4.2.1.2.1. Allowance for static draught uncertainties

It is important to consider the uncertainty related to the static draught of ships, such as trim and list. A comparison can be made between the draught readings displayed on the pilot card of design ships when entering a port facility and the draught reading when the ships are at berth. The methodology used to define the allowance for the static draught uncertainties should be described in a technical report.

2.4.2.1.2.2. Changes in water density

The calculation of hull immersion due to changes in water density can be corrected by considering other factors that may be important, such as the presence of fluid mud. In addition, there may be depth levels with different densities for ships with large draughts in estuarine port regions. The detailed calculation should indicate the chosen safety margin and should be documented.

2.4.2.1.2.3. The squat effect

2.4.2.1.2.3.1. The squat effect in unsteady speed regimes

The squat effect calculated in the Concept Design Project only considers design ships under constant speed conditions and in supposedly straight channels, without sudden changes in their configuration or bathymetry. However, changes in squat can occur in design ships that experience variable speeds. For example, squat can change when a design ship undergoes a sudden transition from deep to shallow waters or when it is accelerating or decelerating.

If a design ship is in relatively shallow waters, ripples on the bottom can also affect its squat. Additionally, proximity to banks and channel bends tend to increase squat, while muddy bottoms may decrease it. The presence of another ship, whether passing, overtaking or moored, can also affect squat, as ships have been known to experience larger squat when interacting with other vessels. To ensure accurate measurement of squat values using numerical and experimental methods, the requirements of Chapter 5 must be met.

2.4.2.1.2.3.2. The squat effect with the design ship at a steady speed

Expressions given in Chapter 5 can also be used to analyze the squat effect in straight sections of a channel and at a constant speed.

2.4.2.1.2.4. Dynamic heel

The dynamic heel of a design ship in a channel is a critical factor for ships with large longitudinal windage areas and low metacentric heights (GM), such as container ships and car carriers (Ro-Ro), which are particularly susceptible to dynamic heeling in strong crosswinds. Rudder action can also produce significant hull/rudder interactions, further exacerbating this issue.

To determine the variables associated with aerodynamic forces, simulation using physical and numerical models is typically employed. The result of this simulation should be presented in a technical report, listing the aerodynamic force coefficients in surge, sway and yaw as a function of the wind angle relative to the design vessel.

The dynamic heel of the design ship, caused by either wind or hull/rudder interaction, can be obtained through physical and numerical models. When using numerical models, the simulation must meet verification and validation requirements and should be performed using fluid mechanics models that accurately represent the ship's behavior. Technical documentation should be prepared to explain the results obtained, as well as the verification and validation processes.

2.4.2.1.2.5. The design ship response to waves

The transfer function that naval architects refer to as the RAO (response amplitude operator) is used to determine the ship's response. This can be obtained through tank tests with reduced scale models or numerical models that accurately represent the behavior of the design ship and solve the fluid mechanics problem. When using numerical or experimental methods, it is important to strictly adhere to the recommendations given in Chapter 3.

2.4.2.1.2.6. Net UKC

The net UKC of the Detailed Design is the same as that of the Concept Design.

2.4.2.1.3. Maneuverability margin of the design ship

The maneuverability margin of the ship in the Detailed Design is the same as in the Concept Design.

2.4.2.1.4. Water depth in muddy areas

The water depth in muddy areas (nautical bottom) is a function of the controllability of the design ship (maneuverability, ability to stop and directional stability) that is affected before it reaches the water/ fluid mud interface. As the vessel becomes increasingly immersed in mud, its maneuverability is degraded until it reaches a critical limit.

It's important to note that the ship's controllability is not only dependent on the density of the mud, but also on its rheological characteristics. Different types of mud can cause the design vessel to behave differently. An initial assessment of the controllability of the design ship navigating on a muddy bottom is highly recommended. To do this, it is recommended to use published results from reduced-scale physical models.

Chapter 6 presents some basic concepts about fluid mud, the nautical bottom and data on the behavior of the design ship in this fluid medium.

2.4.2.1.5. Bottom-related factors

2.4.2.1.5.1. Allowance factor for depth uncertainties

The criteria used in the Concept Design phase should also be applied during the Detailed Design phase. However, more accurate and updated information can be used.

2.4.2.1.5.2. Allowance factor for bottom changes between dredging operations

To account for possible sedimentation or siltation that could occur after or between dredging operations, an allowance factor should be estimated through simulations in physical or numerical models. The model used must accurately represent the physical environment and meet validation and verification requirements. A technical report should be prepared to explain the results obtained, as well as the verification and validation processes.

Areas subject to siltation, such as the channel, turning basin, internal channel, anchorage, maneuvering and berthing areas should be demarcated. The technical report should also include estimated values of depth and width reduction per month and year.

2.4.2.1.5.3. Allowance for dredging uncertainties

The Detailed Design should consider the same criteria as the Concept Design, with the option of utilizing more updated and precise information. Consultation with dredging companies is recommended.

2.4.2.1.6. Air draught (PIANC 121, 2014, item F.2.)

For the Detailed Design phase, it is advisable to calculate the air draught H_{st} using the following formula:

$$H_{st} = H_{kt} - T = H_{kt} - J\,T_{max}$$

where

H_{st} is the air draught, taken from Appendix B tables, given in meters (m);

H_{kt} is the height from the keel to the top, given in meters (m);

T_{max} is the draught in full-load condition, given in meters (m);

J is the draught factor, using cover coefficients of 95%.

Although the expressions presented in the Concept Design and in the Detailed Design appear to be the same as those in the tables in Annex B, respecting the ship type, they may lead to different results.

2.4.2.2. Detailed design of channel horizontal dimensions

The assessment of the channel width must be carried out using simulations that can be conducted using either reduced-scale models or numerical models (real-time and/or fast-time). It is recommended that verified and validated simulators are used in accordance with Chapter 4, and their environment should be verified and validated according to appendix A of the same chapter.

The initial analyses can be conducted preferably in fast-time using autopilot to confirm the viability of the geometry proposed in the Concept Design. The various environmental conditions in the port facility that were previously predicted in the Concept Design should be simulated and tested.

Before conducting simulations, it is important to establish the control and governing procedures of the model, as well as the desired track of the design ship and navigation procedures. These should be discussed in advance with relevant authorities and channel designers, simulator operators, local pilotage, and other specialists who may be required.

In the case of two-way channels, it is important to evaluate and document the interaction effects of both crossing and overtaking of passing ships. This evaluation should include a description of the attractive and repulsive forces and moments, effects on heading, course, speeds in the horizontal plane, and possible increase in the squat effect.

It is recommended to prepare a technical report of the tests with fast-time simulations showing:

a. The track of the design ship;
b. Heading;
c. Heading and acquired drift angle (due to environmental forces, shore effects, shallow water effects, banks, etc.);
d. Loss or gain of forward, lateral, and roll velocities about the Z-axis in the horizontal plane;
e. Rudder angle;
f. Practical and critical conditions observed in time and space;
g. Design ship and navigation control procedures employed in each test performed.

After making the channel width geometry viable in fast-time, the results should be reevaluated in real-time with manual control. The navigation and maneuvering routines of the design vessel should be performed by local pilots when the pilotage zone is compulsory. Simulations must be performed in situations that meet the visibility standards of the setting under study (day, night, fog, rain, buoy lights, beacons, etc.).

A technical report must be prepared listing all the tests performed in real-time, indicating:

a. Environmental conditions;
b. Steering orders and performed control (engine and rudder);
c. Track of the design vessel;
d. Course;
e. Heading and drift angle acquired by the design vessel;
f. Speeds in the horizontal plane;
g. Observed practical and critical conditions.

A risk assessment must be carried out in accordance with the requirements in Chapter 8 of this book.

2.4.2.3. Channel curves

The evaluation of channel curves should be conducted through simulation. Both straight sections and bends can typically be analyzed in a single simulation run.

The same technical recommendations (simulation, reports and procedures) used to define the channel width should be adopted for curves. During the evaluation of curves, particular attention should be paid to the drift angle of the design ship and the time it takes for the vessel to change heading and course.

2.4.3. Maneuvering spaces

The factors associated with the distance and stopping time of the ship, regardless of use of tugs, can be reassessed in simulators.

The same technical recommendations adopted for simulation validation and verification, reports and procedures listed in Chapter 4 and Appendix A of this chapter should be used.

2.4.3.1. Turning basin

The assessment of turning basin dimensions should be done using physical and/or numerical simulations.

When the design ship is assisted by tugs, the diameter of the turning basin can be at least (USACE, p. 9-2, 9-3)

1,2L_{OA}, with current intensity up to 0.3m/s;

1,5L_{OA}, with current intensity up to 0.8m/s.

When the current intensity is greater than 0.8m/s, the turning basin can be elliptical, as represented in Figure 2.21, or have another geometric shape that allows maneuvering with currents.

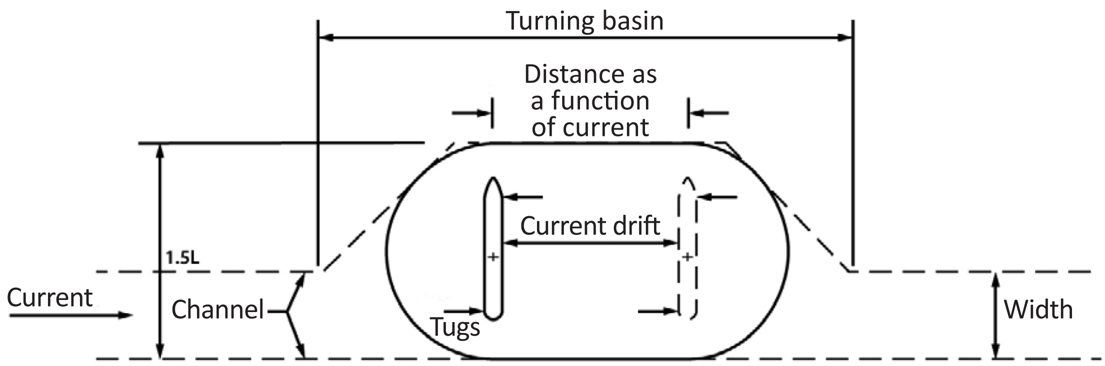


Figure 2.21 Turning basin (taken from USACE 1110-2-1613, figure 9.1)

The same technical recommendations adopted for the validation and verification of the simulation, reports and procedures listed in Chapter 4 and Appendix A of this chapter should be used.

2.4.3.2. Interaction between passing and moored ships

When dealing with navigation channels where there are moored ships, the effects of passing ships must be taken into consideration. These effects are especially concerning when the berths are located in relatively narrow fairways or near shipping lanes, as ships pass in close proximity to the berthed vessels when entering or leaving the port. These events can disrupt loading and unloading operations and put excessive pressure on mooring ropes.

The interaction effects between the passing and moored ships can be even greater for berthed ships that are very sensitive to motion, such as those operating at oil and gas terminals and container terminals. In oil terminals, the loading arms have limited movement, while in container terminals, the cranes and container guides require restricted movements when loading and unloading containers.

Operational limits must be established for the speed and separation distance of passing ships to prevent interaction effects that could cause unnecessary disturbance to the moored vessel and potential damages to the mooring ropes and fenders. If necessary, cargo handling activities may need to be suspended on the moored vessel until the passing ship has passed.

The magnitude of the passing ship effects depends on several factors, including:

a. Speed of the passing ship through the water, as the effects of interaction are proportional to the square of the moving ship's speed through the water. Therefore, this parameter should be carefully considered in the design and a realistic local speed range taken into account;
b. Separation distance between the passing and moored ships, where the effects increase with decreasing separation distance between the moving ship and the moored ship;
c. Size of both ships, as larger ships, deep draughts and high block coefficients tend to generate greater interaction effects and moored vessel movements;
d. Underkeel clearance of both ships, where low underkeel clearances tend to increase the interaction effects, as the blockage effect is higher;
e. Channel geometry, width and local bathymetry, where narrow channels or constrained waterways can accentuate the interaction effect, again due to blockage effects.

The interaction effects between passing ships and other moored ships should be analyzed in simulators. A technical report should be prepared considering the items already presented.

2.4.3.3. Inner or approach channels

The established lateral distances for inner or approach channels in the Concept Design can be re-evaluated using physical and numerical simulations. This assessment should be done in conjunction with the assessment of tugs, including their type, number, mode, and positioning.

The same technical recommendations used for the validation and verification of simulations, reports and procedures presented in Chapter 4 and Appendix A of this chapter should be used.

2.4.3.4. Anchorages

The distances and safety margins established in the Concept Design for anchorages can be re-evaluated through physical and numerical simulation, taking into account the presence of other moored ships and local traffic.

The same technical recommendations used for validation and verification of the simulation, reports and procedures listed in Chapter 4 and Appendix A of this chapter should be used.

A detailed explanation of the model used, the tensions exerted on the anchors as a function of environmental forces and the distance the ship travels per time interval in case of dragging should also be provided.

2.4.3.5. Port facilities

The distances previously established in the Concept Design for port facilities may require reassessment through physical and numerical simulation.

The same technical recommendations used for validating and verifying the simulation, reports and procedures, presented in Chapter 4 and Appendix A of this chapter, should be applied.

2.4.3.6. Bollard pull and pull-push force of tugs

The bollard pull and pull-push forces specified in the Concept Design can be reviewed through physical and numerical simulations.

In the Detailed Design, the mode of tug assistance, whether direct or indirect, must be indicated, as well as the positioning in relation to the design ship, the region within the access where they are being employed and the ship's speed.

The following factors must be taken into account:

a. The interaction between the design ship hull and the tug hull;
b. The interaction between the design ship propeller and the tug hull;
c. The interaction between the design ship's hull and propeller and the tug propellers' thrust force;
d. The interaction between the tug fenders and the design ship hull;
e. The interaction between the towing rope and the tug;
f. The interaction between the towing system and the dynamics of the mooring lines.

The assessment maneuvers in simulators should preferably be conducted in individual control centers (bridges) with local tug masters on tugs and local pilots on design ships.

A technical report should be prepared, listing all tests carried out in fast-time and/or real-time, indicating environmental conditions, steering orders and control effected (engine and rudder), the track and course of the ship and tugs, heading and drift angle acquired by the ship and tugs, speeds in the horizontal plane and practical and critical conditions observed. A graph or table must be presented, detailing the values of the towing ropes pull and the total pull value obtained in each test.

The pier fender system should be modeled to meet berthing and unberthing conditions.

2.4.4. Floating terminals

All the requirements for maneuvering spaces, distance between ships, tugboats and risk analysis specified for fixed piers in the Concept and Detailed Designs apply to floating terminals.

It should be noted that during berthing maneuvers it is not possible to pull the mooring lines to bring a project ship alongside the floating terminal due to the risk of pulling it from its anchoring position.

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APPENDIX A – CHAPTER 2
Environment simulation: verification and validation

This appendix presents some recommendations for the use of numerical methods in flow simulation in channels.

When utilizing numerical treatment, the following items should be adequately described:

- Geometry modelling of the port area
- Description of the computational fluid mechanics code
- Discretization of the mathematical model
- Establishment of initial values and boundary conditions
- Simulation and convergence strategies
- Model verification and validation

The following are specific recommendations for each of the aforementioned items.

Geometry modelling of the port area

The CAD program (or code) used to describe the geometry of the basin and approach channel should be specified. Additionally, it is recommended to provide a description of the technique used in the mesh structure and topology.

Description of the computational fluid mechanics code

The numerical code used to calculate speed, pressure and other variables of the problem should be specified, including the existing numerical methodology used in the code.

Discretization of the mathematical model

The structure and topology of the mesh used should be described. Additionally, the time-stepping and spatial discretization strategies employed in the development of the numerical solution of the fluid mechanics equations should be presented.

Initial and boundary conditions

The input data, parameters and initial and boundary conditions used in the CFD code should be clearly stated.

Simulation and convergence strategies

The criteria used for determining convergence in the numerical solution should be specified, along with details on how the numerical scheme respects principles and conservation laws of fluid mechanics, both locally and globally.

Model verification and validation

The degree of accuracy of the results presented and how it was achieved should be described.

APPENDIX B – CHAPTER 2

Coefficient tables for air draughts

This Appendix presents tables B.1 to B.8 with the coefficients for air draught by ship type.

Table B.1. Container ship (PIANC 121, Appendix F)

COVERAGE RATE	DWT	H_{kt}	T_{FL}	$H_{st} = H_{kt} - JT_{FL}$				
				J = 1.0	J = 0.95	J = 0.9	J = 0.85	J = 0.8
95%	10,000	45.4	8.3	37.1	37.6	38.0	38.4	38.8
	20,000	51.5	10.4	41.1	41.6	42.1	42.6	43.1
	30,000	55.0	11.9	43.1	43.7	44.3	44.9	45.5
	40,000	57.5	12.7	44.8	45.5	46.1	46.7	47.4
	50,000	59.4	13.2	46.3	46.9	47.6	48.2	48.9
	60,000	61.0	13.7	47.3	48.0	48.7	49.3	50.0
	100,000	65.4	14.9	50.6	51.3	52.1	52.8	53.5

Table B.2 Cargo ship (PIANC 121, Appendix F)

COVERAGE RATE	DWT	H_{kt}	T_{FL}	$H_{st} = H_{kt} - JT_{FL}$					
				J = 1.0	J = 0.9	J = 0.8	J = 0.7	J = 0.6	J = 0.5
95%	1,000	25.4	4.4	21.0	21.4	21.9	22.3	22.7	23.2
	2,000	30.0	5.5	24.5	25.0	25.6	26.1	26.7	27.2
	3,000	32.6	6.3	26.3	27.0	27.6	28.2	28.9	29.5
	5,000	36.0	7.4	28.6	29.4	30.1	30.8	31.6	32.3
	10,000	40.6	9.3	31.3	32.2	33.2	34.1	35.0	35.9
	12,000	41.8	9.9	31.9	32.9	33.9	34.9	35.9	36.9
	18,000	44.5	11.3	33.2	34.3	35.4	36.6	37.7	38.8
	30,000	47.9	11.2	36.7	37.8	38.9	40.0	41.1	42.3
	40,000	49.8	12.3	37.5	38.7	39.9	41.2	42.4	43.6
	55,000	51.9	13.7	38.2	39.5	40.9	42.3	43.6	45.0
	70,000	53.5	14.8	38.7	40.1	41.6	43.1	44.6	46.1
	90,000	55.1	16.0	39.1	40.7	42.3	43.9	45.5	47.1
	120,000	57.0	17.6	39.4	41.2	42.9	44.7	46.5	48.2
	150,000	58.5	18.9	39.6	41.5	43.4	45.3	47.2	49.0

Table B.3 Oil tanker or bulk carrier (PIANC 121, Appendix F)

COVERAGE RATE	DWT	H_{kt}	T_{FL}	$H_{st} = H_{kt} - JT_{FL}$					
				J = 1.0	J = 0.9	J = 0.8	J = 0.7	J = 0.6	J = 0.5
95%	50,000	44.1	13.8	30.3	31.6	33.0	34.4	35.8	37.2
	70,000	48.9	13.8	35.1	36.4	37.8	39.2	40.6	42.0
	90,000	52.4	15.2	37.2	38.8	40.3	41.8	43.3	44.8
	100,000	53.9	15.8	38.1	39.7	41.3	42.9	44.5	46.0
	150,000	59.7	18.5	41.2	43.1	44.9	46.8	48.6	50.5
	300,000	69.6	24.0	45.6	48.0	50.4	52.8	55.2	57.6

Table B.4 Roll on/Roll off ship (Ro-Ro) (PIANC 121, Appendix F)

COVERAGE RATE	DWT	H_{kt}	T_{FL}	$H_{st} = H_{kt} - JT_{FL}$				
				J = 1	J = 0.95	J = 0.9	J = 0.85	J = 0.8
95%	3,000	36.3	5.9	30.4	30.7	31	31.3	31.6
	5,000	40.2	7	33.2	33.6	33.9	34.3	34.6
	10,000	45.5	8.8	36.7	37.1	37.6	38	38.4
	20,000	50.7	11	39.7	40.3	40.8	41.4	41.9
	40,000	56	9.9	46.1	46.6	47.1	47.6	48.1
	60,000	59.1	9.9	49.2	49.7	50.2	50.7	51.1

Table B.5 Pure Car Carrier (PCC) (PIANC 121, Appendix F)

COVERAGE RATE	DWT	H_{kt}	T_{FL}	$H_{st} = H_{kt} - JT_{FL}$				
				J = 1.0	J = 0.95	J = 0.9	J = 0.85	J = 0.8
95%	3,000	33.5	5.5	28.0	28.3	28.5	28.8	29.1
	5,000	37.3	6.4	30.9	31.3	31.6	31.9	32.2
	12,000	44.0	8.1	35.9	36.3	36.7	37.1	37.5
	20,000	47.8	9.3	38.5	39.0	39.5	39.9	40.4
	30,000	50.9	10.4	40.5	41.0	41.5	42.1	42.6
	40,000	53.1	10.0	43.1	43.6	44.1	44.6	45.1
	60,000	56.2	11.2	45.0	45.5	46.1	46.6	47.2

Table B.6 LPG ship (PIANC 121, Appendix F)

COVERAGE RATE	DWT	H_{kt}	T_{FL}	$H_{st} = H_{kt} - JT_{FL}$				
				J = 1.0	J = 0.95	J = 0.9	J = 0.85	J = 0.8
95%	3,000	33.3	7.3	26.0	26.4	26.7	27.1	27.5
	5,000	37.0	8.4	28.6	29.0	29.4	29.8	30.2
	10,000	41.9	10.3	31.6	32.1	32.6	33.2	33.7
	20,000	46.9	12.5	34.4	35.0	35.6	36.2	36.9
	30,000	49.8	14.0	35.8	36.5	37.2	37.9	38.6
	40,000	51.8	15.2	36.6	37.4	38.1	38.9	39.7
	60,000	53.4	16.2	37.2	38.0	38.8	39.6	40.5

Table B.7 LNG ship (PIANC 121, Appendix F)

COVERAGE RATE	DWT	H_{kt}	T_{FL}	$H_{st} = H_{kt} - JT_{FL}$				
				J = 1.0	J = 0.95	J = 0.9	J = 0.85	J = 0.8
95%	80,000	64.5	12.3	52.2	52.8	53.5	54.1	54.7
	100,000	71.5	13.0	58.5	59.1	59.8	60.4	61.1
	120,000	77.1	13.5	63.6	64.3	65.0	65.7	66.3

Table B.8 Passenger ship (PIANC 121, Appendix F)

COVERAGE RATE	DWT	H_{kt}	T_{FL}	$H_{st} = H_{kt} - JT_{FL}$				
				J = 1	J = 0.95	J = 0.9	J = 0.85	J = 0.8
95%	3,000	38.5	6.1	32.4	32.7	33	33.3	33.6
	5,000	43	7.2	35.8	36.1	36.5	36.9	37.2
	10,000	49.1	9.1	40	40.5	40.9	41.4	41.8
	20,000	55.2	8.9	46.3	46.8	47.2	47.7	48.1
	30,000	58.8	8.9	49.9	50.4	50.8	51.3	51.7
	50,000	63.4	8.9	54.5	54.9	55.3	55.8	56.2
	70,000	66.3	8.3	58	58.4	58.9	59.3	59.7
	100,000	69.5	8.3	61.2	61.6	62	62.4	62.8

CHAPTER 3
Wave Motion

3.1. Introduction

This chapter provides techniques for evaluating ship wave response during the Concept Design and Detailed Design stages. Waves are generated by wind acting on the ocean surface, and their heights and periods are determined by factors such as wind speed, length of the wind track and duration. The restoring forces are surface tension and gravity, but in situations where surface tension forces are relatively small compared to gravity, they can be disregarded. If the direction of the wind remains constant, the resulting waves will primarily move in the same direction. The height of a wave is determined by the vertical distance between its lowest point (trough) and its highest point (crest). The time taken for two successive crests to pass a fixed observation point in space is known as the period. The distance between two consecutive crests in the direction of wave propagation is called the wavelength. The speed of wave propagation, also known as celerity, is determined by the ratio of wavelength to period. In the region where waves form, periods typically range from one to just over 20 seconds, causing the sea to appear highly irregular due to the mixing of waves with different periods. As waves move away from the area affected by the wind, those with longer periods (i.e., greater lengths and celerities) move more quickly, resulting in a more regular sea state known as swell. The area where waves form is often referred to as a sea of waves. The waves discussed here are known as wind-generated gravitational waves, or simply wind waves or gravitational waves, and are caused by the wind. During propagation, the wave components undergo nonlinear interactions, resulting in energy exchange between components (such as triads and quadruple wave-wave interactions).

Another important aspect to note is that a monochromatic wave, which has a single frequency, has an invariant period, but its length and amplitude change as it propagates into shallower waters. In deep waters the relationship between the wave number $k = 2\pi/L_w$, where L_w (in meters) is the wavelength, and the wave frequency $\omega = 2\pi/T$, where T (in seconds) is the wave period, is given by $\omega^2 = k\,g$, where g is the acceleration of gravity (in meters per second squared), and the latter equation is known as the dispersion relation. In deep waters, the wavelength of a wave can be calculated using the equation $L_w = gT^2/2\pi$. As the wave approaches intermediate waters, which typically occur at a depth of d equal to half the wavelength, the wavenumber is modified and can be expressed as $\omega^2 = k\,g\,\tanh(kd)$. In shallow waters, where the depth is less than or equal to $L_w/20$, the wave celerity can be approximated as $\sqrt{gd}$. Changes in incident waves can have a cascading effect on ship behavior on waves. The diffraction wave, excitation forces, radiated waves, added mass and damping and all ship responses will be altered. It is important to note that the sea is irregular and complex, with a superposition of different monochromatic components that react differently to varying depths. This means that the sea itself changes significantly as the depth changes. Additionally, the effect of friction with the bottom dissipates some of the incident waves, making sea conditions near the coast generally less severe than those in the open ocean.

Although the mathematical problem that models the physical problem of waves is nonlinear, a linear model can be used if the waves have small amplitudes relative to their length. The sea is a complex and irregular phenomenon that can be modeled as a composition of a set of monochromatic harmonic waves with different frequencies, amplitudes and directions. By superimposing these waves, we can obtain the observed sea state.

Ships floating in calm waters, displaced from their equilibrium condition, can perform oscillatory motions of heave, roll, and pitch at or near their natural frequencies. If the ship is in a sea with waves, they will create forces and moments that will impose oscillatory motions of heave, roll, and pitch on the ship. If the dominant period of wave forces is close to the natural period of these oscillatory motions, resonances may occur, amplifying the ship's movements. As the ship moves and oscillates, it generates waves that propagate into the fluid medium. This wave radiation causes damping forces on the ship that limit heave and pitch. For the rolling motion, this damping is small and does not act effectively to prevent motion amplification. On the other hand, viscous effects create additional viscous damping that limits the amplification of the ship's roll. While heave and pitch are movements that strongly sense seas coming from fore or aft, the roll is more strongly affected by beam and quartering seas, depending on the ship's line plane.

The waves also generate oscillatory forces on the horizontal plane of the ship, which can induce oscillatory motions of surge and sway, as well as a moment that can induce yaw motion. However, in these three motions, there are no restoring forces, since the ship remains in equilibrium when displaced from its position in the horizontal plane in calm waters.

These six oscillatory motions of the ship, referred to as the six degrees of freedom, are excited by waves in the same range of frequencies and are known as first-order motions. When waves have small amplitudes, the ship's motions can be modeled as those of a linear mass-spring-damper system. The ship's response in each degree of freedom will be determined by the superposition of its responses for each wave frequency and direction.

The six motions of the ship in response to waves are determined by the frequencies of incident waves, the intensities of wave forces at each frequency, as well as their direction. The intensity of the wave forces depends on the ship's shape, the ship’s length to wavelength ratio, the wave amplitude and the incidence direction. The ship's speed also affects the response motions and changes their frequency. If a ship without surge velocity encounters a monochromatic wave, it will oscillate at the frequency of the wave. However, if the ship is traveling at a speed, its motions will occur at the encounter frequency (as defined in 3.3.5).

The six oscillatory motions have a lag with respect to the wave and to each other. This can be evidenced by observing that their maxima (or minima, or zeros) do not occur simultaneously. Thus, the composition of the keel motions (or any other point) of the ship must respect this lag coherence, combined with the moment arms in relation to the center of gravity.

When a monochromatic wave hits a ship with no surge velocity, the wave undergoes structural changes as it encounters the ship. The extent of these changes depends on the wavelength relative to the dimensions of the ship. Small vessels on long waves will only slightly deform the incident wave. As the wave encounters the ship, a new wave is formed that propagates from the ship into the fluid medium. This phenomenon is referred to as diffraction or scattering in the literature. Some authors use the term "wave diffraction" to describe the composition of the incident wave and its scattering. For the purposes of this discussion, we will refer to the wave generated by the ship from the incident wave as the diffracted wave. The portion of the force or moment that arises from the incident wave is called the Froude-Krylov force or moment, while the portion due to the diffraction of the wave is called the diffraction force or moment.

As previously mentioned, the ship's oscillatory motion induces wave radiation into the surrounding fluid medium, causing the fluid particles to oscillate (displacement, velocity, and acceleration). The fluid particles in closer proximity to the ship will react more strongly, while those farther away will react weaklier. Hence, the ship's oscillatory motion will displace the fluid particles, leading to the formation of waves due to the free surface, propagating away from the ship through the fluid medium. The ship's action on the fluid particles produces a reaction force known as the wave radiation force, which is comprised of a force proportional to the acceleration and another proportional to the velocity of the oscillatory motion of the body. The proportionality coefficients of these forces are known as added mass and potential damping.

Putting together the excitation forces and moments that cause the ship to oscillate, the forces and moments of radiation, the restoring forces and moments and the forces and moments of inertia of the ship, we establish the mass-spring-damper problem with external excitation to determine the ship's behavior, as mentioned earlier. Two situations stand out here. In the case of a ship with small dimensions relative to the wavelength, we have a problem governed by the restoring force and the Froude-Krylov force, since the ship does not deform the incident wave much. A typical case of this situation can be observed when a small boat encounters a long wave, and its heave motion follows the vertical motion of the wave. Both amplitudes of the movements and phases coincide. In the case of a large ship on short waves compared to its dimensions, the problem is caused by inertia and excitation forces. If the wave frequency is higher than the natural frequency of the heave motion, an inverse behavior is observed, where the ship's motion lags behind that of the waves. This phenomenon requires special attention, especially when the ship is assisted by a tugboat operating close to the ship's side. In that section, the vertical motion of the ship may be in antiphase with the tugboat's motion. Furthermore, the wave diffracted by the ship can amplify the tug's response, as the ship behaves like a floating breakwater.

The heave, pitch, and roll motions can cause vertical displacements that, when combined, may result in parts of the ship's hull touching the bottom of the channel. It's important to note that even small angular movements can create significant sinking points on the bottom of vessels that frequent Brazilian ports, due to the large size of these ships.

Now let's consider the case of a ship moving at surge speed. When encountering waves, the ship is excited to oscillate at the encounter frequency. It's important to note the impact of the waves when they hit the ship from aft to forward. The ship's longitudinal speed can be greater than, less than, or equal to the projection of the wave's celerity in the ship's longitudinal direction. Depending on this, the ship can overtake the waves, the waves can overtake the ship, or the ship and waves can move together. In the third case, the ship tends to lose its controllability.

The approach presented so far is linear, meaning that all ship motions are proportional to the amplitude of their components. However, when wave amplitudes are not small, nonlinear effects become significant and affect the ship's behavior on waves, as well as its controllability. Second-order forces and moments have an average value other than zero, which means that the ship undergoes continuous surge, sway, and yaw motions that have to be compensated for by the steering system and the hull through drift angles combined with the surge velocity. In this case, there are no restoring forces or moments, and the ship will experience constant damping, similar to being under the action of an average current or wind.

Thus, it can be said that waves, by causing vertical ship motions (heave, pitch and roll), will influence the design of the channel depth. Waves can also impact the design of the channel's width. As discussed earlier, wave excitation forces, in addition to being first-order forces periodically oscillating with the wave encounter frequency, are also second-order forces. They have both oscillatory and constant components, causing the ship to continuously displace in the horizontal plane. In the case of waves impacting from the stern, there may be a risk of course instability. Other phenomena such as surfing and broaching may also occur due to the following sea influence.

In Chapter 2, a list of factors was presented that must be considered to determine the water level of a channel. Among these factors, the influence of waves was discussed. In Section 2.3.1.2.3.5. (Wave Response Allowance), the impact of waves was addressed, as well as their contribution to the under-keel clearance for estimating the channel water level. The chapter also recommended the use of the trigonometric Japanese and/or Spanish methods during the Concept Design phase.

In the Detailed Design phase, it is recommended to use more advanced methods to consider the effects of waves on the ship's behavior in the channel and to estimate the wave contribution to the under-keel clearance calculation more accurately.

This chapter is divided into two main parts. The first part describes preliminary methods recommended to estimate ship wave response, while the second part covers more advanced methods to estimate wave response.

3.2. Preliminary methods for estimating ship wave response in the Concept Design

These methods include:

a. A fast trigonometric method that provides estimations of wave-induced motions;
b. The Japanese method, which is based on the worst possible combination of motions;
c. The Spanish method, which estimates the maximum wave-induced motions expected on a ship.

3.2.1. Trigonometric or American method (PIANC 121, 2014, p. 49)

This method is quite conservative and it assumes that all motions occur at the same frequency and are out of phase with the incident waves. The maximum values estimated by this method are as follows:

a. Heave is approximately one-fifth of the maximum wave height (H_{max});
b. Pitch is approximately half of the maximum wave height;
c. Roll is approximately half of the maximum wave height.

Then, the maximum value of the vertical distance traveled by the vessel is

$$Z_{max1} \approx 0.2H_{max(heave)} + 0.5H_{max(pitch)} + 0.5H_{max(roll)} \approx 1.2H_{max}$$

which equals, when relating to the significant wave height H_S, to

$$Z_{max1} \approx 1.2H_{max} \approx 2H_S$$

One can also use the following equivalent formula

$$Z_{max1} = Z_\phi + Z_\theta$$

where

$H_S = H_{1/3}$ is the significant wave height, expressed in meters (m); the average height of the upper third of the largest waves;

$$Z_\phi = 0.5\ B\ \text{Sin}\phi_{max} = 0.044\ B;$$

$$Z_\theta = 0.5\ L_{pp}\ \text{Sin}\theta_{max} = 0.0087\ L_{pp}$$

B is the ship's beam, expressed in meters (m);

L_{pp} is the length between perpendiculars of the ship, expressed in meters (m);

ϕ_{max} is the maximum recommended roll angle, 5°;

θ_{max} is the maximum recommended pitch angle, 1°.

3.2.2. Japanese Method (PIANC 121 2014, p. 50)

The Japanese Method considers that the largest values of vertical motion of the ship occur when coupling heave with pitch, Z_2, measured at the bow (Figure 3.1.) and coupling heave with roll, Z_3, measured at the starboard or port bilge keel (Figure 3.2.).

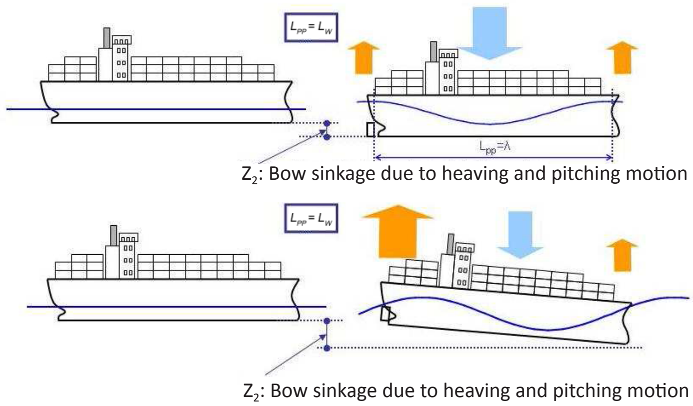

Figure 3.1 Bow sinkage due to heave and pitch (PIANC 121, 2014, figure 2.7)

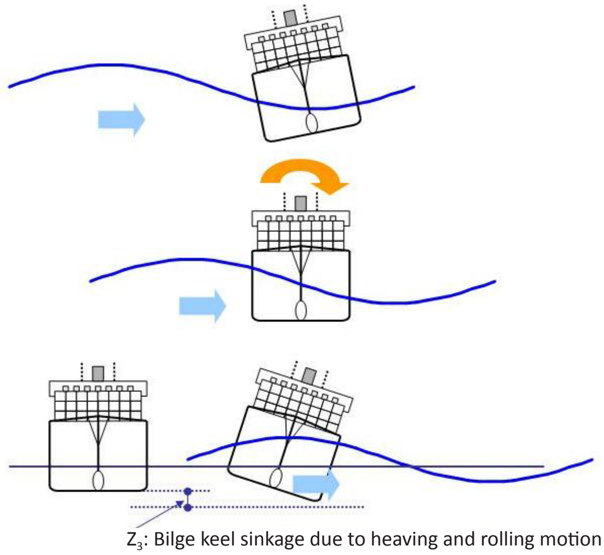

Figure 3.2. Bilge keel sinkage due to heaving and rolling motion (PIANC 121, Figure 2.7.)

Obtaining vertical motion due to waves involves four steps.

Step 1. Definitions and determination of design conditions

The parameters of the design ship type are selected in conjunction with the channel and environmental characteristics.

Step 2. Calculation of vertical motion due to waves measured at the bow, Z_2

The graphs presented in Figure 3.3 can be used to define Z_2, when

$$\sqrt{L_{pp}/L_w} < 1.5 \text{ or when } L_w > 0.45\, L_{pp}$$

Figure 3.3. presents the ship responses for different wave incidence angles ψ, as a function of $(L_{pp}/L_w)^{1/2}$. The angle ψ is shown in the figure.

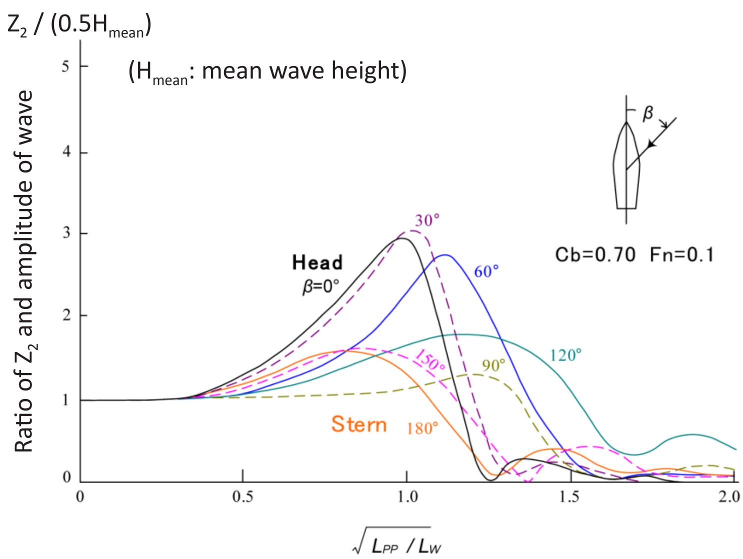

Figure 3.3. Z_2 as a function of ship and wave dimensions (PIANC 121, Figure 2.8.)

The value of Z_2 is considerable when $L_{pp} << L_w$.

The value of Z_2 is critical when $L_{pp} = L_w$.

Step 3. Calculation of vertical motion due to waves, Z_3

The vertical motion due to waves, Z_3, arising from the coupling of heave and roll, has its maximum value generally when the natural period in roll, T_R, is equal to the wave encounter period, T_E.

When the value of $B >> L_w$, the value of $Z_3 = 0$.

When the value of $L_w >> B$, the value of Z_3 is considerable.

$T_R = T_E$, the value of Z_3 is critical.

The bilge keel sinkage Z_3 in meters at T_R can be estimated by

$$Z_3 = 0.7\frac{H_S}{2} + \frac{B}{2}\text{Sin}(5^o)$$

When calculating Z_3, it is essential to examine how close the natural roll period is to the wave encounter period because roll motion increases rapidly as T_R approaches T_E.

Step 4. Selecting the maximum value of maximum vertical wave-induced motion

This is the final step in the Japanese method; the value to define the safety margin for the design ship is the larger value between the calculated values of Z_2 and Z_3.

$$Z_{max} = \max(Z_2, Z_3)$$

3.2.3. Spanish method (see PIANC 121, 2014)

The Spanish method is a semi-probabilistic method that utilizes multiplying coefficients.

It is based on the following initial assumptions:

- The ship is fully loaded and is above 90% of its maximum displacement;

- The Froude number is less than or equal to 0.05 ($F_{nh} \leq 0.05$)

$$1.05 \leq h/T \leq 1.5$$

- The wave direction is aligned with the longitudinal direction of the channel, and a variation of plus or minus 15 degrees is acceptable.

These three assumptions are combined using six multiplier factors in the method. The maximum vertical wave motion is given by the following equation:

$$Z_{max} = H_S\, C_1\, C_2\, C_3\, C_4\, C_5\, C_6$$

Where the significant wave height for the port limiting operational conditions is used, given in meters (m).

3.2.3.1. Step 1: Determination of the C_1 coefficient

C_1 is the coefficient that defines the maximum wave elevation, given by

$$C_1 = 0.707\sqrt{Ln\left[\frac{N_w}{Ln\left(\frac{1}{1 - P_m}\right)}\right]}$$

Ln is the natural logarithm and N_w is the number of waves that the ship is likely to encounter in the channel at each entrance or exit, during its lifetime.

The typical value is 200, with a maximum value of 10,000 when the ship is in the anchorage area. The exceedance probability for each occurrence or critical maneuver, P_m, depends on the probability of exceedance (probability of acceptable failure) over the ship's lifetime (about 15 to 25 years) and is given by:

$$P_m = 1 - (1 - P_{DL})^{1/N_{case}}$$

N_{case} is the total number of critical cases in which the operational limits due to waves will be reached using the channel during the entire design life of the ship (about 15 to 25 years). The values for P_{DL} range from 0.05 to 0.50.

If P_{DL} is, for example, equal to 0.50, we will have:

$$C_1 = 0.707\sqrt{Ln\left[\frac{N_w}{Ln\left(\frac{1}{0.5}\right)}\right]}$$

and

$$P_m = 1 - (1 - 0.5)^{1/N_{case}}$$

3.2.3.2. Step 2: Determination of the C_2 coefficient

The value of coefficient C_2 can be obtained from Table 3.1, which considers the motion of the design vessel based on the significant wave height and its length between perpendiculars. Linear interpolation can be used to determine intermediate values of C_2. Typically, C increases with an increase in H_S and decreases with an increase in the length between perpendiculars.

Table 3.1. Obtaining the C_2 wave transformation coefficient

L_{pp} (m)	Significant wave height, $H_s\{m)$							
	0.5	1	1.5	2	2.5	3	3.5	4
≤ 75	0.20	0.17	0.23	0.29	0.31	0.34	0.37	0.40
100	0.10	0.14	0.19	0.23	0.26	0.29	0.32	0.34
150	0	0.09	0.14	0.17	0.21	0.23	0.25	0.27
200	0	0.05	0.10	0.13	0.16	0.19	0.21	0.23
250	0	0.03	0.07	0.11	0.14	0.16	0.18	0.20
300	0	0	0.05	0.08	0.10	0.13	0.16	0.17
400	0	0	0.03	0.06	0.08	0.11	0.14	0.15

3.2.3.3. Step 3: Determination of the coefficients C_3, C_4, C_5, C_6

Coefficients C_3, C_4, C_5 and C_6 are obtained from Table 3.2.

The coefficient C_3 considers the ship's loading condition, assuming it is fully loaded at 90%.

C_4 adjusts the ship's speed based on the Froude number, F_{nh}, which depends on the water depth.

C_5 adjusts the depth-to-draught ratio, which should be between 1.05 and 1.50.

C_6 adjusts for the incidence angle of waves with respect to the ship's longitudinal axis, with three values provided. The first two conditions are for quartering seas and the last one refers to beam seas.

Linear Interpolation is required to determine all coefficients for the conditions listed in Table 3.2.

Table 3.2. Coefficients C_3, C_4, C_5 and C_6
(for intermediate conditions, linear interpolation between the listed conditions should be used)

Symbok	Coefficient name	Value	Condition
C_3	Load condition	1	Displacement ≥ 90%
		1.20	Displacement ≤ 50%
C_4	Ship speed	1	$F_{nh} \leq 0.05$
		1.25	$F_{nh} = 0.15$
		1.35	$F_{nh} \geq 0.25$
C_5	Water deph	1	$h/T \geq 1.50$
		1.10	$h/T \leq 1.05$
C_6	Wave incidence angle	1	$\psi \leq 15°$
		1.40	$\psi = 35°$ deg
		1.70	$\psi = 90°$ deg (beam)

3.3. Methods for estimating the ship's response to waves in the Detailed Design

The wave motion of a vessel is used to determine the maximum motions of design ship's critical bottom points. These points are where pitch and roll combine with heave to produce the greatest possible sinkage, and the relative phases of the motions are included in the definition of the maximum sinkage. It is important to note that due to the large dimensions of some of the fleet in Brazilian ports, even small angular movements can result in large sinkage points on the vessel's bottom. For example, even small pitch angles can cause significant sinking at the ends of a long vessel.

The calculation of ship motion in waves follows the ship motion methodology (see PNA, Principles of Naval Architecture). It is assumed that the ship moves forward in a straight line with constant speed VS in its longitudinal direction in the presence of a monochromatic wave with frequency ω. The wave's celerity has an angle of attack μ with the ship's speed (see Figure 3.4).

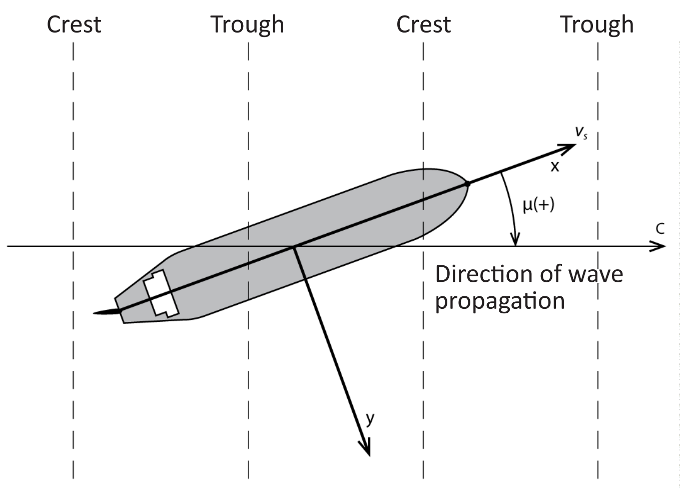

Figure 3.4. Convention adopted for wave incidence angles

3.3.1. Methodology

To determine the maximum sinkage, two approaches can be used: numerical or experimental procedures. Each approach has limitations and can produce different values, but either can be used as long as the limitations are respected. The ship motion calculation can be done through evaluations in the frequency domain with probabilistic analysis or simulations in the time domain. The second approach is advantageous as it can include strong nonlinearities, while the first approach only allows weak nonlinearities. It should be noted that different simulations in the time domain, with the same ship in the same sea, can lead to different results, because the generation of incident waves from a set of waves depends on their phases, which are randomly generated. The simulation time also influences the most extreme value. The longer the simulation, the greater the chances of achieving higher extreme values.

If a numerical procedure is used, simulations should be done using a potential flow model by the boundary element method or strip theory, both validated. If other methods are used, a substantiated technical justification or evidence of its applicability and limitations should be provided.

Regardless of the approach used, the data presented should include:

a. The vessel's range of motion operators in six degrees of freedom: surge, sway, heave, roll, pitch, and yaw, synchronized with each other in case of time domain calculations or with relative phases for frequency domain calculations;
b. The ability to calculate the response amplitude operators (RAO) in the period range between 2s and 50s;
c. The ability to calculate the response amplitude operators considering all incidence directions.
d. The consideration of several discretizations (number of panels or strips) for numerical convergence calculations.
e. For navigation in channels with velocities above 7 knots, the numerical code employed should be able to include the effects of headway speed in the numerical solution.
f. The inclusion of additional viscous damping in the degrees of freedom, properly documented.

3.3.2. Consideration of shallow water effects

If the procedure employed can consider the shallow water effect, this can result in less conservative estimates of response amplitude operators or vessel motions. If this approach is not possible and waves in the region have peak periods of less than 20s, the response amplitude operators at infinite depth can be used. However, if the waves in the region have longer periods, shallow water effects must be included in the calculation of the response amplitude operator. Empirical corrections can be used, provided that they are properly justified.

The depth to be used in the numerical calculation with the inclusion of shallow water effects should be consistent with that used for squat calculation, including tidal effects. The depth value does not correspond to the nominal depth of the channel, but to the value from the approved bathymetric survey.

If the bathymetry value within the channel varies by not more than 50cm, the average of bathymetry values can be used in the calculation. However, if the difference exceeds 50cm, the calculation must be performed in several stretches of the channel where variations are less than 50cm, always using the average value for each stretch. In the case of depressions or elevations whose limiting contour exceeds one-tenth of the design ship's length, the effects of the variations may be included in the numerical calculation to provide more accurate results.

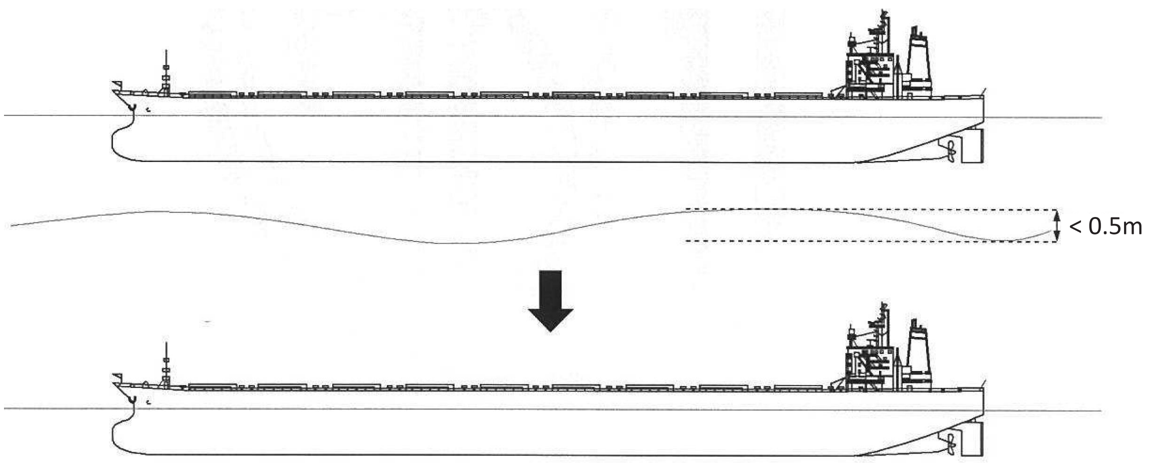

Figure 3.5. Geometry simplification for locations with variations of less than 50cm

For squat values of less than 50cm, it is not necessary to add this sinkage when calculating the ship's motions.

When the ship is within one vessel length from the shore, the effects of side walls or slopes, particularly in channels, should be taken into account.

3.3.2.1. Additional damping

The calculation of vessel motions, whether in the frequency or time domain, should include an additional linear damping coefficient in the roll degree of freedom when using a numerical calculation procedure based on potential theory. This coefficient is expressed as a percentage of the critical value, and a value of 5% is commonly used as it is both realistic and conservative. In practice, viscous damping tends to increase as the ship approaches the bottom due to greater flow confinement. Applying additional damping to other degrees of freedom is not recommended unless it has been experimentally validated. The value of the damping coefficient should remain constant regardless of the period, direction and height of the incident wave unless there is evidence or reasonable justification for its variation, such as through an extensive experimental campaign.

3.3.2.2. Relative angle in the direction of the incident wave

Initially, the angle of incidence of the wave on the ship should consider the design alignment of the channel with the ship sailing without a drift angle. However, the vessel motions should be calculated with a heading variation of +20 degrees and -20 degrees from the design channel alignment to account for sailing under adverse conditions.

3.3.2.3. Center of gravity and inertia

The ship's center of gravity and inertia matrix should be calculated using a weight and center of gravity model that considers realistic loading scenarios during port entry or exit, whichever results in the greatest static draught. The model should include the position of the ship's center of gravity and inertia.

The weight and center of gravity model should consider at least the following data:

1. The ballast displacement of the vessel and the height of the center of gravity based on the inclining test results, adjusted for any liquid or mobile loads present during the test;
2. The weight of cargoes in the tanks for the studied positions and loading conditions. The cargo should be considered as an equivalent parallelepiped containing the section of the cargo tank and the reference level consistent with the ship's capacity plan. The center of gravity and inertias should be considered assuming that the cargo is homogeneously distributed;
3. The ballast weight needed to achieve the design draught, using the same guidelines as for the cargoes;
4. The weight of any works or changes in ballast displacement that cause a center of gravity variation of more than 2%;
5. The weight of consumables under the analyzed loading conditions.

Note: This information is part of the ship's stowage plan, which is available on board the vessel.

Corrections for virtual elevations of the center of gravity should be applied for tanks containing liquid bulk cargoes or any other types of cargoes that have free surface effects and are partially loaded, with values between 5% and 95% of their nominal capacity, having discounted the tank's permeability coefficient. These corrections can be calculated by expression (1), for each tank, i, individually. The total virtual elevation of the center of gravity will be given by expression (2)

$$GG_{Vi} = \frac{\rho_{tank,i}}{\rho_{water}} \frac{I_{t,i}}{\nabla} \quad (1)$$

$$GG_{V} = \sum_{i=1}^{N_{tanks}} GG_{Vi} \quad (2)$$

where

GG_{Vi} is the virtual elevation of the center of gravity of each tank i, expressed in meters (m);

∇ is the vessel's underwater volume, expressed in cubic meters (m^3);

$\rho_{tank,i}$ is the density of the liquid inside tank i, expressed in kilograms per cubic meter (kg/m^3);

ρ_{water} is the density of the water in which the ship floats, expressed in kilograms per cubic meter (kg/m^3);

$I_{t,i}$ is the moment of inertia of the free surface area, of tank i, expressed in meters raised to the fourth power (m4);

GG_V is the virtual elevation of the ship's center of gravity, expressed in meters (m);

N_{tanks} is the total number of tanks.

Note: If a free surface effect is used, it must be explained.

If the exact centers of gravity and inertias are not known, the heights of the center of gravity (KG) can be estimated to produce the metacenter heights specified in Table 3.3, based on the type and size of the ship. However, vessels that are not included in the table should be evaluated using a weight and center model, as previously stated.

Table 3.3. Metacentric height/draught ratio estimates (GM/T) for a range of ship types

Type of ship		GM/T
Bulker	Capesize	0.30 to 0.40
	Panamax	0.25 to 0.30
	Post-Panamax	0.50 to 0.60
Container ship	Panamax	0.05 to 0.10
	Post-Panamax	0.10 to 0.15
Ro-Ro	Panamax	0.10 to 0.15
Tanker	VLCC	0.30 to 0.40

The values of the moment of inertia vary depending on the type of vessel and the properties of the cargo being carried. In the absence of an appropriate weights and centers model, the values shown in Table 3.4 for the loaded vessel may be used. However, if a specific case is not covered, it should be evaluated using a dedicated model.

Table 3.4. Turning radius/beam ratio estimates for loaded vessels

Type of ship	r_{xx}/B	r_{yy}/L_{pp}	r_{zz}/L_{pp}	Length range (m)	Beam range (m)
Tanker	0.30 to 0.40	0.22 to 0.28	0.22 to 0.28	$100 < L_{pp} < 350$	$30 < B < 60$
Bulker	0.30 to 0.40	0.20 to 0.30	0.20 to 0.30	$100 < L_{pp} < 350$	$25 < B < 50$
Container ship	0.40 to 0.45	0.22 to 0.30	0.22 to 0.30	$100 < L_{pp} < 350$	$25 < B < 50$

3.3.2.4. General requirements

In order to obtain reliable estimates of ship motions in waves, numerical simulations must demonstrate convergence and accuracy in their results.

It is recommended to perform convergence tests for simulations conducted in either the time or frequency domain, until convergence is achieved with results of less than 2%. For example, in the case of simulations in the time and frequency domain, the following tests can be applied:

A variable $x^{d1}(t)$ (heave, pitch and/or roll) is observed over time using the discretization d_i. Next, a more refined discretization d_{i+1} is used and the variable $x^{d1+1}(t)$ is observed. The differences between the two series squared are then integrated and diff is calculated using the expression:

$$diff = 100\frac{\sqrt{\int_0^{t_{sim}}[x^{d1}(t) - x^{d2}(t)]^2\,dt}}{t_{sim}}$$

where

t_{sim} is the simulation period considered in seconds (s);

$x^{d1}(t)$ is the time series of the observed motion (heave, pitch or roll) of the vessel, considering the discretization d_i, in the dimensionless forms x(t)/a for heave or x(t)/(k a) for pitch and roll;

$x^{d2}(t)$ is the time series of the observed motion (heave, pitch or roll) of the vessel, considering the d_{i+1} discretization, in the dimensionless forms x(t)/a for heave or x(t)/(k a) for pitch and roll;

k e a are the wave number and wave amplitude for monochromatic waves, respectively. If the simulations are performed in irregular seas, these parameters should be adapted to the characteristics of the sea: significant height and average period.

Convergence analysis for simulations in the frequency domain is performed by the expression shown below, where the variable x(ω) is a response amplitude operator. The amplitude response operator is calculated for periods between 2s and 50s with increments of 0.25s. The convergence analysis should be analyzed for all directions of incidence.

$$diff = 100_{max}\left\{\frac{2(x^{d1}(\omega) - x^{d2}(\omega))}{x^{d1}(\omega) + x^{d2}(\omega)}\right\},\ \omega_{min} \leq \omega \leq \omega_{max}$$

If convergence within the 2% tolerance is not possible and the differences are limited to a maximum of 10%, appropriate and consistent extrapolation methods must be used to calculate the motion results.

Once the numerical model has undergone the convergence analysis, the response amplitude operators for all degrees of freedom in deep water should be provided. These values should asymptotically approach 1 as the frequencies approach zero, considering the angles of incidence and dimensioning shown in Table 3.5.

Table 3.5. Response amplitude operators

Degree of freedom	Incidence angle	Nondimensionalization
Surge	0º and 180º	$\lvert x_G \rvert / a$
Sway	90º and 270º	$\lvert y_G \rvert / a$
Heave	—	$\lvert z_G \rvert / a$
Roll	90º and 270º	$\lvert \theta_1 \rvert / (k\, a)$
Pitch	0º and 180º	$\lvert \theta_2 \rvert / (k\, a)$

The potential damping curves for all degrees of freedom should approach zero asymptotically for both low periods (less than 2s) and high periods (greater than 50s).

3.3.2.5. Time domain simulations

Time domain simulations should be conducted for a minimum period of three hours or for the estimated sailing time in the channel at the slowest sailing speed, whichever is longer, to ensure that the extreme motions are captured. These simulations should use irregular seas, and care should be taken to prevent reflected waves from recurring on the vessel. Coefficients of less than 10% in terms of sea level are acceptable.

To obtain the maximum vertical sinkage of a hull point with coordinates (l_x, l_y, l_z) with respect to the ship's coordinate system, the vertical motions of critical points as defined in 3.2.2. should be calculated. It is acceptable to assume that the roll angle θ_1 and pitch angle θ_2 are small, and the vertical motion can then be calculated as:

$$z_p(t) = z_G(t) + \theta_1(t) l_y - \theta_2(t) l_x$$

The vertical sinkage of each point should be calculated by considering the entire time series of the point's motion during the simulation period.

The maximum displacement value, Δz_{max}, to be used as the wave motion contribution, should be the highest among all the sea conditions present in the environmental conditions survey.

3.3.2.6. Frequency domain simulations

The simulations conducted in the frequency domain provide the response amplitude operators of the vessel, which are then utilized to determine the RAO of the bottom critical points. To do this, equation (3) should be used, where the response amplitude operators are represented in a complex form, including the relative phases.

$$z_p(\omega, \mu) = z_G(\omega, \mu) + \theta_1(\omega, \mu) l_y - \theta_2(\omega, \mu) l_x \qquad (3)$$

$z_G(\omega, \mu)$ is the response amplitude operator (RAO) in heave expressed in meter over meter for a given angular frequency ω incident on the vessel with relative angle μ;

$\theta_1(\omega, \mu)$ is the linear response operator (RAO) in roll, expressed in radians divided by meter, for a given angular frequency ω incident on the vessel with relative angle μ;

$\theta_2(\omega, \mu)$ is the linear response operator (RAO) in pitch, expressed in radians divided by meter, for a given angular frequency ω incident on the vessel with relative angle μ;

μ is the angle of incidence of the wave with respect to the longitudinal axis of the ship as indicated in Figure 3.4.

The spectral density function or, in short, the motion response spectrum S_R of each point can be calculated by equation (4)

$$S_R(\omega, \mu) = |z_p(\omega, \mu)|^2 S_\zeta(\omega, \mu) \quad (4)$$

Where S_ζ is the sea spectrum. After integrating S_ζ, it provides the variance of the point's motion, which follows a Gaussian distribution with a mean of zero, as shown in equation (5).

$$m_{0R} = \int_0^\infty S_R(\omega, \mu) d\omega \quad (5)$$

The maximum expected value of the vertical motion of a generic point under the keel can be calculated using the following expression, which is dependent on the vessel's sailing time in the channel and the period of sea peak present

$$Z_{pMAX} = 4\sqrt{m_{0R}} \sqrt{\frac{\text{In}\left(\frac{t}{T_z}\right)}{2}}$$

where

t is the expected transit time of the ship in the channel, expressed in seconds (s);

ω_d is the period between ascending zeros of the considered sea state, incorporating probable corrections of the encounter frequency, expressed in seconds (s).

The sinkage Δz^a_{max} for a given sea condition corresponds to the greatest value among all bottom points, obtained by the expression:

$$\Delta z^a_{max} = \max\{|z_{pMAX}|\}, \quad p = 1, 2, \ldots N_p$$

3.3.2.7. Ship geometry

The ship geometry used for numerical calculations must be compatible with the design ship of the channel. The representation of the geometry must be of the ship class for which the channel is designed. This geometry will determine the maximum draught for all other ships within that class.

The geometry should be created based on the lines plane of the design ship. If the design ship geometry is not available, it can be constructed from similar ships of the same class that have undergone tank testing. Alternatively, it can be obtained from literature sources, as long as the differences in volume between the design ship and the similar ship are lower than the limits specified in Table 3.6.

Table 3.6. Maximum acceptable variations between the design ship and a similar hull

Displacement	4%
Length	3%
Beam	3%
Draught	3%

3.3.3. Critical points

The critical points for potential bottom contact are those that correspond to the lowest vertical dimension of the ship at rest in calm waters. If the ship has bulbs, rudders, propellers or other immersed appendages, those points must also be included in the calculations to ensure that the largest vertical motions are calculated. Figure 3.6 illustrates an example of the critical points located on bottom of a ship.

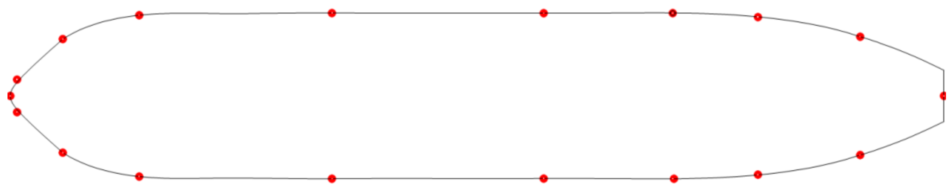

Figure 3.6. Example of critical points on the bottom of a ship

3.3.3.1. Sea spectrum

The sea spectrum used for calculating the ship's motion should be obtained by field data collection and data processing. The chosen source or methodology for defining the sea spectrum in the region must be specified.

If a specific sea spectrum model is not available for the study location, it is recommended to use a spectrum of the JONSWAP type (see ITTC 2002), regardless of the calculation methodology (experimental or numerical) to be applied, given by:

$$S_J(\omega) = \alpha H_S^2 \frac{\omega_P^4}{\omega^5} \exp\left(-\frac{5}{4}\frac{\omega_P^4}{\omega^4}\right) y^a \tag{6}$$

Where ω_P is the circular peak frequency of the spectrum, and H_S is the significant sea height.

$$a = \exp\left[-\frac{(\omega - \omega_P)^2}{2\,\omega_P^2 \sigma^2}\right]$$

$$\sigma = \begin{cases} 0.07 \text{ se } \omega \leq \omega_P \\ 0.09 \text{ se } \omega > \omega_P \end{cases}$$

$$\alpha = \frac{0.0624}{0.230 + 0.0336y - 0.185(1.9 + y)^{-1}}$$

$$y = 3.3$$

To incorporate the effect of depth d, it is recommended to use a sea spectrum of the TMA-type. This involves modifying the equation used to calculate the spectrum, resulting in:

$$S_{TMA}(\omega) = S_J(\omega)\phi(\omega_d)$$

where (7)

$$\omega_d = \omega(d/g)^{1/2}$$

and the function $\phi(\omega_d)$ is given by

$$\phi(\omega_d) = \left[\frac{(k(\omega, d))^{-3}\frac{\partial}{\partial\omega}k(\omega, d)}{(k(\omega,\infty))^{-3}\frac{\partial}{\partial\omega}k(\omega,\infty)}\right] = \frac{k(\omega, d)^{-3}\ \frac{\partial k(\omega, d)}{\partial\omega}}{2g^2\omega^{-5}}$$

which can be roughly calculated by

$$\phi(\omega_d) = 1 - \frac{1}{2}\frac{B\omega_d^3 + 3A\omega_d^2 + 2}{(A\omega_d^2 + 1)}$$

where

$$A = 1 + 0.6522\omega_d^2 + 0.4622\omega_d^4 + 0.0864\omega_d^8 + 0.0675\omega_d^{10}$$
$$B = 0.6522\omega_d + 0.9244\omega_d + 0.3456\omega_d^7 + 0.3375\omega_d^9$$

Figure 3.7 shows the function $\phi(\omega d)$

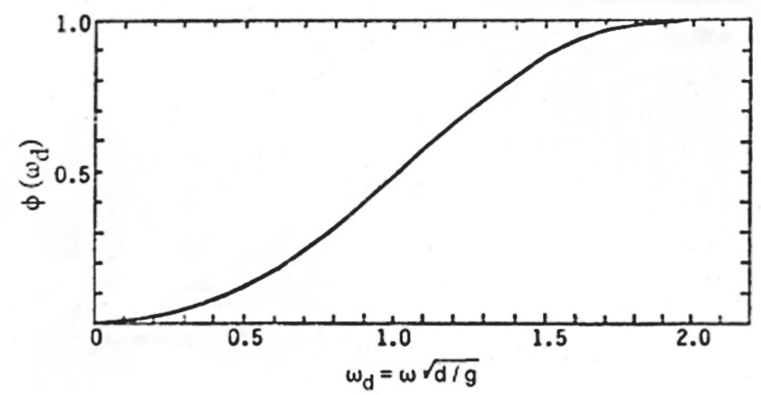

Figure 3.7. Distribution function $\phi(\omega_d)$ for the TMA spectrum

If there are bidirectional seas present in the region, the spectral variances must be considered when calculating the maximum expected motion. The total variance in motion can be calculated using equation (8), where $S_1(\omega, \mu_i)$ and $S_2(\omega, \mu_j)$ represent the sea spectra for directions i and j, respectively.

$$m_{0R} = m_{0Ri} + m_{0Rj} = \int_0^\infty |z_p(\omega, \mu_i)|^2 S_1(\omega, \mu_i) d\omega + \int_0^\infty |z_p(\omega, \mu_j)|^2 S_2(\omega, \mu_j) d\omega \qquad (8)$$

3.3.4. Considered wave conditions

The calculation of the maximum sinkage Δz_{max} should be conservatively adopted as the maximum value among those obtained for all environmental conditions existing in the region.

This calculation, however, can be performed less conservatively by considering only the wave conditions in which the vessel can be controlled, as defined in the Concept Design.

3.3.5. Encounter frequency (ref. PNA and Price and Bishop, 1974)

If vessels require speeds above 7 knots to keep navigating in the channel under the considered wave conditions, the impact of encounter frequency on the wave spectrum must be analyzed carefully. The encounter period can be calculated using equation (9).

$$\omega_e = |\omega - kV_S \cos\mu| \qquad (9)$$

The relative angles between the ship forward motion and the incident wave should be measured according to the convention shown in Figure 3.4. In this way there will be three regions with different methods to calculate the correction to the wave spectrum

1. head seas: $90^o < \mu < 270^o$

2. beam seas: $\mu = 90^o$ or $\mu = 270^o$

3. following seas: $0^o < \mu < 90^o$ or $270^o < \mu < 360^o$

3.3.5.1. Head seas

In the case of head seas, (where the angle between the direction of wave propagation and the ship's speed is greater than 90 degrees but less than 270 degrees), equation (10) can be used to correct the encounter frequency. For each wave component in the sea, there will be only one corresponding encounter frequency

$$S_{\zeta e}(\omega_e; \mu, V_s) = \frac{S_\zeta(\omega)}{\left|1 - \frac{dk}{d\omega} V_s \text{Cos}\mu\right|} \tag{10}$$

3.3.5.2. Beam seas

Beam seas (where the angle between the direction of wave propagation and the ship's speed is equal to 90 degrees or 270 degrees) will not imply additional corrections to the encounter frequency, since the incidence is perpendicular to the ship, so that the encounter spectrum is identical to the incident spectrum, as shown in equation (11)

$$S_{\zeta e}(\omega_e; \mu, V_S) = S_\zeta(\omega) \tag{11}$$

3.3.5.3. Following seas

When the ship enters a channel with waves entering the same channel, it can encounter the following seas condition (where the direction of wave propagation and the ship's speed form an angle of up to 90 degrees or greater than 270 degrees, but less than 360 degrees). In this condition, the encounter frequency can become null, making it difficult to steer the ship. Therefore, special attention must be paid to this condition.

To account for the following sea condition, the encounter frequency needs to be corrected using equation (9). It is important to note that there will be no one-to-one relationship between the encounter frequency and the wave frequency, as shown in Figure 3.8.

Under this condition, for $\omega_e < g/(4V_S \text{Cos}\mu)$ there will be three frequencies of the sea spectrum that will contribute to the encounter spectrum, given as the real roots of equation (12)

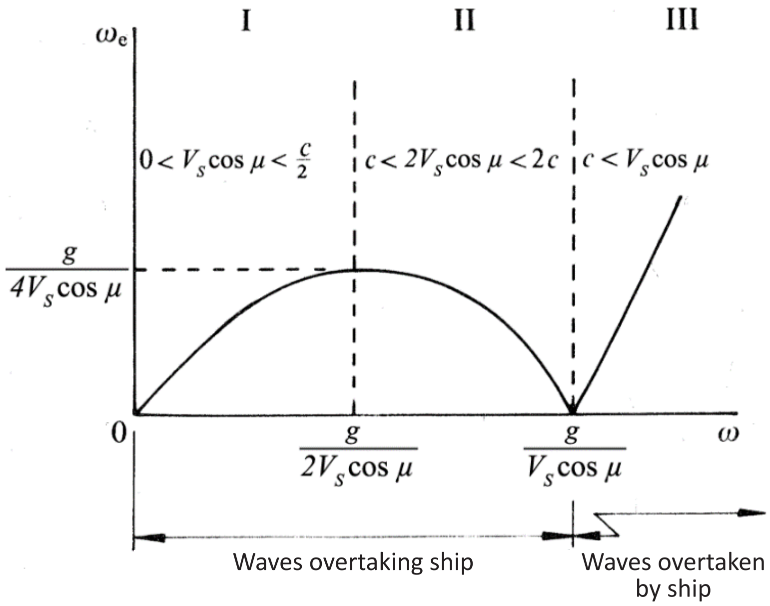

Figure 3.8. Relationship between encounter frequency and wave frequency for following seas (Price and Bishop, 1974)

$$KV_S\text{Cos}\mu - \omega \pm \omega_e = 0 \tag{12}$$

Therefore, the encounter spectrum value in this region will be determined by the contribution of the three values of the sea spectrum at the frequencies defined above, following the procedure illustrated in Figure 3.9 to obtain the corrected encounter spectrum.

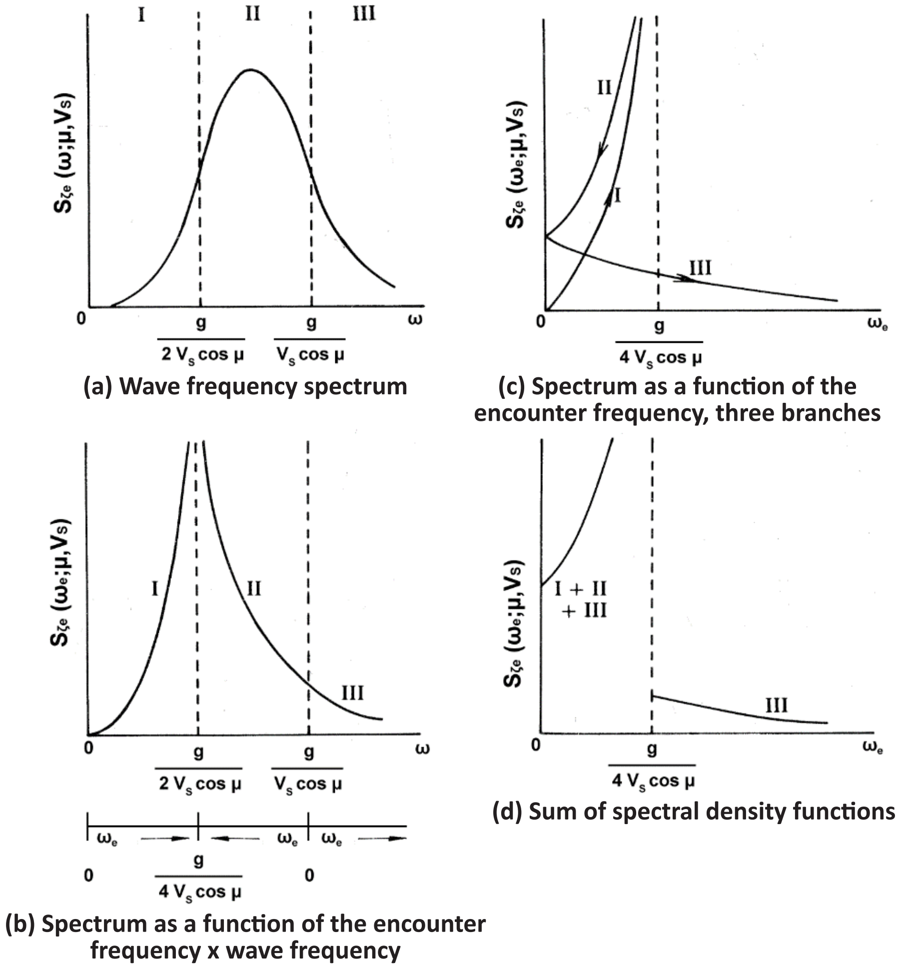

Figure 3.9. Conversion from sea spectrum to encounter spectrum on following seas (Price and Bishop, 1974)

Figure 3.9.(a) displays the frequency spectrum of waves, while 3.9.(b) illustrates the spectrum as a function of the encounter frequency plotted against the frequency of waves. The horizontal axis shows the encounter frequency, indicating three branches of variation of the encounter frequency. Figure 3.9.(c) displays the spectrum as a function of the encounter frequency, bringing the three branches together. In Figure 3.9.(d), the sum of spectral density functions is represented.

It should be noted that, although Figure 3.9.(c) shows three portions of the spectral density function in the frequency range from 0 to $g/(4V_S \text{Cos}\mu)$ and Figure 3.9.(d) shows the sum of the three values of the spectral density function, when performing the calculation of the response spectra as a function of frequency for each of sections I, II, and III, the spectrum at the encounter frequency multiplies different values of the transfer functions (RAOs), since these are functions not only of the encounter frequencies, but also depend on the wave frequencies.

3.3.6. Dynamic draught calculation

The use of dynamic draught aims to expand operational windows in ports by allowing real-time monitoring of environmental conditions. In such ports, the maximum draught can be defined or changed based on the environmental factors that act on the ship when entering or leaving the port. This is no longer a static rule based on the depth and tide height.

Under these circumstances, numerical metoceanographic models should predict the following values over time:

– Tide;
– Current vector field;
– Wind vector field;
– Wave directional field.

Based on these forecasts, squat and wave motion estimates should be defined for different sections of the channel over the forecast time window. The values of environmental agents at the estimated time of passing and the ship's speed that ensures steerability must be considered. The ship's speed in the channel must be sufficient to ensure its steerability.

Therefore, the dynamic draught analysis should provide the following information over time for the estimated ship positions:

– Maximum squat, according to the predefined methodology;
– Maximum wave motion, according to the predefined methodology.

Sinkage calculations combined with vessel loading conditions will determine the operational windows for both vessels waiting at anchorage to enter the channel and loaded vessels waiting for appropriate conditions to depart. It is important to note that the environmental conditions forecast model should be calibrated with field measurements for at least six months to ensure the accuracy of the estimates.

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CHAPTER 4
Ship Maneuverability

4.1. Introduction

Established in 1948 in Geneva as the Intergovernmental Maritime Consultative Organization and renamed the International Maritime Organization in 1982, IMO is a UN agency dedicated to technical issues, including maritime safety.

On November 19, 1987, IMO adopted Resolution A.601(15), Provision and Display of Manoeuvring Information on Board Ships, which was published on January 4, 1988. Appendix 3 of this resolution, "Recommended information to be included in the manoeuvring booklet", contains a series of recommendations proposed with a view to navigation safety, which make up a Maneuver Booklet. It is also worth mentioning IMO Resolutions MSC 1053 and MSC 137(76), as well as the publication of Working Group 20 of the PIANC Permanent Technical Committee II - supplement to *Bulletin* 77 (1992), which served as support for the content of this and other chapters in this book of recommendations.

This chapter initially presents a section with basic concepts related to the development of a maneuver simulator, including tests to be performed and documented regarding the maneuverability of the design ship, which will compose the Maneuver Booklet. Subsequently, it lists recommendations on what a maneuver simulator should be able to evaluate in terms of the ship's maneuverability, taking into account environmental conditions, bank effects, stopping maneuvers, passing and overtaking other ships, performing very small zig-zag maneuvers, using thrusters, azimuthals or tugboats, and maneuvering with stern waves.

4.2. Basic concepts for development of a ship maneuvering simulator

Vessels that depend on external support to move are equipped with propulsion and maneuvering systems. Depending on the size and purpose of the vessel, these systems can be quite complex and sophisticated, and the same equipment may act as both propulsive and steering element. Some ships are equipped with a single propeller and rudder. An engine, driven by orders from the ship's crew, generates rotational motion in the propeller, generating forces that lead the ship to move forward in the sea. Similarly, the rudder can be moved and, with the water flow around it caused by the ship's forward speed, generate hydrodynamic forces that change the ship's heading. However, the resulting motion of the ship depends not only on the actions of the propeller and rudder, but also on the reaction of the hull to the sea surface.

The search for tools for obtaining the force generated by the propeller as a function of its rotation and the ship's speed and the force generated by the rudder as a function of its angle of attack and the ship's speed, as well as the ship's behavior as a function of these forces has led to the development of experimental and mathematical methods (analytical and numerical) to model the actions and reactions of the hull, rudder and propeller in this context.

In this process, a reduced model of the ship's hull is attached to a small kart that, resting on the edges of a towing tank, can tow the model at various speeds. The forces and moments (relative to a given distance point from the model's center of gravity) acting on the hull are measured. A model can be placed at an attack angle to the speed direction of the model. With these tests (pure drift) information is gathered about the hydrodynamic actions (forces and moments) as a function of the model speed and the imposed drift angle. The tests can be more sophisticated, for example, by moving the model in the longitudinal direction of the tank, keeping the model speed constant in the direction of its longitudinal axis, which coincides with the longitudinal axis of the tank, and applying an oscillatory speed in the transverse direction. With these tests (pure sway) we have hydrodynamic actions (forces and moments) on the hull as a function of the model's longitudinal and lateral velocities. The model can also be moved in a similar way as above, but with variations on the direction of the model's longitudinal velocity in such a way that it is tangential to the trajectory of the model's center of gravity. In this case, the model would keep the drift angle at zero, executing a pure yaw motion. With these tests (pure yaw) we have the hydrodynamic actions (forces and moments) on the hull as a function of the longitudinal velocities and yaw velocities of the model, which support the mathematical model of ship maneuvering.

The propeller can be placed in a tunnel filled with circulating water at a constant speed. A constant rotation is applied and the hydrodynamic actions on the propeller are measured. The same procedure can be applied to the rudder, under different speeds and attack angles, in some cases including the interactions between these elements.

Since the propeller operates behind the hull in a real ship, and the rudder behind the hull and the propeller, more elaborate tests should be carried out in models that closely resemble the real ship. This inevitably increases the level of complexity and requires more sophisticated experimental procedures.

Nowadays, more and more advances in computational hydrodynamics are being achieved, and many of these tests are numerically elaborated, allowing for the study of very complex conditions for experimental reproduction. It should be noted that in tests, the smaller the models, the more complex the measurement process of the quantities of interest, and the greater the uncertainties of the measurements obtained, as well as of the scale effects themselves. Thus, numerical tools emerge as an important complement, but it is always necessary to have a verification and validation procedure for these models. It is important to keep in mind that in the naval industry, prototypes are generally not tested, but rather scaled-down models, requiring an appropriate procedure for extrapolating the so-called scale effects.

Analytical and empirical models are also used in this process of determining hydrodynamic actions as a function of ship movements, propeller and rudder. It should be emphasized that simplified theoretical models do not necessarily provide accurate results of the observed variables of the phenomenon under study, but can provide elements for understanding the physical phenomenon, which is usually the initial stage of study. As methods become more sophisticated, a greater amount of resources (physical/financial) is necessary, and there is a trade-off relationship between accuracy, precision and available resources.

Simulations of ship motions with a propeller and rudder use equations of motion based on Newton's second law of motion for a rigid body subject to hydrodynamic forces due to the fluid reactions to the body, the propeller and rudder. However, the real case is more complex and must consider gravity, hydrostatic and dynamic actions of waves, wind, currents, banks, other vessels and the bottom. If the propulsion and steering systems are more complex than only the propeller and rudder, it will also require mathematical expressions to represent it.

In the literature on maneuverability, there is a vast number of publications presenting maneuver models. It should be noted that the model will always be a representation of reality and, consequently, will have limitations. Knowing these limitations is even more important than knowing the capabilities of the model, as it prevents erroneous analyses and conclusions from being made with models incapable of representing the desired phenomena. This section presents the conception of formulation of the equations of motion of a ship, without focusing on a specific model.

4.3. Maneuver Booklet

The maneuver booklet is a document that provides a concise and straightforward description of the mathematical model used in the simulator, as well as the procedures and studies undertaken to validate the ship's modeling.

This document should be written in a clear and concise manner, so that users without advanced knowledge in hydrodynamics, maneuverability and mathematical modeling can understand it.

At a minimum, this section of the document should include the following items:

a. Mathematical model (description of the model structure, number of degrees of freedom, integration technique, basic equation of motion, coordinate axes, etc.);

b. Modeled phenomena, their validation and applicability, especially:
- Modeling of the main engine;
- Modeling of the steering gear;
- Modeling of the thruster motors;
- Hydrodynamic forces on the hull;
- Propeller forces;
- Rudder forces and thrusters;
- Interaction of hull, propeller and rudder;
- Confined water effects (shallow waters and banks);
- Ship-to-ship interaction effects;
- Wind modeling and its action on the design ship;
- Wave modeling and its action on the design vessel;
- Modeling of the anchoring system and forces on the design vessel;
- Modeling of the mooring lines and fenders;
- Modeling of tugs and their interaction with the design vessel;

c. Methods used to collect the data used to model the ships;

d. Methods used to validate the mathematical models of the ships.

It is recommended to provide an objective description of the data source used in the simulator, such as whether it was obtained through scale model testing, computational fluid dynamics (CFD), parameter identification systems, databases or a combination of these methods. Furthermore, the document should describe the validation procedures used for the models, including whether they were compared with tests of a real or reduced scale ship, databases of similar ships, or any other methods.

4.4. Design ship maneuverability documentation

The document for design ship maneuverability should contain complete information on each design ship and the type used in the simulation study, using standard formatting. It is recommended to include the following details:

a. General characteristics of the design ship;
b. General arrangement and 3D image of the model;
c. Displacement, deadweight, cargo information;
d. Main dimensions;
e. Main engine data;
f. Propeller data;
g. Rudder data;
h. Thruster data;
i. Geometric data of the blind zones and viewing angles;
j. Engine characteristics and speeds;
k. Table of maneuvering speeds (rotation, pitch, speed);
l. Reversion times for emergency maneuvers;
m. Minimum rotation and corresponding speed;
n. Maximum number of consecutive starts;
o. Reverse power.

It is recommended that documentation concerning the maneuverability of the ship contain the results of standard and additional maneuvers, and some that illustrate the environmental effects on the ship's maneuverability considering the limits of wind speed, current, and wave action defined in the Concept Design.

4.4.1. Standard deep-sea maneuvers (h/T ≥ 3) with zero environmental conditions, where h is depth and T is the ship's draught

The recommended standard maneuvers described here are the classic ones: turning circles, zigzags and a crash stop.

4.4.1.1. Deepwater turning circle maneuvers with zero environmental conditions

Turning circle maneuvers should be performed in the following cases:

a. Full sea speed and half speed;
b. Hard port and hard starboard rudder.

For each of the maneuvers, the following results should be presented:

- Advance, tactical diameter, transfer;
- Velocities and times for 90, 180, 270 and 360 degrees variations in heading relative to the initial condition;
- Comparison of the results with values required by IMO;
- Trace-plot of overlapping maneuvers.

4.4.1.2. Deepwater crash stop maneuvers (h/T ≥ 3) with zero environmental conditions

Crash stop maneuvers should be performed in deep water without environmental actions with a focus on engine control:

a. Full sea speed to full astern;
b. Full speed to full astern;
c. Half speed to full astern;
d. Slow speed to full astern;
e. Dead-slow speed to full astern.

For each maneuver, the following results should be submitted:

- Distance traveled, longitudinal and lateral reach;
- Stopping time;
- Graph of rotation, speed and distance traveled over time (within 1min to 1min);
- Comparison with values required by IMO;
- Trace-plot of the overlapping maneuvers.

4.4.1.3. Zigzag maneuvers in deep water (h/T ≥ 3.0) with zero environmental conditions

Zigzag maneuvers should be performed under the following engine and rudder commands:

a. Full sea speed and half speed;
b. 10/10, 20/20, 35/35, very small zig zag (0/5).

For each maneuver, the following should be presented:

- First and second overshoot and associated times;
- Graph of turning angle and rudder angle over time;
- Comparison with IMO required values;
- Trace-plot of the overlapping maneuvers.

Note: If applicable, the validation method used should be indicated.

4.4.2. Standard maneuvers in shallow water (h/T = 1.5 and 1.2) with zero environmental conditions

The recommended standard maneuvers are the classical ones: turning, zigzags and crash stops, as described below.

4.4.2.1. Turning circle for h/T = 1.5 and 1.2 with zero environmental conditions

Turning circle maneuvers should be performed for the two depths, h/T = 1.5 and 1.2, and the following cases of engine control and rudder control:

a. Full sea speed and half speed;
b. Hard l port and hard starboard rudder.

For each of the maneuvers, results should be presented for the following:

- Advance, tactical diameter, transfer;
- Speed and time for heading variations equal to 90, 180, 270 and 360 degrees in relation to the initial condition;
- Comparison of the results with values required by IMO;
- Trace-plot of the overlapping maneuvers.

4.4.2.2. Crash stop maneuvers for h/T= 1.5 and 1.2 with zero environmental conditions

Crash stop maneuvers should be carried out for two depths, h/T = 1.5 and 1.2, and the following engine orders:

a. Full sea speed to full astern;
b. Full speed to full astern;
c. Half speed to full astern;
d. Slow speed to full astern;
e. Dead-slow speed to full astern.

For each maneuver, the following results should be presented:

- Distance traveled, longitudinal and lateral reach
- Stopping time;
- Graphs of rotation, speed and distance traveled over time (within the maximum interval of 1min to 1min);
- Comparison with values required by IMO;
- Trace-plot of the overlapping maneuvers.

4.4.2.3. Zigzag maneuver for h/T = 1.5 and 1.2 with zero environmental conditions

Zigzag maneuvers should be performed for two depths, h/T = 1.5 and 1.2, and the following engine and rudder orders:

a. Full sea speed and half speed;
b. 10/10, 20/20, 35/35, very small zigzag (0/5).

For each maneuver, the following results should be presented:

- First and second overshoot and associated times;
- Graph of turning angle and rudder angle over time;
- Comparison with IMO required values;
- Trace-plot of the overlapping maneuvers.

Note: If applicable, the validation method used should be indicated.

4.4.3. Additional maneuvers

As mentioned earlier, it is recommended to perform an additional set of maneuvers and their results should be presented. These additional maneuvers should be performed in deep waters ($h/T \geq 3.0$) and shallow waters ($h/T = 1.5$ and 1.2).

4.4.3.1. Turning maneuvers with acceleration and deceleration in deep waters (h/T ≥ 3.0) and in shallow waters (h/T = 1.5 and 1.2) under zero environmental conditions

Turning maneuvers with zero environmental conditions, in deep waters and in shallow waters ($h/T = 1.5$ and 1.2) when accelerating and decelerating should be performed, where

a. The ship initially at rest is accelerated to the speed defined in the Concept Design with hard port rudder and with hard starboard rudder;
b. The ship, initially at the design speed for the channel, is decelerated to a stop, with full astern engine, with hard port rudder and with hard starboard rudder.

The trace-plot of the overlapping maneuvers should be presented.

4.4.3.2. Turning maneuvers with acceleration and deceleration in deep water (h/t≥ 3.0) under environmental conditions defined in the Concept Design

Turning maneuvers under environmental conditions defined in the Concept Design, in regimens of acceleration and deceleration, where

a. The ship, initially at rest, is accelerated to the speed defined in the Concept Design with hard port rudder and hard starboard rudder;
b. The ship, initially at the design speed for the channel, is decelerated to a stop employing full astern engine with hard port rudder and hard starboard rudder.

The trace-plot of the overlapping maneuvers should be presented.

4.4.3.3. Turning maneuvers under wind action defined in the Concept Design without the contribution of other environmental force components, in deep water (h/T ≥ 3.0) and in shallow water (h/T = 1.5 and 1.2)

Turning maneuvers under wind action should only be performed under the conditions defined in the Concept Design, which are:

a. Use the speed defined in the Conceptual Project for the channel as the initial condition;
b. Perform turning circles with hard port rudder and with hard starboard rudder.

For each maneuver, the following results should be presented:

• Advance, tactical diameter, transfer;
• Velocities and times for 90, 180, 270, and 360 degree heading variations relative to the initial condition;
• Trace-plot of overlapping maneuvers.

4.4.3.4. Turning circles under the action of currents defined in the Concept Design without the contribution of other environmental force components in deep waters (h/T ≥ 3.0) and shallow waters (h/T = 1.5 and 1.2)

Turning maneuvers under the action of currents should only be carried out under the conditions defined in the Concept Design:

a. Use the speed defined in the Conceptual Project for the channel as the initial condition;
b. Perform turning circles with hard port rudder and with hard starboard rudder.

For each maneuver, the following results should be presented:

• Advance, tactical diameter, transfer;
• Velocities and times for 90, 180, 270 and 360 degrees heading variations;
• Trace-plot of the overlapping maneuvers.

4.4.3.5. Deceleration performance of the design ship under the environmental conditions defined in the Concept Design in deep water (h/T ≥ 3.0) and in shallow water (h/T = 1.5 and 1.2)

Evaluate the deceleration performance of the ship under the environmental conditions defined in the concept design in deep water (h/T ≥ 3.0) and shallow water (h/T = 1.5 and 1.2), with the following changes in engine orders

a. Full ahead to half ahead;
b. Half ahead to slow ahead;
c. Slow ahead to dead slow ahead;
d. Dead slow ahead to engine stopped.

For each maneuver, it is recommended that graphs of rotation, speed and distance covered along the time (at the maximum interval of 1 minute) are presented.

4.4.3.6. Low speed maneuvering under the environmental conditions defined in the Concept Design in deep water (h/T ≥ 3.0) and in shallow water (h/T = 1.5 and 1.2)

a. As the initial condition, the speed defined in the Concept Design should be used;
b. Determine the minimum propeller rotation and corresponding speed, at which the ship can maintain its heading with rudder amidships (fixed control);
c. Determine the minimum speed at which the ship can still maintain heading using the rudder (mobile control) after the engine has stopped;
d. Determine the maximum lateral thruster capacity;
e. Evaluate the turning performance for zero ahead speed and with dead slow ahead and slow ahead engine orders for bow and stern thrusters, individually and in combination.

4.4.3.7. Spiral maneuver in deep waters (h/T ≥ 3.0) and shallow water (h/T = 1.5 and 1.2)

a. Conduct spiral maneuvers in both deep waters and shallow waters;
b. Create graphs showing the turning rate plotted as a function of the rudder angle, highlighting any hysteresis loop in the case of unstable ships.

Also, provide a trace plot of the overlapping maneuvers.

4.4.4. Assessment of environmental effects

4.4.4.1. Effects of winds considering their limiting speed defined in the Concept Design

It is recommended that the effects of wind on a ship sailing in the channel, inner channel, turning basin or approaching the pier be evaluated through a properly documented analysis of the drift angle, sideways drift and heeling values as a function of the ship's speed and maneuvering time.

4.4.4.2. Effects of currents considering their limiting speed defined in the Concept Design

It is recommended to evaluate the effects of current action on the ship sailing in the channel, inner channel, turning basin or approaching the pier by means of a properly documented analysis of the values of drift angle and sideways drift as a function of ship speed and maneuvering time.

4.4.4.3. Effects of wave action according to data defined in the Concept Design

The effects of wave action are divided into first-order effects and second-order effects, as presented in Chapter 3.

An analysis of first-order wave effects, characterized by the maximum values of heave, pitch, and roll as a function of the encounter frequency for deep and shallow water conditions is recommended.

An analysis of the effects of mean drift wave forces on the lateral ship motion, different ship depth/draught ratios, as a function of the encounter frequency for deep-water and shallow-water conditions is also recommended.

4.4.5. Assessment of ship stopping and going astern

It is recommended that the evaluation of the stopping maneuver of the design ship be performed employing simulators that display stopping time and the values of heading angle, course deviation and distance traveled over time. This evaluation should be conducted for deep water and for shallow water with low initial speed. Three environmental conditions for the rudder should be used: rudder amidships, rudder to port and rudder to starboard.

The following conditions should be considered:

a. Ship going ahead and propeller rotation or pitch forward;
b. Ship going ahead and propeller rotation or pitch astern;
c. Ship going astern and propeller rotation or pitch astern;
d. Ship going astern and propeller rotation or pitch forward.

4.4.5.1. Assessment of ship stopping and going astern in simulators under environmental forces

The results of the motion of the design ship during the stopping operation and when moving astern should be presented, including the influence of environmental conditions such as wind, current, and wave action as established in the concept design. Simulators should be used to obtain these results and should indicate the effects of environmental conditions on the distance traveled and the stopping time.

4.4.6. Assessment of ships passing and overtaking

The results generated by simulators of the movements of the ship as it navigates along the channel should be presented. These movements should include surge, sway, and yaw due to the passage or overtaking of another ship, as a function of the distance between them and their speeds, according to data from the Concept Design. The rudder angle used to compensate and maintain heading should also be indicated. Critical situations that occur during these maneuvers should be reported.

It is important to note that these interactions are of a non-permanent nature, and therefore, their behavior over time should affect the vessels' drift and rudder angles.

4.4.7. Shallow water effect

It is recommended that results are presented showing the ship motions in surge, sway and yaw, and the drift angle as a function of decreasing depth.

Additionally, the critical design ship speed in the channel should be provided as a function of the channel blockage factor.

4.4.8. Bank effect (where applicable)

The resulting motion in the simulation of the ship sailing along the channel should be presented, according to data from the Concept Design. This motion depends on the ship speed and its distance from the bank. The distance at which the bank effects are considerable and cause changes in the ship's heading with the rudder amidships should be indicated.

The limit distances from the bank to enable the ship to maintain straight or constant heading when using rudder angles with maximum values of 15 and 20 degrees should be presented. These results should be obtained through simulations that consider the values of channel width, depth and ship speed defined in the Concept Design.

4.4.9. Very small zigzag

The purpose of this test is to show the basic maneuverability of a ship. It is recommended that this maneuver be performed using the channel geometry, ship speed, and environmental conditions defined in the Concept Design.

4.4.10. Performance of thrusters and azimuthals

In maneuvers employing bow-thruster and/or stern-thruster or azimuthals, the limit values of the actuator forces as a function of ship speed and environmental conditions should be reported.

4.4.11. Tug performance

When the operations to be performed require tug assistance, the simulator must be able to generate the capability plot of each tug used in the real case, considering losses due to ship speed or current.

4.4.12. Assessment of ship maneuvering in following seas

When maneuvering into an exposed channel in following seas, under the environmental and speed conditions of the design ship given in the Concept Design, the ship may be affected by surfing and broaching phenomena, which can make the maneuver critical. Simulators should be used to determine the maximum angle μ, as shown in Figure 4.1, at which the ship can still be controlled with the rudder while respecting the geometric limits of the channel. The angle χ is formed by the velocity vectors of the ship and the wave propagation speed, also shown in Figure 4.1.

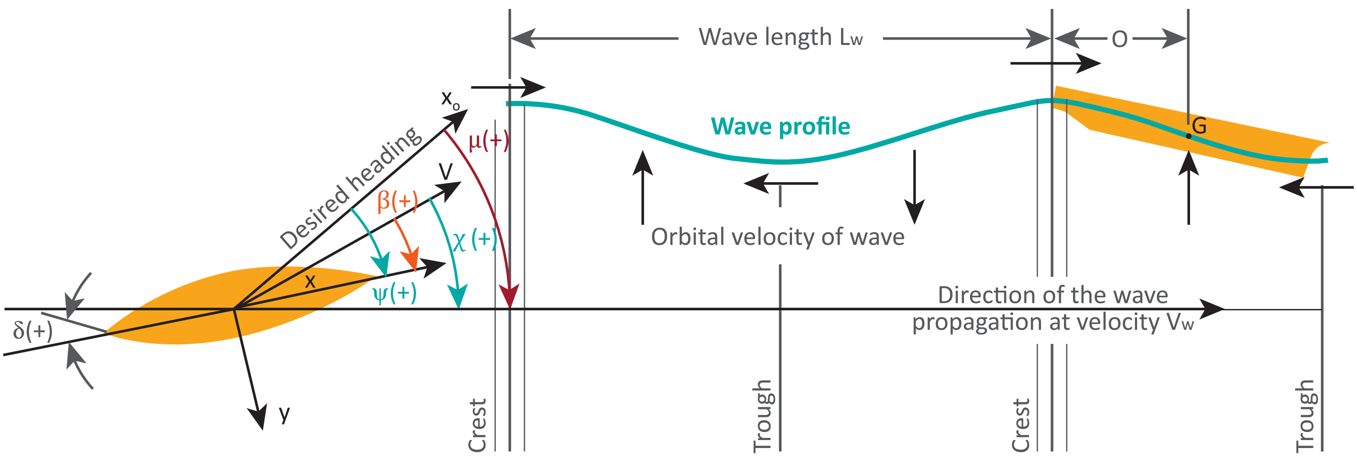

Figure 4.1. Defining the wave propagation direction, desired heading and design ship speed (PNA vol. 3, Figure 90)

Three types of situations can occur and they should be analyzed:

a. The projection of the ship's speed in the direction of the wave propagation $V\cos\chi$ is lower than the wave propagation velocity V_w (overtaking seas) $V\cos\chi < V_w$. In this case, the encounter frequency is lower than the frequency of the waves, which overtake the ship;

b. The projection of the ship's speed in the direction of the wave propagation $V\cos\chi$ is equal to the speed of the wave propagation V_w (semistatic seas) $V\cos\chi = V_w$. In this case, the encounter frequency is zero, and the ship moves with the wave;

c. The projection of the ship's speed in the direction of the wave propagation $V\cos\chi$ is greater than the velocity of wave propagation V_w (following seas) $V\cos\chi > V_w$. This case can also result in a low encounter frequency. A stationary observer on land may perceive that the waves and the ship are moving in opposite directions, while an observer on the ship may feel that the waves are passing astern of the vessel.

Note: When applicable, indicate the validation method employed.

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CHAPTER 5
Bottom Effects in Shallow Water Navigation

5.1. Introduction

This chapter is dedicated to the assessment of squat, a bottom effect, during the Concept Design and Detailed Design phases.

When a ship navigates in a channel, the pressure field in the area between the hull bottom and the channel bottom changes, potentially causing sinking. This tendency to sink may be associated with a trim by the bow or stern, and this depends on the speed of the ship and the shape of the hull. This effect is known as squat.

The impact of depth and lateral restrictions on a ship sailing in a channel includes not only the squat phenomenon but also the waves generated by the ship, which are influenced by the depth and width constraints of the channel. It is important to note that these effects are dependent on the ship's speed relative to the critical speed of the channel.

When a ship without any propulsive forces is in a fluid at rest, its equilibrium is defined by hydrostatic pressures acting on its hull and the distribution of its mass. The center of gravity and the center of buoyancy are aligned along the same vertical plane in this state. By determining the ship's design waterline, one can establish the location of the center of thrust/buoyancy. The distribution of weight on the ship is arranged to maintain hydrostatic equilibrium, where the center of weights is situated on the vertical line that passes through the center of buoyancy. Because the ship's volume is symmetrical with respect to the diametrical plane, the center of buoyancy is located on this plane. In order for the ship to maintain a level position without any trim or list, its mass distribution must be such that the center of gravity is also on this plane and aligned with the same vertical plane passing through the center of buoyancy.

When a ship moves at a constant speed in deep, initially still water, it displaces the fluid particles, causing them to change the pressure distribution over the hull due to their different velocities. In addition to the hydrostatic component, there is also a dynamic component in the pressures. Furthermore, a hydrodynamic force is added to the static thrust force. As a result, the ship will no longer maintain the same static waterline and will sink. This phenomenon is known as sinkage. Additionally, the ship may experience trim, as the resultant force of this additional component of pressure may not act on the same vertical as the thrust force. This can cause the hull to rotate around the center of flotation in order to restore the force equilibrium condition.

Lord Kelvin (1887, 1904) demonstrated that a pressure point moving at a constant velocity on the surface of water at infinite depth creates a system of waves consisting of divergent waves originating from the point and transverse waves radiating out from the point. This wave system is enclosed between two half-lines from the pressure point, each forming an angle of 19 degrees and 28 minutes with the direction of the velocity vector (as shown in Figure 5.1). Both divergent and transverse waves have a certain curvature. The transverse waves begin at the pressure point, are contained between the boundary lines at 19 degrees and 28 minutes, and their ends meet on these boundary lines where they intersect with the ends of the divergent waves.

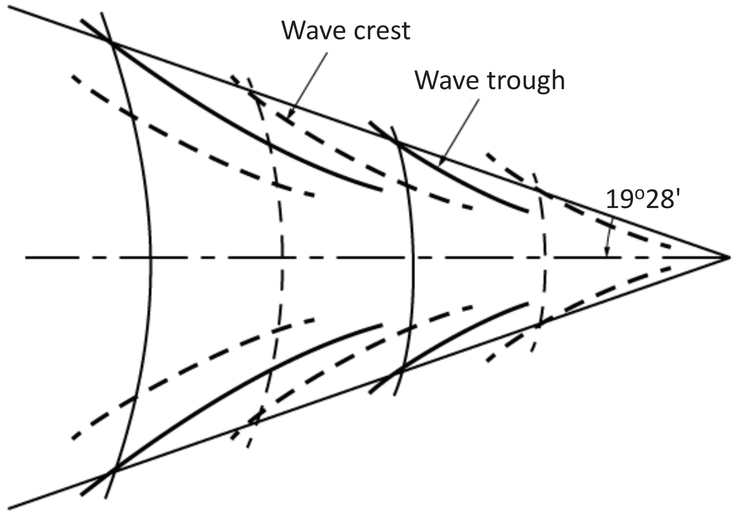


Figure 5.1. Kelvin waves generated by a pressure point moving on the free surface (PNA vol. 2, Figure 6)

In deep and initially still waters, when a ship moves at a constant speed, the resulting wave pattern on the sea surface is similar to that of Kelvin waves. The ship's wave pattern is the result of the superposition of multiple pressure points interacting with one another. At the bow of the ship, divergent waves are predominant, with transverse waves forming between them. The crest lines of the transverse waves are perpendicular to the ship's longitudinal motion. The transverse waves are especially noticeable behind the ship. (See Figure 5.2.)

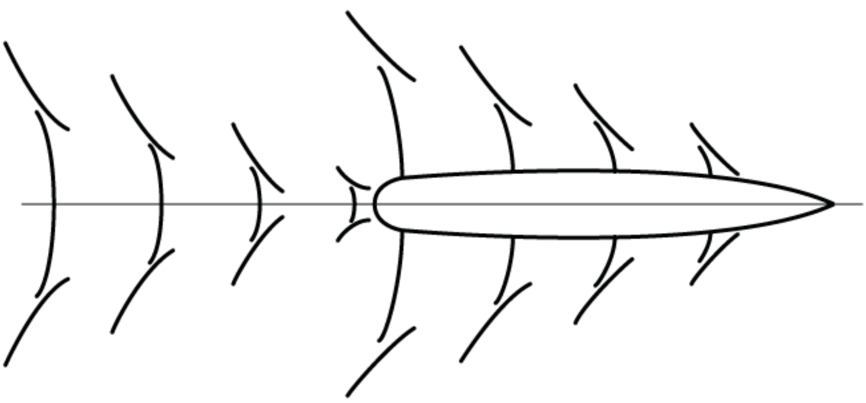


Figure 5.2. Scheme of the wave system generated by a ship (PNA vol. 2, Figure 8)

The pressure distribution over the hull changes as the speed of the ship varies, leading to different vertical displacements and trims of the hull. At low speeds, there is general sinking with a small trim by the bow. As speed increases, the bow tends to rise. Once the Froude number reaches 0.3 ($F_n = V/\sqrt{gL}$, where V is the ship's speed, g is the acceleration due to gravity, and L is the ship's length), the bow rises significantly while the stern sinks, causing the ship to take an appreciable trim by the stern. This condition is typical of planning and semi-planning vessels.

When a ship sails in shallow waters, the effects of sinkage, trim, and waves become more pronounced compared to deep waters. The restriction in depth causes the fluid velocities near the bottom to increase, resulting in a more significant drop in pressure, which strongly affects the ship's sinkage and trim.

The depth also affects the pattern of Kelvin waves, as the bottom interacts with the waves themselves, which can affect smaller vessels (such as speedboats, tugboats, canoes, etc.) anchored or moored in areas of restricted waters. Consider a flat bottom with a very smooth variation in depth, without lateral restriction, and a pressure point moving from deep to shallow waters, with the velocity vector perpendicular to the isobaths. For the same velocity ahead, as the depth decreases, the angle α that limits the region of propagation of divergent and transverse waves can increase significantly. For disturbance velocities up to $V \leq 0.4\sqrt{gh}$, where h is the local depth, the angle remains $\alpha = 19°28'$, and as the velocity increases beyond that value, the angle increases (as shown in Figure 5.3). When the disturbance velocity reaches the celerity value of a progressive wave in shallow waters, $V = \sqrt{gh}$, the angle α becomes 90 degrees, and the divergent and transverse waves form a single translational wave. When the disturbance velocity exceeds this value, the angle α begins to decrease, and no more transverse waves are formed. The system is composed of divergent waves with the boundary lines being crest lines, and the innermost divergent waves become concave. Normally, merchant ships do not reach the critical disturbance velocity due to a lack of power. As mentioned in the PIANC document, usually, tankers and container ships can reach speeds such that the depth Froude numbers ($F_{nh} = V/\sqrt{gh}$) are equal to 0.6 and 0.7, respectively.

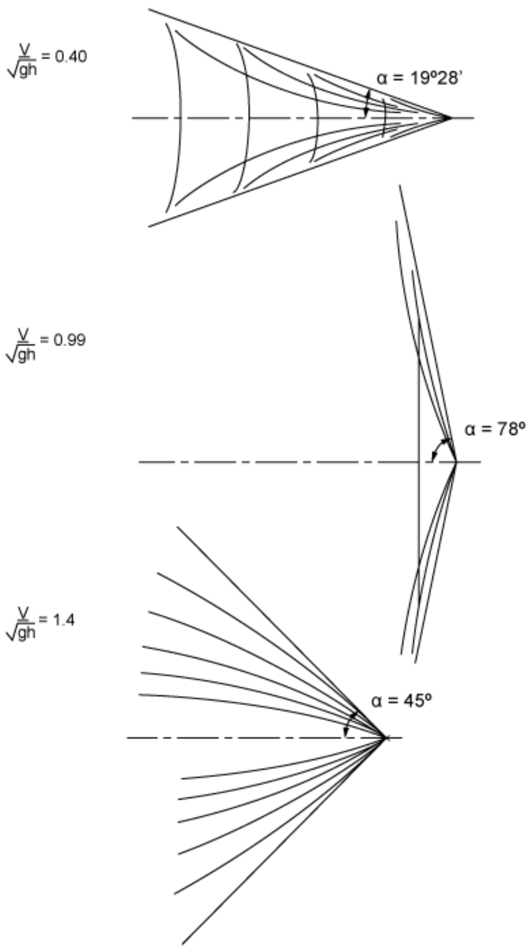


Figure 5.3. Effects of depth on the Kelvin wave pattern (PNA vol. 2, Figure 43)

The problem becomes more complex when navigating in channels with lateral restrictions, as the presence of a ship creates a partial blockage of the section through which the flow will occur, resulting in a significant increase in squat.

As previously mentioned, a moving ship experiences a change in pressure distribution over its hull when it is in motion compared to when it is at rest, which is a dynamic effect caused by the relative velocities of the hull and water. This effect causes the ship to experience a tendency to sink and acquire a trim, which is commonly known as the squat effect. As a result, the water depth under the keel of the ship reduces, which can become a critical issue in shallow waters. The magnitude of the squat effect depends heavily on the ship's speed and is more significant in shallow waters.

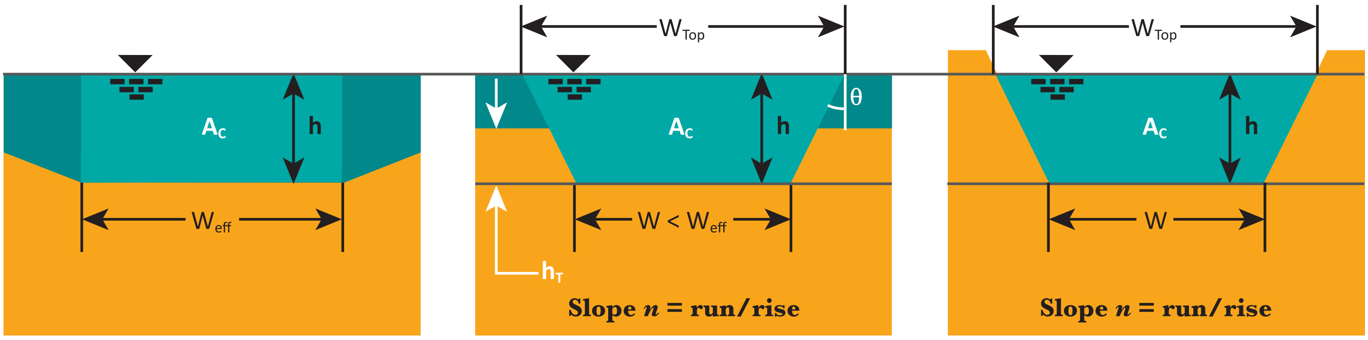
There are various methods available to evaluate squat. Some are appropriate for preliminary assessments, while others are more advanced and suitable for later stages of the project.

Initially, important parameters are presented for defining channel geometry and characterizing physical aspects of the problem, which are then used to evaluate the effects on navigation in the channel. Subsequently, methods suitable for the Concept design are presented, followed by methods recommended for the Detailed design. The text is mainly based on the PIANC Report 121 from 2014, with definitions similar to those used in ROM and USACE. Since many of the calculations are based on semi-empirical regressions (sometimes combined with semi-analytical methods), it is important to verify the validity range of the adopted regressions.

5.2. Characteristic parameters

5.2.1. Channel parameters

Navigation channels can be classified into three types, which are schematically presented in Figure 5.4 (based on Figure D-3 of PIANC 121). This figure was previously introduced in Chapter 2 of this book. It represents important parameters used to describe the three types of navigation channels: the bottom width (W), the projected width up to the highest part (W_{Top}), the water depth (h), the average water depth (h_M), the water depth in the restricted channel (h_{MT}), the height of the trenches (h_T) (distance from the bottom of the channel to the highest part of the bank), the slope of the banks (n), and the transverse area (A_C).



Unrestricted channel - U   Restricted channel - R   Canal - C

Figure 5.4. Types of channels (PIANC 121, 2014, p. 184)

Table 5.1. presents the parameters needed to describe each configuration of the different channel types, including when each should be calculated or when it is just input data.

Table 5.1. Channel parameters [PIANC 121 (2014) Table D-1]

Parameter	Symbol	Channel type		
		Unrestricted (U)	Restricted (R)	Artificial (C)
Width input				
Channel width	W	--	Input	Input
Effective width	W_{Eff}	Calculated	--	--
Projected width at top	W_{Top}	--	Calculated	Calculated
Depth input				
Water depth	h	Input	Input	Input
Mean water depth	h_M	--	Calculated	Calculated
Restricted water depth	h_{MT}	--	Calculated	--
Height of trench	h_T	--	Input	--
Slope input				
Inverse bank slope	n	--	Input	Input
Cross-sectional area	A_C	Calculated	Calculated	Calculated

An unrestricted channel (open) has no defined W width. Thus, its width is defined by an effective width W_{Eff}. The distance W_{Eff} varies from 8B to 12B, B being the beam of the ship for which the channel is being dimensioned.

For h/T (where T is the ship draught) between 1.10 and 1.40, W_{Eff} can be calculated by (see PIANC 121, 2014, equation D-4; Barrass, 2004)

$$F_B = W_{Eff} = \left(\frac{7.04}{C_B^{0.85}}\right) B$$

where C_B is the ship block coefficient.

The mean values of F_B are of the order of 8.1B to 8.9B for oil tankers and bulk carriers (in which C_B varies from 0.85 to 0.76), 8.6B to 9.4B for general cargo ships (in which C_B varies from 0.79 to 0.71), and 9.4B to 10.7B for container ships (in which C_B varies from 0.71 to 0.61).

Approach channels with gentle side slopes (depth/width = tanθ), 1:10 or gentler, can be considered as unrestricted channels, even if their width W is less than W_{Eff}.

The side slope is the inverse of the bank slop n (that is, n = horizontal run/vertical rise = cot(θ) = 1/tan(θ). Although not necessarily an integer number, the value of n is usually of the order of n = 3, representing side slopes of 1:3 (vertical rise/horizontal run). However, steeper values (smaller than 3) and flatter (larger than 3) are possible. As mentioned in the PIANC text, "The unprotected underwater banks of a dredged trench depend on the bottom material (for instance, fine or coarse sand) and its stability to resist to currents, waves and actions of ships".

The projected width at the top of the channel W_{Top}(m) is employed for artificial channels and restricted channels, and is given by

$$W_{Top} = W + 2\,n\,h$$

For calculating the wetted area of the cross-section A_c of an artificial channel or the equivalent wetted area of a restricted channel, the slope is projected to the water surface

$$A_c = W\,h + n\,h^2$$

For unrestricted channels, it is recommended the use of W_{Eff} for channel width W, and n = 0.

The mean water depth h_M(m) is a standard hydraulic parameter for artificial and restricted channels, defined by

$$h_M = \frac{A_C}{W_{TOP}}$$

The water depth h_{MT}(m) for restricted channels is a function of h, h_M and hT, given by

$$h_{MT} = h - \frac{h_T}{h}\,(h - h_M)$$

5.2.2. Combined ship and channel parameters

Combined parameters are several dimensionless coefficients that are ratios of both ship and channel parameters. They include h/T ratio, blockage factor, velocity return factor S_2, Froude depth number F_{nh} and critical speed in the channel.

5.2.2.1. Relative depth ratio h/T

The water depth to draught ratio h/T is a measure of the channel relative depth. It is recommended to employ a minimum value of 1.1 to 1.15 in calm water and 1.15 to 1.4 when waves are present.

5.2.2.2. Blockage factor S

The blockage factor S is defined as the fraction of the waterway cross sectional area A_C that is occupied by the ship's underwater midships cross-section A_S

$$S = \frac{A_S}{A_C}$$

Figure 5.5. shows cross sectional areas A_S and A_C of a channel, as well as the net cross sectional area of the channel A_W.

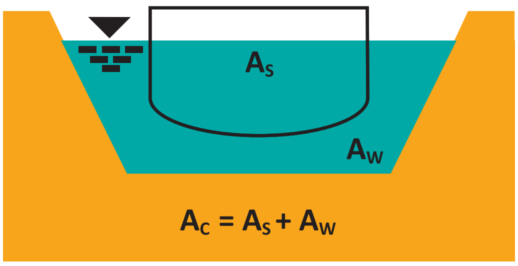


Figure 5.5. Canal and ship cross sectional areas (PIANC 121, 2014, p. 184)

Characteristic S values can vary from 0.10 to 0.3 or larger for restricted channels and artificial channels, and 0.10 or less in unrestricted channels. The value of S is a factor in the calculation of the design ship's critical speed in artificial and in restrict channels. A blockage factor S = 0.10, for instance, is equivalent to a river or channel with no lateral restriction and deep waters.

5.2.2.3. Velocity return factor S_2

The velocity return factor S_2 is similar to S, except for the fact that it is the ratio between the ship's cross sectional area A_S and the net cross-sectional area of the waterway A_W, defined as

$$S_2 = \frac{A_S}{A_W} = \frac{A_S}{A_C - A_S} = \frac{S}{1 - S}$$

5.2.2.4. Depth Froude number F_{nh}

It is a dimensionless parameter that indicates the intensity of the design ship's resistance to forward motion in shallow water. As defined above, F_{nh} is given by

$$F_{nh} = \frac{V_S}{\sqrt{gh}}$$

Where g é is the gravitational acceleration expressed in meters per second squared (m/s^2) and V_S is the ship's speed relative to the water in meters per second (m/s).

5.2.2.5. Critical speed in restricted channels

Critical speed V_{Cr} is a limit speed due to increase in the ship's force of resistance to forward motion in a restricted channel, given by the solution to

$$\frac{V_{Cr}}{\sqrt{gh_M}} = \left[\frac{2}{3}\left(1 - S + \frac{V_{Cr}^2}{2gh_M}\right)\right]^{1,5}$$

or, making explicit the solution of this equation

$$\frac{V_{Cr}}{\sqrt{gh_M}} = K_C = \left[2\ \mathrm{Sin}\left(\frac{\mathrm{Sin}^{-1}(1 - S)}{3}\right)\right]^{1,5} = 2\ \mathrm{Cos}\left(\frac{\pi}{3} + \frac{\mathrm{Cos}^{-1}(1 - S)}{3}\right)^{1,5}$$

5.3. Empirical equations recommended in the preliminary assessment

For assessing the squat in the preliminary studies, it is recommended to employ ICORELS, Barrass3 or Yoshimura equations (presented in PIANC 121, 2014) due to their simplicity and easy utilization.

5.3.1. ICORELS method

The use of the ICORELS (International Commission for the Reception of Large Ships) method is recommended for outer channel (open water) or with no lateral restriction. The maximum squat S_{bI} occurs always by the bow and is given by S_{bI}

$$S_{bI} = C_S \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}}$$

where

$$C_S = \begin{cases} 1{,}7 \rightarrow C_b < 0.7 \\ 2{,}0 \rightarrow 0.7 \leq C_b < 0.8 \\ 2{,}4 \rightarrow C_b \geq 0.8 \end{cases}$$

$\nabla = C_b L_{pp} BT$ is the ship displacement volume (submerged volume).

For large container ships, it is recommended to employ $C_S = 2$, even if $C_b < 0.7$. For ships with an immersed transom stern it is recommended to employ $C_S = 3$, since the stern of these ships exceeds those of conventional ships.

The restrictions to the use of this formula are (PIANC 121 Table D.2)

$$1.1 \leq h/T \leq 2$$
$$2.19 \leq B/T \leq 3.5$$
$$5.5 \leq L/B \leq 8.5$$
$$16.1 \leq L/T \leq 20.2$$
$$0.6 \leq C_B \leq 0.8$$
$$0.22 \leq h_T/h \leq 0.81$$

The Froude depth number $F_{nh} = V/\sqrt{(gh)}$ must be $F_{nh} \leq 0{,}7$, and the ship's speed must be less than the critical speed.

5.3.2. Barrass3 method

The Barrass3 can be employed in any type of channel. The maximum squat S_{max} may occur either by the bow or by the stern, and is determined as a function of the ship's speed in knots (V_k), of the ship's block coefficient C_B, and of the previously defined blockage factor S.

By the Barras3 method, the maximum squat (by the bow or by the stern) S_b is given by

$$S_b = \frac{C_B V_k^2}{100/K}$$

where

$$K = 5.74\ S^{0.76}$$

Restrictions to the use of this formula are

$$1.1 \leq h/T \leq 1.4$$
$$0.1 \leq S \leq 0.25$$
$$0.5 \leq C_B \leq 0.85$$

For assuming that the squat is proportional to the square of the ship's speed, it is recommended to make sure that the ship's speed is kept below the critical speed.

5.3.3. Yoshimura (Y) method

The Yoshimura (Y) method can be employed in open or closed channels, with immersed banks or not.

The maximum squat by the bow S_{bY} is given by

$$S_{bY} = \left[\left(0.7 + 1.5\frac{1}{h/T}\right)\left(\frac{C_B}{L_{pp}/B}\right) + 15\frac{1}{h/T}\left(\frac{C_B}{L_{pp}/B}\right)^3\right]\frac{V_e^2}{g}$$

The term V_e (m/s) corresponds to an equivalent velocity for including the blockage factor effect in laterally restricted channels with lateral restrictions defined by

$$V_e = \begin{cases} V_S & \rightarrow \text{for U channels} \\ \dfrac{V_S}{1 - S} & \rightarrow \text{for R or C channels} \end{cases}$$

5.4. Empirical methods for calculating ship squat in the Detailed Design

Tuck, Huuska/Guliev, Römisch and Ankudinov empirical methods are presented below.

5.4.1. Tuck method (see Gourlay, 2010)

The Tuck method is applied only to laterally unrestricted channels, and is given by

$$S_{bT} = (C_Z + C_\theta)\frac{\nabla}{L_{pp}^2}\frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}}$$

where

C_Z is the coefficient based on the ship's hull characteristics for sinkage;

C_θ is the coefficient based on the ship's hull characteristics for mean trim;

L_{pp} is the length between perpendiculars in meters (m);

F_{nh} is the depth Froude number $F_{nh} = \frac{V_S}{\sqrt{g\,h}}$

Obtaining these coefficients is usual in naval architecture, where such method is known as "universal" for squat calculation. The Tuck formula introduced the effect of critical speed, which corresponds to $F_{nh} = 1$. The way how these coefficients are obtained must be documented.

$$C_S = \frac{L_{pp}}{2\pi A_{WP}\nabla} \int_{-L/2}^{L/2} \int_{-L/2}^{L/2} \frac{dS}{d\xi} \frac{B(x)}{x - \xi} \, d\xi \, dx$$

$$C_\theta = \frac{-L_{pp}^{\ 3}}{2\pi I_{LCF}\nabla} \int_{-L/2}^{L/2} \int_{-L/2}^{L/2} \frac{dS}{d\xi} \frac{(x - LCF)\,B(x)}{x - \xi} \, d\xi \, dx$$

and

$I_{LCF} = \int_{-L/2}^{L/2} (x - LCF)^2 \, B(x) \, dx$ is the second moment of the waterplane area;

$B(x)$ is the breadth of the cross sections along the longitudinal axis;

$S(\xi)$ is the area of the cross sections along the longitudinal axis;

x e ξ are coordinates of the ship longitudinal axis, from $-L/2$ to $L/2$;

LCF is the longitudinal position of the center of flotation;

A_{WP} is the waterplane area;

∇ is the underwater volume.

The development of the theory that originated these expressions is due initially to Tuck who, in 1966, published his solution for the case of ship sinkage, treating the body as slender, the fluid as non viscous and incompressible, and the potential flow. Afterwards, Tuck extended his theory to the case of shallow water. Tim P. Gourlay published in Tuck Memorial Issue (v. 70, n. 1-2, pages 5-16) of *Journal of Engineering Mathematics*, an article on the development of theTuck theory that attracted other collaborators and was the basis for other methods for estimating squat of ships sailing in shallow waters.

5.4.2. Huuska/Guliev method (PIANC 121, 2014)

The Huuska/Guliev method can be applied to any type of channel, and is given by

$$S_{bH} = C_S K_S \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}}$$

C_S is a coefficient usually adopted as 2.40 of the mean value, although the original works adopted between 1.9 and 2.03. K_S is a dimensionless constant for the three types of channels, determined from

$$V_e = \begin{cases} 7.45\ S_1 + 0{,}76 \rightarrow S_1 > 0.03 \\ 1 \rightarrow S_1 \leq 0.03 \end{cases}$$

S_1 is the blockage factor given by channel type

$$S_1 = \begin{cases} 0.03 \rightarrow \text{U channel} \\ \dfrac{S}{K_1} \rightarrow \text{R channel} \\ S \rightarrow \text{C channel} \end{cases}$$

The relationship between K_1 and S can be seen in Figure 5.6.

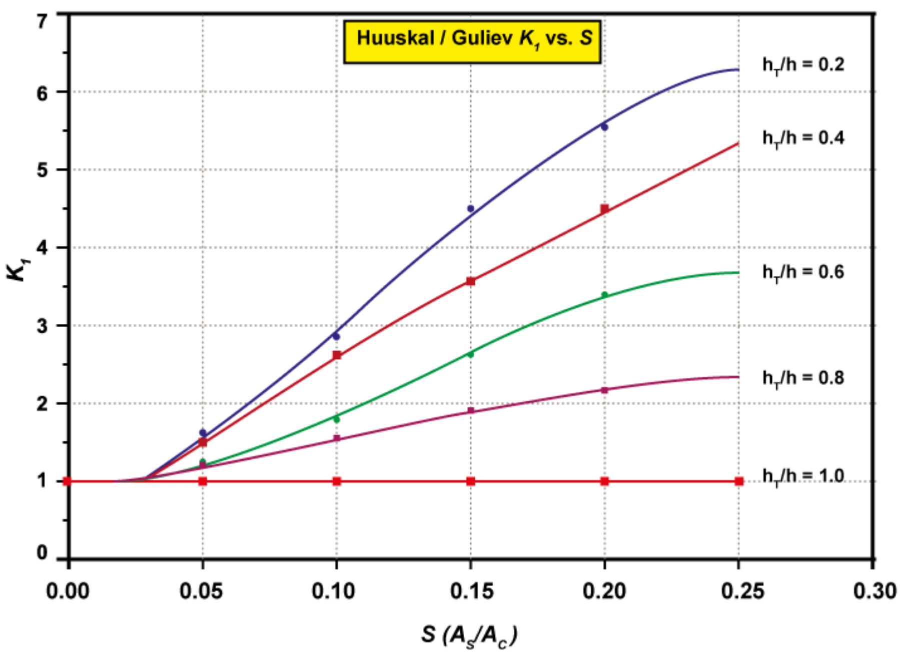


Figure 5.6. Graphic of dependences between K1 e S (PIANC 121, Figure D-6)

Restrictions to the use of this formula are

$$F_{nh} \leq 0.7$$
$$1.1 \leq h/T \leq 2$$
$$2.19 \leq B/T \leq 3.5$$
$$5.5 \leq L/B \leq 8.5$$
$$16.1 \leq L/T \leq 20.2$$
$$0.6 \leq C_B \leq 0.8$$
$$0.22 \leq h_T/h \leq 0.81$$

5.4.3. Römisch method (PIANC 121, 2014)

Römisch formulae for squat were developed by means of physical models for three types of channels for squat by the bow $S_{b,R}$ or by the stern $S_{s,R}$

$$S_{b,R} = C_V C_F K_{\Delta T} T$$
$$S_{s,R} = C_V K_{\Delta T} T$$

in which

C_V is a correction factor for ship's speed;

C_F is a correction factor for the ship's shape;

$K_{\Delta T}$ is a correction factor for squat at a critical speed of the ship.

These dimensionless coefficients of the ship are defined as

$$C_V = 8\left(\frac{V}{V_{cr}}\right)^2\left(\frac{V}{V_{cr}} - 0.5\right)^4 + 0.0625$$

$$C_F = \left(\frac{10\ C_B}{L_{pp}/B}\right)^2$$

$$K_{\Delta T} = 0.155\sqrt{h/T}$$

The critical speed V_{cr} varies as a function of the channel configuration, given by

$$V_{cr} = \begin{cases} C_U K_U \rightarrow \text{U channel} \\ C_C K_C \rightarrow \text{R channel} \\ C_R K_R \rightarrow \text{C channel} \end{cases}$$

The three parameters of mean speed C_U, C_C and C_R (m/s) are defined as

$$C_U = \sqrt{g\,h}$$

$$C_C = \sqrt{g\,h_m}$$

$$C_R = \sqrt{g\,h_{mT}}$$

h, h_M and h_{MT} were previously defined. Römisch correction factors K_U, K_C and K_R for unrestricted, artificial and restricted channels are respectively defined as

$$K_U = 0.58\left[\left(\frac{h}{T}\right)\left(\frac{L_{pp}}{B}\right)\right]^{0.125}$$

$$K_C = \left[2\,\mathrm{Sin}\,\frac{\mathrm{Sin}^{-1}(1 - S)}{3}\right]^{1.5}$$

$$K_R = K_U(1 - h_T/h) + K_C\,(h_T/h)$$

Restrictions for use of this formula are

$$1.9 \leq h/T \leq 2.25$$
$$B/T \leq 2.6$$
$$L/B \leq 8.7$$
$$L/T \leq 22.9$$

Besides these variables, squat must have a dependency greater than the square of the speeds, and the critical speed must be higher than the ship's speed.

5.4.4. Ankudinov method (as per USACE, ERDC/CHL CHETN-IX-19 presentation)

Maximum squat S_{max}, is a function of two components: midships cross-sectional sinkage S_m and ship trim T_r, given by

$$S_{max} = L_{pp}\,(S_m \pm 0.5\ T_r)$$

S_{max} may occur either by the bow or by the stern, depending on the trim sign, T_r. The negative sign is used for indicating squat by the bow, S_s, and the positive sign for squat by the stern S_s.

5.4.4.1. Calculation employed for defining midships cross section sinkage

S_m is defined by

$$S_m = (1 + K_p^S)\ P_{hu}\ P_{Fnh}\ P_{+h/T}\ P_{Ch1}$$

K_p^S is a parameter associated with the propeller, defined by

$$K_p^S = \begin{cases} 0.15 \rightarrow \text{single propeller ships} \\ 0.13 \rightarrow \text{twin propeller ships} \end{cases}$$

P_{hu} is a factor associated with the contribution of the hull in shallow waters, given by

$$P_{hu} = 1.7\ C_B \left[\frac{B\ T}{L_{pp}^2}\right] + 0.004\ C_B^2$$

P_{Fnh} is a factor associated with the Froud depth number $F_{nh} = \dfrac{V}{\sqrt{g\ h}}$,

calculated by means of an approximation of the expression $\dfrac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}}$ as

$$P_{Fnh} = F_{nh}^{\ 1.8 + 0.4\ F_{nh}}$$

$P_{+h/T}$ is a parameter associated with the depth effects defined by

$$P_{+h/T} = 1 + \frac{0.35}{(h/T)^2}$$

P_{Ch1} is a variable associated with channel effects, given by

$$P_{Ch1} = \begin{cases} 1 \rightarrow \text{U channels} \\ 1 + 10\, S_h - 1.5\,(1 + S_h)\sqrt{S_h} \rightarrow \text{R or C channels} \end{cases}$$

S_h is a channel depth and ship geometry factor, given by

$$S_h = C_B \frac{S}{h/T} \frac{h_T}{h}$$

S is the blockage factor previously defined, and h_T the slope height.

5.4.4.2. Calculation of ship's trim contribution

The second component employed in the squat calculation is given by the contribution of trim, given by

$$T_r = -\,1.7\, P_{hu}\, P_{Fnh}\, P_{h/T}\, K_{Tr}\, P_{Ch2}$$

Parameters P_{hu} and P_{Fnh} are the same already calculated for midships section sinkage.

$P_{h/T}$ is a parameter that considers the reduction of trim due to the action of propeller in shallow waters, given by

$$P_{h/T} = 1 - e^{\left[\frac{2.5\,(1 - h/T)}{F_{nh}}\right]}$$

Parameter K_{Tr} is given by a series of factors

$$K_{Tr} = C_B^{nTr} - (0.15\, K_P^S + K_P^T) - (K_B^T + K_{Tr}^T + K_{T1}^T)$$

The first factor $C_B = C_b^{nTr}$ corresponds to the blockage coefficient raised to the power nTr, given by

$$nTr = 2.0 + 0.8\, \frac{P_{Ch1}}{C_B}$$

The remaining factors define the effects of the propeller on the ship's trim.

K_P^S is the same factor defined for midships sinkage.

K_P^T is determined by

$$K_P^T = \begin{cases} 0.15 \rightarrow \text{single propeller ships} \\ 0.2 \rightarrow \text{twin propeller ships} \end{cases}$$

The last three factors define the effect of a bulbous bow K_B^T, a transom stern K_{Tr}^T and an initial ship's trim K_{T1}^T.

K_B^T is defined by

$$K_B^T = \begin{cases} 0.1 \rightarrow \text{ships with bulbous bow} \\ — \rightarrow \text{ships with no bulbous bow} \end{cases}$$

The transom stern parameter is defined by

$$K_{Tr}^T = \begin{cases} 0.04 \rightarrow \text{ships with transom stern} \\ — \rightarrow \text{ships with no transom stern} \end{cases}$$

The factor associated to the initial trim is given by

$$K_{T1}^T = \frac{T_{ap} - T_{fp}}{T_{ap} + T_{fp}}$$

T_{ap} and T_{fp} are the static draughts taken respectively at stern and bow perpendiculars.

Finally, P_{Ch2} is the trim correction parameter for the channel, defined by

$$P_{Ch2} = \begin{cases} 1 \rightarrow \text{U channels} \\ 1 - 5\ S_h \rightarrow \text{R or C channels} \end{cases}$$

The use of the Ankudinov formula is not recommended when the Froude depth number is less than 0.6.

5.5. Use of numeric and experimental methods for determining squat

Methods for determining squat in shallow waters were presented here. They structure was based on empirical methods and on the analytical work develop by Tuck.

For a more accurate assessment of squat calculation, numerical and/or experimental methods can be complementarily employed in the Detailed Design phase.

Independently of the methodology employed, it is recommended to take into account the critical conditions in terms of sinkage, considering the minimum underkeel clearance as a result of the combination of tide, channel project depth and ship draught, and disregarding motion in waves, probable static trim and heel effects.

Squat effects must be assessed at sailing speeds that ensure steering conditions to the ship, so that it can, by its own means, employing engine and rudder and within the limits of the drift angle, keep sailing in the channel limits under the environmental conditions prevailing in the area.

5.5.1. Numerical calculation

Squat calculation can be done by means of computational fluid dynamics methods, as finite element method (FEM), finite volume method (FVM) and finite difference method (FDM), considering the viscous effects. It must be emphasized that the use of potential theory has proved to be sufficiently efficient for squat calculation, it being the basis of the semi analytic work developed by Tuck. Thus, besides the finite element method (FEM) and finite volume method (FVM) for potential flow, the boundary element method (BEM) and methods based on the strip theory stand out. Therefore, it can be perceived that there is a great number of numeric methods available in the literature, and the use of each one will depend on the studied scenery, on the desired accuracy and on the resources available.

Irrespective of the numeric method adopted, the following requirements must be met

a. Detailing of discretizations (number of panels, strips or elements) for calculation of numerical convergence, mainly for very small underkeel clearances;

b. Description of the methodology employed for calculation of trim and dynamic sinkage, especially the metacentric height for calculation of dynamic trim;

c. Simplifications adopted in the discretization of the design ship hull;

d. Methodology employed for treatment of drift angle, trim and static heel;

e. Methodology employed for discretization of the approach channel geometry.

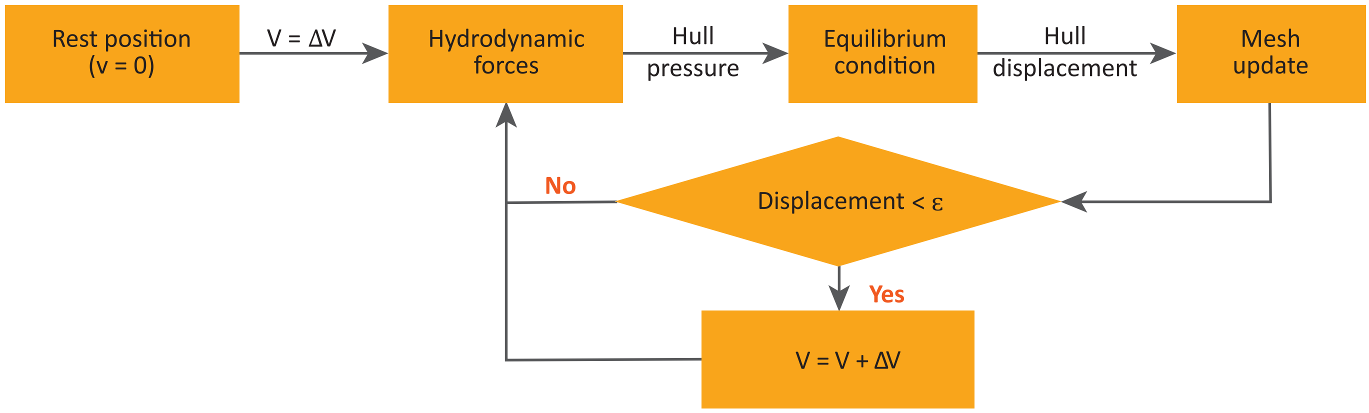


Figure 5.7. Schematic diagram for numerical calculation of squat and its consequences on the positioning of the ship

PIANC 121 proposes a procedure for numerical assessment of squat for reproducing the physical phenomenon from a work developed by Debaillon et al. (2004, 2009a e 2009b). The modelling procedure is composed of three phases: (a) a hydrodynamic model for calculating the flow around the hull; (b) an equilibrium model for moving the ship, with balanced force and momentum equations and (c) a mesh updating model to account for the ship and the free surface displacements/motions. The equations that govern the hydrodynamic problem are initially solved for the ship in its position of hydrostatic equilibrium at low forward speed, creating speed and pressure fields on the ship's hull. These values are inserted in a force and equilibrium model, and moments on the hull can be determined therefrom. A new equilibrium position of the ship is then established. The numerical modelling mesh is then updated, and the ship's speed is increased to the desired one. The quality of squat prediction depends strongly on the mesh quality and on the convergence criteria. Figure 5.7. represents the flow chart of the proposed method.

When employing numerical methods for calculating squat, it is important to make a result convergence study as a function of spatial and temporal discretizations, as recommended for every application of numerical methods in engineering. Furthermore, it is important to make an estimation of errors and to determine the uncertainty of the presented result, so that its reliability can be established. Regarding discretization errors, CFD (Computational Fluid Dynamics) good practices recommend that a mesh convergence study should be performed.

5.5.2. Experimental test

Determination of squat can also be performed by means of tests with reduced models, bearing in mind that some scale effects will be disregarded. The basic principle followed in such tests is that, when employing a reduced model in a scale $\lambda = L_N/L_M$, where L_N and L_M are respectively the ship's length and the model's length, all intervenient forces must be reduced to a single force scale. It means that the equality of the Froude numbers for the ship and for the model must be respected

$$F_{nN} = \frac{V_N}{\sqrt{gL_N}} = F_{nM} = \frac{V_M}{\sqrt{gL_M}}$$

where V_N and V_M, are respectively the ship's and the model's speeds $R_{eN} = V_N L_N / \nu_N = R_{eM} = V_M L_M / \nu_M$, where ν_N and ν_M are the kinematic viscosities of the fluid being utilized in the experiment.

It is impossible to satisfy simultaneously the equality of Reynolds and Froude numbers. Thus, in the experimental approach, Froude similarity and experimental techniques are employed that ensure that the results of the experiment with reduced model can be extrapolated to the ship. Once the Froude similarity is respected, the scales of length, time, speed, acceleration, rotation, force and area al will follow the similarity ratios shown in Table 5.2.

Table 5.2. Scale ratios for squat test

Unit	Ratio
Length	λ
Time	$\sqrt{\lambda}$
Speed	$\sqrt{\lambda}$
Acceleration	1
Rotation	1
Force	λ^3
Area	λ^2

The hull model to be tested must be made in a geometrical scale that ensures the quality of measurement of forces and moments, which are small when compared to the vessel's total displacement. This way, the largest scale possible must be employed, provided that the blockage effects due to the tank walls do not affect the quality of the measurements, except if such effects are desired for studies of interaction with the wall.

It is recommended that the preparation of the model follow a ballasting plan that can assure that the length, the height of the gravity center and the displacement observe the tolerances indicated in Table 5.3. A guide for experimental good practices is provided by ITTC (International Towing Tank Conference).

Table 5.3. Geometrical tolerances for the model

Item	Tolerance
Displacement	2%
Height of gravity center	3%
Dimensions	1%

The verification of the gravity center height must be done by means of a static heel test. A 2% maximum difference is acceptable in terms of metacentric height. The test must be performed with port and starboard heeling in the range between -5 and +5 degrees.

For squat calculation, the main approach can be done in two different ways: with the hull free or captive during the experiment. Calculations with captive hull keeps it at the design trim and static draught, and must perform force and moment measurements that are posteriorly converted into dynamic sinkage and trim.

It is recommended that the free model approach be performed in such a way that the ship movements can be precisely monitored. The apparatus employed for dragging the model must assure that it will be free for presenting heave and pitch motions, without influence instruments or arrangements on the vessel dynamics. In such cases, the choice of instruments and number of support points of the model must be made very carefully, in such a way as to allow the control of measurement noises.

It must be emphasized that the tank walls blockage effects must be carefully assessed for models dragged with large drift angles. Specific procedures for quantification of such effects can be seen in ITTC recommendations.

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CHAPTER 6
Nautical Bottom in Muddy Channels

6.1. Introduction

Chapter 2 section 2.2.1.2. of this book presented recommendations made by PIANC in their Report 121, 2014, section 2.1, on the depth of a channel. It was shown how, from the channel water level, from the bottom characteristics, from the ship characteristics, from the experience of pilots/masters and from risks of human errors, the depth of the channel is determined. In Chapter 2, the presence of mud on the bottom of the channel was not considered. Some recommendations in such respect are presented here, following the documents PIANC 121, 2014 and "Approach Channels – A Guide for Design" (PTC II-30 Final Report of the joint PIANC-IAPH Working Group II-30 in cooperation with IMPA and IALA – Supplement to *Bulletin* no. 95 of June 1997).

Factors directly connected to the ship that influence on definition of depth are: (static) draught, squat, trim, heel, vertical motions induced by waves and net underkeel clearance. Such values are influenced by the water density, by the ship's speed, by the turning rate and by calculation uncertainties. As for approach channels exposed to significant wave action, given the wave height randomness, the critical vertical motion they induce becomes the greatest probabilistic factor for determining gross underkeel clearance. Another aspect to be observed concern to the sea bottom geotechnical conditions. Touching the sea bottom may bring more drastic consequences when the bottom is hard. On the other hand, when there is mud in suspension, the ship maneuverability is affected. Therefore, the channel bottom must be at a distance from the bottom of the ship that assures its safety as to shocks, as well to its controllability.

Besides the previously mentioned factors there are others related to the channel bottom that must be considered

a. Allowances for uncertainties on the bottom relief,

b. Allowances for alterations to bottom configuration between dredging, and

c. Tolerances to dredging execution.

The channel depth definition (nominal, declared or announced) must take into account all those factors. In case of channels with muddy bottoms, other considerations must be included.

6.2. Channels with muddy beds

Many navigational channels have bottoms covered with a fluid layer that actually consists of fluid mud suspensions, a "black water" layer. Such layer is denser than water (1.050 - 1.300 kg/m^3), but with similar rheological properties. If the superior limit of the fluid mud is adopted as the channel depth limit, there will be no damages to the ship when reaching such limit. If the water-mud interface is accepted as part of the nautical bottom, a reduction of the required UKC can even be considered. It can even be accepted a permanent contact of the keel with the mud, that is, to sail with a negative UKC relatively to the water-mud interface.

On the other hand, it is questionable to choose the water-mud interface as the reference bottom, since in such conditions, the bottom is not clearly defined. Even the identification of the limits of water, water-mud and mud layers becomes difficult.

Techniques as echo sounding cause interpretation problems. High frequency signals reflect on the water-mud interface, while low frequency waves penetrate the sediment deposits and indicate a deeper water depth than the actual one.

Although considering that the muddy layer is accepted as the upper boundary of the nautical bottom, it may cause problems for waterway maintenance, since it is difficult to maintain water-mud interfaces, for instance, by means of common dredging methods, as such interface may vary significantly with tides and seasons of the year.

Another aspect regards to the fact that safety of navigation requires that master/pilot must be able to compensate for the effects of mud on ship behavior by employing the control systems or external assistance, as the use of tugboats

Ship sinkage and trim depend on speed and underkeel clearance, and are affected by the presence of fluid mud on the bottom of the channel. The ship in motion is a surface with distribution of pressures that moves in the channel. Such pressure distribution causes undulations in the water-mud interface that, interacting with the pressure distribution on the ship, modifies the distribution of vertical forces along the ship's length, altering its trim and sinkage. When the ship's keel penetrates the mud layer, the hydrostatic pressure distribution on the ship is affected by the alteration of the local density, which causes variation to the hydrostatic force (buoyancy) acting on the ship.

As the ship moves near or even through the fluid mud on the channel bed, it causes a deformation to the muddy layer which will affect its vertical motions. PIANC Report 121, 20014 presents two figures herein highlighted. The first one, reproduced here as Figure 6.1., is a schematic of four situations in which a ship sails in the channel in presence of mud: (a) with no contact with the interface; (b) in contact with the mud interface; (c) with no contact with the interface; and (d) with negative underkeel clearance. The blue, brown and black lines represent respectively the water surface, the mud layer interface and the solid bottom.

If there is no contact between the keel and the mud layer (Figures 6.1a and 6.1c), a rising interface yields an increased velocity of the ship relative to the water and, as a result, a pressure drop and a local water depression. On the other hand, a water-mud interface sinkage leads to a local decrease of the relative velocity and to an increased pressure, compared to the solid bottom case. In case of contact between the keel and a rising mud interface (Figure 6.1b), the mud velocity relative to the ship's surface decreases. Contact with a lowered interface with negative underkeel clearance (Figure 6.1d) leads to an increased relative velocity of the fluid, with local pressure fluctuations acting on the ship's keel.

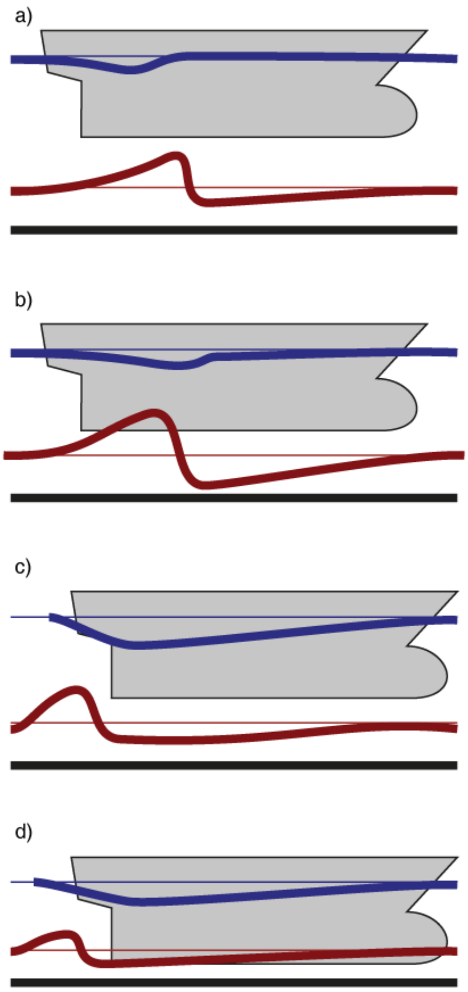

Figure 6.1. Effect of mud layers on sinkage and trim
(PIANC 121, 2014, p. 212; van Craenenbroeck et al. 1991)

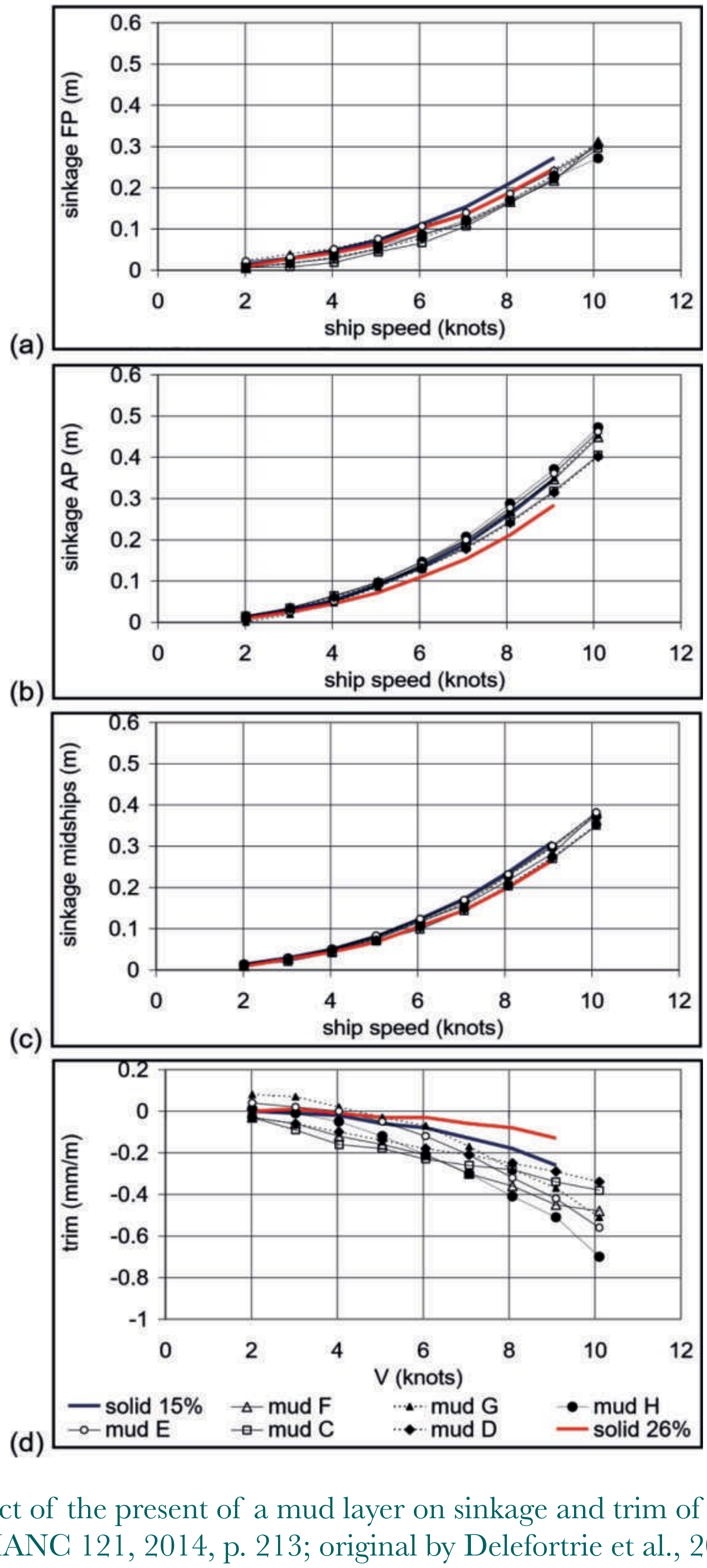

Figure 6.2. Effect of the present of a mud layer on sinkage and trim of a container ship (PIANC 121, 2014, p. 213; original by Delefortrie et al., 2007)

Figure 6.2., the second one taken from the PIANC publication, results from a publication by Delefortrie (2007). It shows the effect of a mud layer on sinkage and trim of a container ship, in a situation where the initial underkeel clearance is large enough so that the interface undulations do not cause any contact between the keel and the mud layer. This figure shows the sinkage (a) forward; (b) aft; (c) amidships and trim (d) as a function of the ship's speed for a container ship (L_{OA} = 300m, B = 40.3m, h = 13.5m) sailing on a 1.5-meter-thick mud layer, with a 15 percent clearance relative to the mud-water interface (26% relative to the solid bottom).

For a ship sailing in a muddy bottom condition, the sinkage is smaller compared to what happens when the bottom is solid. As put forward in PIANC Report 121, 2014, the ship "feels" the solid bottom more than the mud layer, and as a consequence, there is a larger sinkage. On the other hand, if the mud layer is replaced by water, the sinkage is decreased relatively to the mud layer condition. However, it does not take into account the extra buoyancy effect, which is important in very dense mud layers and/or if the ship has significant penetration in the mud. Generally, the influence on trim is more important than on sinkage, since the mud layer causes the ship to be dynamically trimmed by the stern over its whole speed range. Therefore, the effect of mud layers on the average sinkage is only marginal, since trim is much more important.

Appendix E of PIANC Report 121, 2014 and Appendix D of the Final Report of the joint PIANC-IAPH Working Group in cooperation with IMPA and IALA (1997) contains a full description of depth approach in muddy areas, including the nautical bottom. It also presents information on mud characteristics, on criteria for determining the nautical bottom and on behavior of ships in silty areas.

6.3. The nautical bottom approach

As adequately put forward in the 1997 PIANC document, a new approach to the problem forces the introduction of new and more appropriate concepts for treating the channel bottom and its depth.

The approach proposed by PIANC is to employ the expressions nautical bottom and nautical depth with very clear definitions.

Nautical bottom is the level at which physical characteristics reach a critical limit, beyond which the contact with the keel of a ship will cause damages or unacceptable effects on its controllability and maneuverability.

Nautical depth is the "local and instantaneous vertical distance between the nautical bottom and the free surface in calm waters".

It must be observed that, in such definitions, no reference is made to muddy bottoms, so that the definitions can also be applied to rigid bottoms subject to probable uncertainties on their formation and geotechnical characteristics at its deepest level. It is evident that a damage caused by contact between the ship and such nautical bottoms is more evident than in case of muddy bottoms, when the ship will probably suffer controllability problems instead of damages.

This definition of nautical bottom does not specify what physical characteristics serve as basis for such criterion. Neither does the criteria establish rigorously what would be the ship acceptable behavior. According to PIANC 121, 2014, from a practical and operational point of view, implementation of the nautical concept requires

- A practical criterion (that is, selection of the mud physical characteristics acting as a parameter for the nautical bottom approach and for its critical values);
- A practical survey method for determining the acceptable level and the water-mud interface in a reliable and efficient manner;
- Minimum UKC required regarding such nautical bottom;
- If necessary, either a minimum required UKC regarding the water-mud interface to ensure a minimum risk of contact and an acceptable ship behavior, or a maximum value for penetration of the keel into the mud layer, in case the contact with mud is considered to be acceptable according to the local conditions;
- Knowledge about and training in ship behavior in such situations and, if necessary, measures for compensating adverse effects on controllability and maneuverability.

6.4. Recommendations on nautical bottom

In spite of the definition of nautical bottom having been elaborated for application to muddy bottom channels as well as to channels with no presence of mud, practically the nautical bottom approach must be employed where there is mud covering the bottom. Its presence can be perceived by observing the different echo sounding responses between high and low frequencies identifying the water-mud interface. Pilots must be provided with information on the keel position on the mud layer, so that they can assess the cause-and-effect relationship of the ship behavior sailing on a mud layer and evaluate the need for tug assistance, etc. If there is a possibility of ships frequently penetrating the mud layer, it is recommended that the feasibility and safety of the maneuvers be assessed by means of advanced simulation techniques. It is also recommended the utilization of the water-mud interface depth for assessment of squat (Delefortrie et al., 2010).

6.5. Nautical bottom factors

Four nautical bottom factors must be employed in the Detailed Design.

6.5.1. Allowances for nautical bottom uncertainties

These are determined according to the knowledge about the site under consideration. The use of a minimum 0.1m allowance is recommended for uncertainties on the bottom level.

6.5.2. 6.5.2. Allowances for alterations in the bottom configuration between dredging

Alterations to the bottom configuration between dredging are specific to the local. Therefore, an allowance for such alterations must be adopted according to the knowledge about the site. It is recommended a minimum allowance of 0.2m or 1% of the channel depth for alterations between dredging.

6.5.3. Dredging execution tolerance

It is recommended a dredging execution tolerance of 0.2 to 0.5m, according to the bottom and type of dredger.

6.6. Criteria for determining the nautical bottom

6.6.1. Echo sounding criteria

It can initially be understood that the utilization of high and low frequency signals can provide a good definition of the mud layer limits: water-mud interface and bottom. High frequency signals (100-210Khz) indicate the water-mud interface, whereas low frequency levels (15-33Khz) penetrate the mud layer and reach the well consolidated bed, or rigid bottom. Figure 6.3., taken from PIANC 121, 2014, originally published by De Brauwer (2005), shows an example of use of echo sounding for identifying such limits. The 210Khz frequency identifies the water-mud interface, while the 33Khz frequency identifies the bottom.

Although the channel bottom is well defined in the example shown in the figure, the result is not always so clear, since low frequency waves are sometimes reflected at different levels. The reflection of low frequency acoustic signals on the mud seems to depend on many parameters, as for instance, gas bubbles, sand horizons, density gradients, experience of the operator, etc.

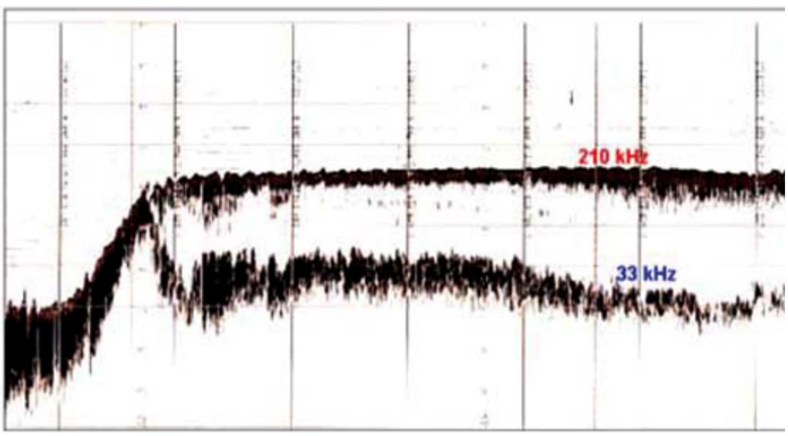

Figure 6.3. Echo sounding example (PIANC 121, 2014, p. 227)

6.6.2. Rheology-related criteria

These criteria are based on mud rheological properties for defining the nautical bottom. The forces exerced on the ship by the mud affect its controllability and maneuverability, and such forces are related to the rheological properties of the mud. It is necessary to measure the rheological properties locally, which is possible by means of equipment fixed to the site. The complexity of the rheological behavior of the mud, however, has as consequence the fact that the measurements depend on the equipment and on the analysis method.

Section 6.7. presents some basic notions on mud rheology.

6.6.3. Ship behavior criteria

These criteria are based on knowledge of the ship behavior when sailing in a channel with mud on the bottom. The most delicate question is to establish the degree of acceptance of ship controllability and maneuverability. It depends on different objective and subjective factors as environmental conditions, knowledge and training of pilots, availability of tugboats, quality of aids to navigation systems and economic factors.

6.6.4. Mud density level criteria

There are currently different systems that can be employed for continuous measurement of mud density. Consequently, there is a tendency to employ an acceptable mud density in procedures for determining the nautical bottom in a given location. However, mud rheological properties are not pure functions of density. Besides that, the critical density value of mud depends on the location, and is based on the rheological properties of local mud. In PIANC 121, 2014, the following disadvantages are listed.

- The critical density that defines the nautical bottom depends on the location. Therefore, it is not possible to establish a universal value.
- At a given site, the characteristics of mud (for instance, residence/consolidation time, seasonal effects) may vary. Therefore, the critical density must be frequently changed.
- For practical reasons, a critical density value must be selected for determining the nautical bottom in a navigational area. Such selection is always a compromise between safety and economy.
- If, for safety reasons, the lowest observed density is selected, there will be doubts about whether the proposed density will represent the most economical solution.
- Occasionally, density profiles present steps in which the density is barely changed over several meters of depth. It means that, associating nautical bottom to a density value may lead to uncertainties.

6.7. Rheology

Rheology is the science that studies the flow of matter or the deformation and the flow of matter. The rheological behavior of a fluid is graphically represented by a rheogram (flow curve), providing the ratio between shear rate $\dot{\gamma} = d\gamma/dt$ and shear stress τ. The inclination of the $d\dot{\gamma}/d\tau$ curve is called dynamic differential viscosity, and $\dot{\gamma}/\tau$ ratio is called dynamic apparent viscosity. For a Newtonian fluid (for instance, water), there is no difference between them, so their rheological behavior is fully characterized by a sole parameter, their dynamic viscosity. μ (see Figure 6.4.). Mud rheology is much more complex, and, for engineering purposes, it is often simplified by means of a Bingham model, determined by two parameters: the (differential) dynamic viscosity μ and the yield stress or initial ridigidy τ_0, that is, the shear stress that must be overcome for initializing material flow.

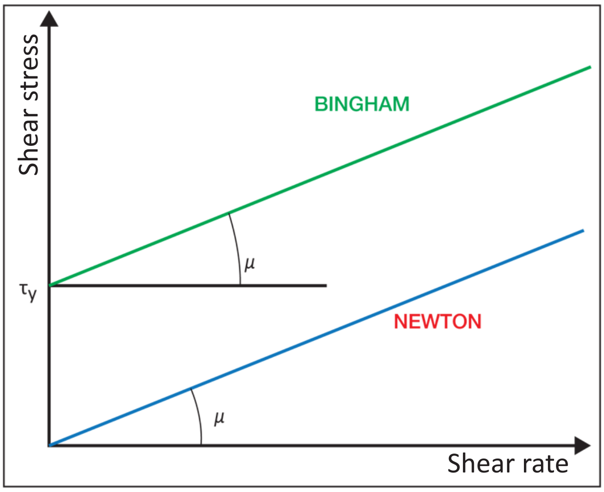

Figure 6.4. Example of rheogram (built from Figure E1. of PIANC 2014 121, p. 222)

6.7.1. Density

An important physical property in the study of mud behavior is its density ρm, which depends on the quantity of water and solid material existing on it. Specific mass is given by

$$\rho_m = \rho_a(1 - \varphi) + \rho_s\varphi = \rho_a(1 - \varphi) + T_s$$

where ρ_a and ρ_s are respectively the densities of water and solid material (sediment); φ is the volume of solid fraction (number resulting from the division of the volume of solid particles that compose a mixture by the sum of the volumes of all components of such mixture, when still separated), and T_s is the solid material concentration.

6.7.2. Density-rheology relationship

In general, shear stress increases with density, so that a larger fraction of solid matter will lead to a behaviour similar to that of the Bingham model. Density, however, is not the only determining parameter, that is, there is no unique relationship between density and rheology. Mud rheology also depends on many physical and chemical parameters such as mud content, spectrum of particle diameter, clay mineralogy, percentage of organic material, water chemistry (pH, salinity) and even (rheological) history and measurement technique.

A distinction can be made between fluid and plastic mud, as shown in Figure 6.5. (presented in PIANC 121, 2014, from Galichon et al., 1990), defined as

– Fluid mud with low solids fraction (low density) is a loose suspension similar to water (sometimes called "black water"), with viscosity and yield stress that do not depend, or depend slightly, on density.
– Plastic mud with a higher solids fraction (higher density) is a deposit of sediments with nonnewtonian rheological properties that depend strongly on density. Besides viscous behavior, such kind of mud presents elastic behavior, comparable to a soil. This combination is referred to as visco-elasticity (or elasto-viscosity).

An example of rheological profiles and density in loose mud deposits is shown in Figure 6.6. (presented in PIANC 121, 2014, from De Meyer and Malherbe, 1987) as a function of depth. Density increases irregularly with depth, as it was observed that there are steps in which density does not increase with depth. On the other hand, the initial rigidity curve clearly shows the rheological transition level. In Figure 6.6., a first jump of the rheological profile of small amplitude occurs at less than 0.5 meter below the water-mud interface, while a second and more drastic transition is observed at the depth of 3 to 4 meters below the water-mud interface.

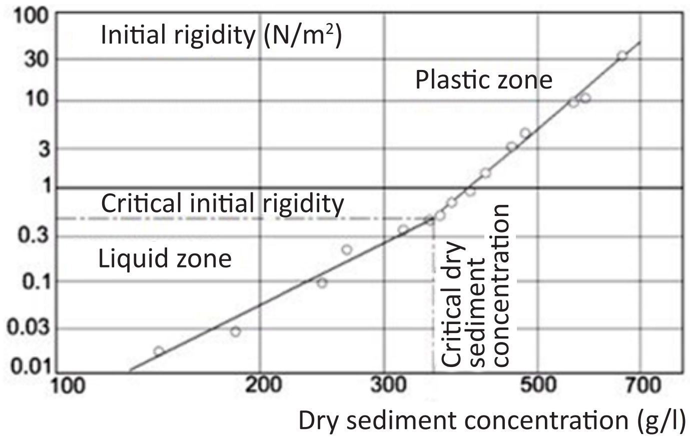

Figure 6.5. Distinction between fluid and plastic mud (PIANC 121, 2014, p. 225)

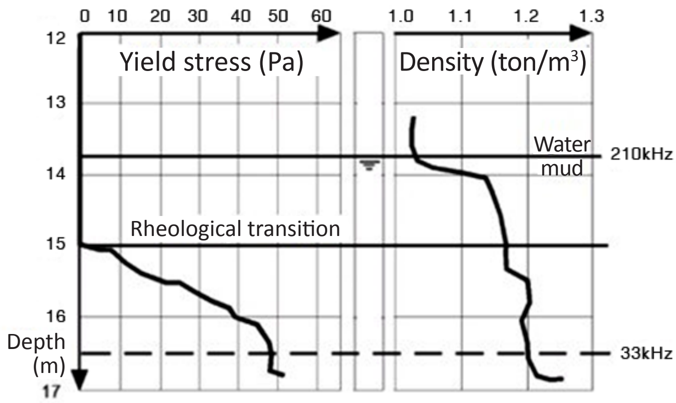

Figure 6.6. Rheological and density profiles (PIANC 121, 2014, p. 225)

Figure 6.7. (presented in PIANC 121, 2014, from de Vantorre et al., 2006) shows a schematic of an example of a muddy bottom rheological profile, emphasizing that the water-mud interface is identified by a 210kHz signal slightly under 12.5 meters depth, and that at 13 meters depth (about 0.5 meter below the water-mud interface) and at 16 meters two rheological transitions appear.

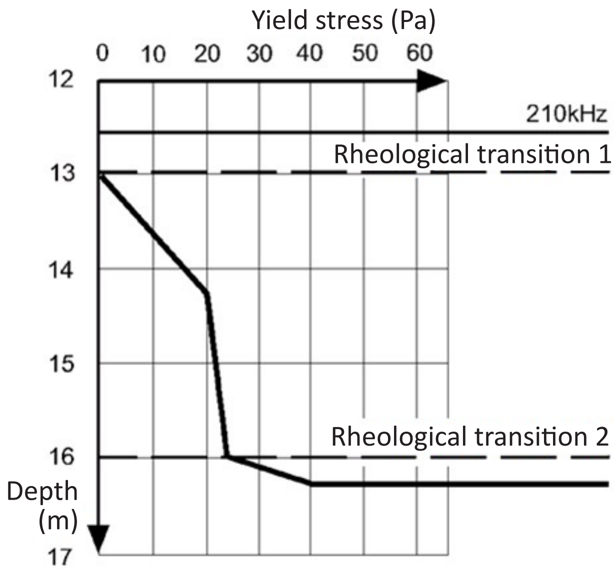

Figure 6.7. Example of rheological behavior with depth (PIANC 121, 2014, p. 226)

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CHAPTER 7
General Classification of Merchant Ships

7.1. Introduction

Maritime transport is the oldest known means of transport. It appears in the history of the Vikings and other important civilizations, besides having, in the navigation era, allowed European countries to discover new lands and use them to their benefit.

The need for transportation grew considerably and continued increasing. As a consequence, vessels employed in navigation have also evolved greatly. Vessels that were previously propelled by sails and rows evolved to coal and are nowadays propelled by oil byproducts, reaching higher speeds. In the same way, cargo capacity also evolved – we have, nowadays, the Chinamax class vessels, of which the MV Vale Brasil is an example, of 362 meters length between perpendiculars an 400 thousand tons of cargo capacity, while the first cargo ships capacity was 1,000 tons (Prandi, 2013).

According to the Brazilian government official site, in 2017 the maritime transport carried abroad of 90% of the Brazilian products. According to the International Chamber of Shipping, in the same year the maritime transport responded for more than 90% of the international trade (essential for the foreign trade, the maritime transport makes progress in Brazil).

These data are sufficient for demonstrating the current importance of maritime transport for the world economy. Together with such importance and with the diversification of cargoes and vessel purposes, new classes of ships appeared.

Another factor of great importance for the appearance of new classes of ships was the growth of cargo capacity, with a corresponding growth in ships dimensions.

Cargo ships have been modernized along the years, aiming at carrying higher volumes of cargo. Progress regarding fuel savings, reduction of CO^2 emissions and safety of navigation allowed the design of larger vessels, which consequently reduced the cost of maritime freight.

Taking as an example the container ships, in the 1970s such class had a cargo capacity of 3 thousand TEU, which can nowadays exceed 20 thousand TEU. For receiving these sea giants of up to 400 meters length and 60 meters breadth, port installations must be constantly adapted, following the growth of ship sizes.

One of the greatest challenges faced by ports and channels is refers to ships draught, that is, the depth of fairways and mooring berths. For keeping or increasing the depth of their navigational channels, berths and approaches, the ports execute dredging works for their maintenance or deepening.

This is the reason why there is a barrier as to the growth of ships. Launching ships with greater and greater dimensions enlarges their cargo capacity and reduces the cost of freights. However, it oppositely reduces ship operationality, with each time less route options and ports suitable for their dimensions. An example of breaking such barrier was the launching of Post Panamax vessels, which will be addressed forward. Owners feared to launch vessels that could not access the Panama Channel due to their dimensions, which would cause alterations to routes and distances to be sailed. Simultaneously, however, there was the growing need for ships with more cargo capacity, which determined the appearance of the Post Panamax class.

Another obstacle to increasing ship dimensions is propulsion power. The cruise speed is a very important factor for expedited cargo delivery. However, increase of propulsion power causes a fuel consumption jump. Therefore, operational costs become quite higher and, consequently, freight costs again increase.

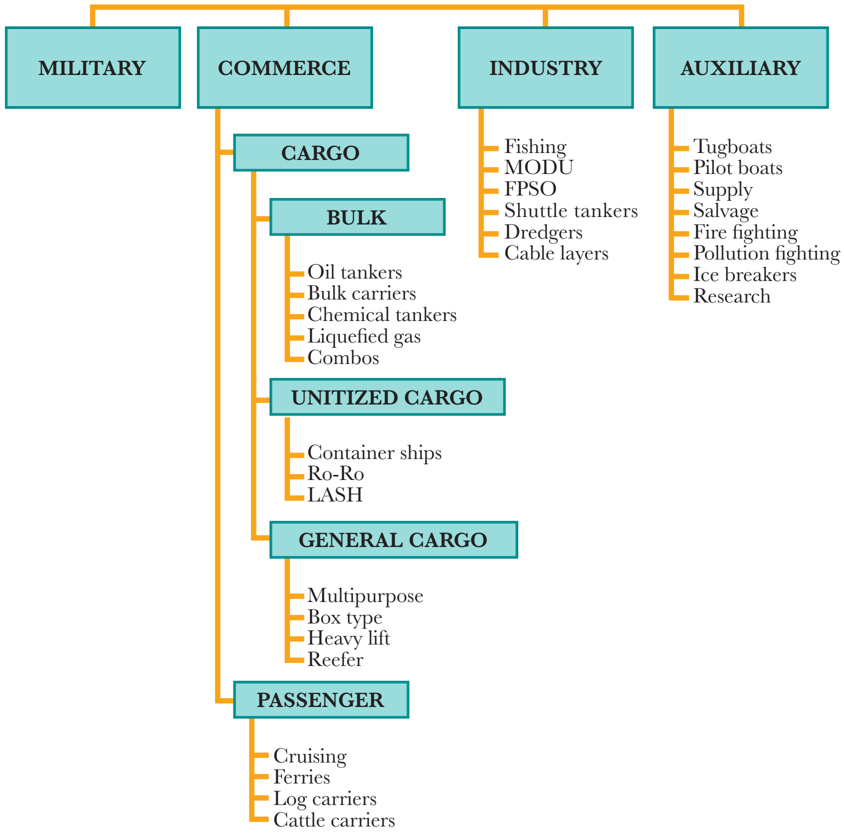
Generally speaking, for doubling ship speed it is required a propulsion power at least eight times higher than the original one.

In the same way, by reducing the speed of a vessel in 10 percent, there can be a reduction of about 25 percent in fuel consumption for a certain voyage condition.

It can be concluded that, to increase ship dimensions and propulsion power, it is necessary to adopt alternative routes, ports that accept such dimensions and other ways to alleviate excessive fuel consumption, as draught control and a more economic trim for the voyage.

These are obstacles to the increase in ships dimensions that have been overcome along the time. But there are still many challenges along the way.

Ship classification is nowadays essentially related to their main activity – if a cargo ship, to the kind of cargo it carries, to the traffic and its maximum volume of cargo. It can be exemplified with the diagram that follows



This chapter aims at showing the differences between ships within the above categories and comparing their evolution along the time.

7.2. Passenger/cruise ships

This type of vessel, employed in transport of passengers, became an important worldwide option for tourism/leisure around the world.

The main differences between this class of ship and those employed in carriage of solid and liquid cargoes are the great number of accommodations offered, the hull painted in white, the large load on the upper decks and the high technology to prevent uncomfortable rolling due to their great metacentric height (represented by GM).

The purpose of the first ships to cruise the oceans was not to carry passengers, but cargoes. However, they slowly began to carry only passengers instead of cargoes and mail.

In 1891, Albert Ballin launched the first cruise ship exclusively for passengers, christened the *Augusta Victoria*, and started this huge industry. The vessel began its maiden voyage carrying 174 guests and 245 crew members.

Albert Ballin, from Hapag-Lloyd, however, was not pioneer in the cruising business. Ten years before, the *Ceylon* was bought for performing the first round-the-world trip, which ended in 1883.

In 1894, at the other side of the ocean, Quebec Steamship Company started operating "Special Cruises" departing from New York. The success was such that, next year, the Company dedicated three vessels for operating in this kind or trip (Chronology of ocean liners and cruise ships).

White Star Line launched the most luxury passenger ships, with swimming pool and golf course, the *Olympic* and the *Titanic*. Priority was given to comfort of passengers relatively to speed, thus producing ships with larger beams and more stability.

In 1911 the 269 L_{OA}, 28m beam *Titanic*, the biggest cruise ship of that era, was launched. On April 10, 1912, following her sea trial, the ship commenced her maiden voyage with 2,207 passengers and crew members. In the night of April 14, 1912 the ship collided with an iceberg, sinking in the early ours and killing more than 1,500 people (Brief History of the Passenger Ship and Cruise Industry).

The First World War interrupted the development of this class of vessels. After the war, the period between 1920 and 1940 was considered to be the most luxurious years for the class.

In 1922, the first official round-the-world cruise was performed by the *Laconia*, with only first class accommodations.

During the Second World War, the growth of this class of ships once more stagnated. Following that and with the advent of aviation, cruising ships, employed in trips between continents, lost their customers.

In 1960, the modern cruise industry began. Focused on vacation trips, especially around the Caribbean, it built the image of leisure aboard ships. Many entertainment options appeared, with focus on the trip itself (Papanikolaou et al., 2010).

Since the 1970s, the size and passenger capacity of this type of ship increased remarkably, and on account of that, they were ranked according to their characteristics.

7.2.1. First generation – Small RoPax

RoPax are vessels that combine Ro-Ro and passenger vessel operations. In their first generation, they were small barges that carried cars on their main deck. They have capacity for 240 cars and 800 passengers, besides a crew of up to 50 persons.

Their dimensions are:

Length	120m
Beam	22m
Maximum draught	5.20m
Number of passengers	800

7.2.2. Second generation – Small RoPax

These vessels also combine Ro-Ro and passenger ship operations, but are equipped with an elevated platform for cars, and their stern is used as a loading ramp. They can carry 153 private cars or 19 trucks and three cars, besides a maximum of 800 passengers and 28 crew members.

Their dimensions are as follows:

Length	89m
Beam	16.40m
Maximum draught	4m
Number of passengers	800

7.2.3. Medium RoPax

Vessels for short international voyages. They are equipped with two car decks and a garage on the lower deck and can carry 2,080 passengers and 120 crewmembers.

Their dimensions are as follows:

Length	162.85m
Breadth	27.60m
Maximum draught	7m
Number of passengers	2,080

7.2.4. Grand RoPax

It is a large and modern cruise barge, with Ro-Ro deck for trucks and trailers, a hold for automobiles and an additional deck at the superstructure. It has a great number of cabins and public spaces for the comfort of up to 3,300 passengers and a maximum of 200 crewmembers.

Its dimensions are as follows:

Length	214.32m
Breadth	33.60m
Maximum draught	6.70m
Number of passengers	3,300

7.2.5. Panamax Vessels

The term Panamax designates vessels built to cross the Panama Canal, with maximum dimensions sized to the canal dimensions until 2016. Among such dimensions, we would specially mention the beam, which would typically reach 32.20m until 2016. In that year, new lockers were built to increase the flow of larger vessels through the canal. The capacity of these vessels exceeds 3,000 passengers plus up to 1,000 crewmembers.

Their dimensions are as follows:

Length	294m
Beam	32.20m
Maximum draught	8m
Number of passengers	3,000

7.2.6. Post Panamax vessels

These are modern passenger ships, built for round-the-world voyages, which exceed the Panama Canal dimensions. Their capacity exceeds 5,400 persons: 4,200 passengers and 1,200 crewmembers. The objective of this class of ships is to optimize the utilization of the space on board, for scale economy in their voyages.

Their dimensions are:

Length	360m
Beam	55m
Maximum draught	9.20m
Number of passengers	4,200

7.3. Container ships

Container ships are prepared for stowage of intermodal containers by means of cell guides positioned in their holds and by means of lashing on the hatch covers. Their loading and discharging operations are fast and their total cargo capacity in TEU increased significantly in the last 60 years since they came into operation.

Since the beginning of the containerization process in the mid-50s, this class of ships underwent six waves of changes, each one representing a new generation of vessels.

The first container ship came from the adaptation of a military tanker ship employed in Second World War, called *Ideal-X*.

The first generation of container ships arose from the adaptation of tankers and general cargo vessels. In the beginning of the 1960s, containers were a way of transport that was proving to offer cheaper operation with smaller risks. The ships were, in their majority, equipped with their own cargo gears, since most of the terminals were not yet equipped for handling containers. These vessels were relatively slow, and could carry unitized cargo o only n their decks.

In the beginning of the 1970s, containers began to be employed on a large scale, and thus appeared the first FCC ships, fully dedicated to the transport of containers.

7.3.1. FCC – Full Container Carriers

Vessels dedicated exclusively to the transport of containers, the second Generation of container ships, which were not adapted from other classes of ships.

The first units of this class were called C7, and were launched in 1968.

Generally, vessels of this class can carry containers stacked two high on their decks.

In general, the cargo gear was removed to allow the transport of a larger number of containers. However, there are exceptions still today, as the case of specialized vessels.

These vessels were faster, and could reach speeds between 20 and 24 knots, which are still references for container ships.

7.3.2. REFC – Reefer Container ships

These are vessels with a great part of their cargo capacity reserved for reefer containers – at least half of their total carriage capacity.

7.3.3. Feeder ships

These are medium size vessels, whose main task is to carry containers from smaller terminals to a bigger central terminal, where the boxes are loaded into a larger vessel.

7.3.3.1. Small feeder

Ships with cargo capacity between 100 and 500TEU, that is, between 100 and 500 20 foot containers.

7.3.3.2. Feeder

Usual capacity between 500 and 1,500TEU.

7.3.3.3. Feedermax

With capacity of up to 3,000TEU.

7.3.4. Panamax

Vessels built for sailing in the Panama Canal, therefore observing maximum dimensions as regards to length, draught and beam. These dimensions became known as Panama standard. Their length cannot exceed 291.4m, their beam 32.31m and their maximum draught 12.04m in tropical waters.

In the 1980s, great economic growths impelled the need for enlargement of the container ships, that is, the largest number of containers being transported for the lowest possible cost by TEU.

Their capacity varies between 3,000 and 5,100TEU.

7.3.5. Post-Panamax I and II

These are vessels that exceed the sizes accepted in the Panama Canal. On account of that, their capacity is greater, usually above 4,500TEU.

Exceeding the Panama Canal measures was considered to be a risk for the operation of ships and a need for larger infrastructure, besides causing limitation to port of calls due to draught.

In 1988, the first container ship to exceed the 32.3m beam of the canal was launched, inaugurating the APLC10 class, with capacity of 4,500 TEU.

In 1996, vessels thoroughly out of the limit measures of the Panama Canal were launched, with capacity of 6,600 TEU.

Once the limits of the Panama Canal were exceeded, the ships grew quickly, their capacities reaching 8,888 TEU (Post-Panamax II).

On account of such growth, draught restrictions became a problem, pressing the ports do execute dredging for accommodating these vessels.

7.3.6. New Panamax

As a consequence of the intense local traffic and of ships growing capacity, new lockers with a larger capacity were built in the Panama Canal. New Panamax vessels were designed to be compatible with the dimensions of the new lockers, inaugurated in June 2016. After that, the dimension limits for the canal changed to 366m length, 49m beam and 15.2m draught, which allowed vessels of up to 12,500 TEU capacity to navigate in the canal.

These vessels can establish routes mainly between, on one side, the Americas and the Caribbean and, on the other side, Europe and Asia. They are still up-to-date ships with good perspectives of becoming a standard for port infrastructure for decades.

7.3.7. ULCS – Ultra Large Container Ships

Ships with capacity above 11,000TEU. Their length surpasses the previous class 366m, getting close to 400m.

In 2006, a third class of Post-Panamax ships appeared, when Maersk launched their E-class *Emma Maersk*, whose capacity varies between 11,000 and 14,500TEU.

This class was named Ultra Large Container Ships, since it exceeds the dimension limits of the new Panama Canal lockers.

In 2017, an even larger expansion of these vessels forced Maersk to launch their new class of vessels, the Triple E, for 18,000TEU. In the same year, a new growth of such class of ships made their cargo capacity exceed 20,000TEU. Thereby, these vessels are getting near the limits of the Suez Canal, with the risk of causing a drastic decrease in their commercial value.

There are Projects of even larger vessels with capacities between 27,000 and 30,000TEU, as the *Malacca Max*, but they are not expected to be built before the flow of cargoes increase in the routes where they could trade.

The reference speed of container vessels, as it was already said, is has stagnated between 20 and 25 knots, and it is unlikely to improve due to the additional fuel consumption it would demand. The advantages of improving the speed of these vessels would not compensate the consequent increase in freight rates.

Moreover, there are shipping companies that prefer to adopt lower speeds of up to 20 knots due to the rises in bunker prices.

Due to restrictions as to draught and equipment, each generation of ships is facing a decrease in the number of ports where they can operate. For the purpose of scale economy, shipping companies are encouraged to built larger vessels. However, ports and channels need to invest huge amounts of money to accommodate them.

It is due to such difficulty that the above-mentioned feeder vessels still exist. They are more flexible relatively to the ports they can call and to the markets they can serve. On the other hand, restrictions on the increase of scale economy in container ships are caused by commercial rather than technical reasons (Evolution of container ships).

7.4. Tankers

The main purpose of tanker ships is the carriage of large quantities of petroleum by-products. Some of them can heat their cargoes. Tankers are fitted with double bottoms and double hulls as an extra protection against oil leakages in case of collision and stranding. Their peculiar equipment are hoses, valves and cargo pumps, which perform the transfer of cargo to shore terminals or single buoys.

After the Second World War, a great part of tanker ships was of 16,000 DWT. In the beginning of the 1950s, their average Deadweight tonnage had jumped to 30,000DWT. These vessels were called supertankers. Subsequently, larger vessels were called mammoth tankers (*Naval Encyclopedia*, Bulk Carriers).

These vessels carry cargoes of two main categories

– Products – petroleum by products as kerosene, gasoline, etc.
– Crude oil – transport of crude oil for refineries.
– Chemicals – in their majority, flammable and/or toxic cargoes.

In chemical tankers, each tank has its own loading/discharging system, with a separate pump. Due to this characteristic, this kind of vessel can carry various kinds of cargo simultaneously.

Crude oil can be distinguished according to the region from which it is extracted.

• Europe/North Sea – light product, low viscosity, black;
• West Africa – more viscosity than the oil from North of Europe. It becomes more viscous under temperatures below 19 degrees Celsius, and quickly volatile under temperatures above 27 degrees Celsius;
• South America – heavy, viscous product;
• Persian Gulf – heavy, also viscous product;
• Asia/China – very heavy product.

Light and heavy classification of products is given by their API grade, which is a classification largely employed and is based on oil physical properties, as stablished by the American Petroleum Institute (API) (Ventura). The table below represents the API classification (Santos et al.).

Oil classification	°API
Light	°API ≥ 31
Medium	22 ≤ API < 31
Heavy	10 ≤ API < 22
Very heavy	°API ≤ 10

Product carriers can be divided in "clean" – those that carry "clear" products as gasoline, kerosene and diesel – and "dark products" – those that carry intermediary raw material/feedstock, as vacuum gas-oil and bunker.

Another class of ships specific for carriage of oil from offshore fields is that of the shuttle tankers. They are equipped with a loading and discharging system compatible with their operation area, and are normally equipped with Dynamic Positioning Systems. This system keeps the relative position of the vessel relatively to the oil platform, thus compensating the three degrees of freedom of the vessel that is not equipped with automatic restoration: sway, surge and yaw.

The largest classes of these ships usually carry crude oil for long distances, for instance, from Persian Gulf to the United States, or from Europe to the Far East.

Such ships can be classified, as to their size and cargo capacity, as (Karini Rodrigues):

7.4.1. Coastal ships

Vessels of up to 50,000DWT, employed mainly in transport of petroleum by-products. They must be double hulled, and comply with all the requirements for the safe carriage of oil.

Their dimensions are as follows:

Length	200m
Beam	32.2m
Draught	12.6m

7.4.2. Panamax

As it was already seen as to other classes of vessels, this term designates vessels that, due to their dimensions, reached the limit size for passing through the lockers of Panama Canal until 2016, when it was enlarged. Their DWT lays between 50,000 and 70,000 tons. They are generally employed for carriage of crude oil.

Their dimensions are as follows:

Length	272m
Beam	32.2m
Draught	8m

7.4.3. Aframax

Oil tankers for carriage of crude oil. They are largely employed in the Black Sea, North Sea, and also in the Caribbean, China and Mediterranean seas. They were originally used as reference for vessels above 79,999DWT by the average freight rate assessment (AFRA). Currently, the term is used to designate vessels between 70,000 and 120,000 DWT.

The dimensions of ports and channels in some oil exporting countries, especially those that do not belong to OPEP, are not large enough to accommodate VLCC and ULCC vessels, which will be addressed next. For this reason, the AFRAMAX class is usually employed in such cases.

7.4.4. Suezmax

Suezmax are tankers whose dimensions allow their traffic in the Suez Canal. Their Deadweight range between 125,000 and 180,000 DWT, the maximum original capacity of that canal.

Their dimensions are as follows:

Length	285m
Beam	45m
Draught	23m

7.4.5. VLCC – Very Large Crude Carrier

With capacity up to 320,000DWT, these vessels are usually employed for carriage of crude oil. Some of them can be accommodated by the new dimensions of the Suez Canal. Their length usually varies between 300 and 330 meters.

Their dimensions are as follows:

Length	330m
Breadth	55m
Draught	28m

7.4.6. ULCC – Ultra Large Crude Carrier

Also employed for carriage of crude oil, their capacity exceeds 320,000DWT. The biggest vessel even built has a deadweight of 550,000 tons.

Their dimensions are as follows:

Length	415m
Breadth	63m
Draught	35m

7.5. Gas carriers

This class of vessel has an exclusive IMO code, the International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (known as "Gas Carrier Code"), adopted by IMO Resolution MSC 5(48), applicable to vessels built after July 1st, 1998.

They can carry four classes of cargo:

a. Liquefied natural gas (LNG), as methane, and chemical gases, as ammonia and butadiene;
b. Liquefied Petroleum Gas (LPG) as propane and butane;
c. Ethane (ethylene);
d. Chemical gases, as chlore, ammonia and vinyl chloride monomer (VCM).

The transport of LPG by vessels began in 1926, with two adapted American tankers. They performed the transport of butane and propane at room temperature, which is not appropriate.

The first vessel exclusively for carriage of liquefied gas was built in the United States in 1931. The *Agnita*, with a capacity of 2,100m^3. was destined to the carriage of butane and sulphuric acid.

In Europe, this kind of vessel commenced to be built only in the 1950s.

These vessels, however, faced a problem: their tanks were built in thick steel, with a high concentration of sulphur, which rendered it brittle with temperature variations.

Reefer techniques and metals more resistant to temperature variations made the transport of gases possible at lower temperatures in the form of liquefied gases.

The first semi pressurized vessels allowed also the transport of gases under lower pressures through reduction of their temperature. The first ones went into operation in 1959. In the following decade, the first vessels totally refrigerated appeared for transport of LPG, LNG and some chemical gases (Lelis).

Here are the main classes of vessels relating to cargo and capacity.

7.5.1. LPG

7.5.1.1. Coastal ships

Small ships, generally with capacity of less than 6,000m³, employed in short range navigation and in coastal trade.

7.5.1.2. Ocean-going ships

Medium size ships with capacity between 20,000 and 60,000m³, fully refrigerated, trading in long distance routes.

7.5.1.3. VLGC – Very Large Gas Carrier

Large ships with capacity between 75,000 and 100,000m³, also fully refrigerated.

7.5.2. LPG

7.5.2.1. Small gas carrier

Small ships with capacity between 2,000 and 20,000m³.

7.5.2.2. Medium gas carrier

Medium size ships with capacity usually between 20,000 and 40,000m³.

7.5.2.3. Large gas carrier

Large ships with capacity usually between 50,00 and 70,000m³.

7.5.2.4. VLGC – Very Large Gas Carrier

Their cargo capacity usually varies between 70,000 and 135,000m³.

7.5.2.5. ULGC – Ultra Large Gas Carrier

The largest ones currently built have a 265,000m³ cargo capacity and a length of 350 meters.

7.6. Bulk carriers

Ships built for carriage of solid bulk, that is, non-liquid or gaseous cargoes, generally uniform, in their holds.

Presently, bulk carriers represent 15 to 20% of the world fleet. Their main risks are cargo spontaneous combustion and saturation.

Like a great part of container vessels, this class of vessels is not equipped with cargo gear, and differently from tankers, they are equipped with large covers on their holds.

The first vessel built for carrying bulk cargoes from which there are records was the *SS John Bowes*, of 1852, which went for scrap in 1933 after two large restorations, in 1864 and 1883.

The evolution of this class of ships was slow, and consisted of new devices for opening and closing hatch covers and new ballasting equipment.

With the advent of cargo unitization and the first container vessel, there was a revolution in the transport of cargoes. In spite of that, old vessels were employed until the end of the 1980s. Bulk carriers subsisted, with the aid of self-loading systems, ballasting systems and improvement of cargo capacity.

This class of vessels can be divided according to their cargo capacity, as follows (Cordon):

7.6.1. Handysize

Vessels between 25,000 and 39,000 DWT, usually called small handies.

7.6.2. Handymax

Vessels in the range between 40,000 and 60,000 DWT. Their greatest advantage is their main dimensions (L_{OA}, BEAM and draught), which allow them to call at a great number of ports around the world.

7.6.3. Panamax

Vessels in the range between 40,000 and 60,000 DWT. Their greatest advantage is their main dimensions (L_{OA}, BEAM and draught), which allow them to call at a great number of ports around the world.

7.6.4. Post-Panamax

Ships with beam and draught exceeding the ones allowed according to the original dimensions of the Panama Canal until the new lockers were built, in 2016; their Deadweight vary between 80,000 e 119,000 tons.

7.6.5. Capesize

Ships above 120,000 DWT. They are so classified because, in interoceanic voyages, they cannot acess the Panama Canal due to their dimensions, which exceed the capacity of the lockers. They have, therefore, to pass by the Cape of Good Hope, in South Africa, or by the Suez Canal, in Egypt. Vessels with maximum dimensions allowed at the Suez Canal are classified as Suezmax.

7.6.6. VLOC – Very Large Ore Carriers

These are very large ships, usually dedicated to transport iron ore. The deadweight of this class varies between 200,000 and 400,000 tons.

Huge ships, employed usually for transport of ore. Their DWT varies between 200,000 and 400,000 tons. The biggest bulk carriers have between five and nine hatch covers, and are equipped with cranes between them for operating at terminals with less infrastructure. Presently, the biggest ore carrier as to cargo capacity is the 404,389 DWT *Vale Beijing*.

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CHAPTER 8
Risk Analysis in Port Planning

This chapter focuses on the risk analysis to be performed as part of the port planning, both for the conception phase and the Detailed Design phase. Such analysis helps organizing and consolidating knowledge about safety aspects of port operation, besides helping formulating proposals of mitigation or contingency actions, if necessary, so aggregating significant value to the decision-making process (Kristiansen, 2005).

The risk analysis that is part of port planning can be performed both in qualitative and quantitative ways. In nautical approach projects, the qualitative analysis is generally performed in the most incipient conception phasis, or when the quantity or quality of available information do not allow a deeper probabilistic analysis. Quantitative analysis, on the other hand, is recommended for the Detailed Design phasis, when there is more certainty about the solution to be adopted. It is, therefore, supported by the analysis performed in the previous phasis of the project.

Application of risk analysis techniques is expected to enhance the choice of good cost/benefit solutions associated to reasonable risks, and to facilitate risk management in the operational phasis of the port. Based on such analysis it is possible, for instance, to make recommendations as to: a) type of vessels that can berth at each wharf; b) power and kind of tugboats to be made available; c) risks associated to operating in different port configurations. In this sense, risk analysis is also a basic tool for supporting decision making in different phasis of the project of nautical approaches to the port and its vicinity – for instance, in the proposal of solutions to contour potentially dangerous events, or helping chose barriers for dangerous events that cannot be contoured in the project.

Generally speaking, risk analysis focus on undesired events that may happen, its probabilities of occurrence and consequences. Thus, hazards and hazardous situations[1] are identified, and their frequency and consequences are assessed in three essential steps: a) identification of hazards: recognition of hazards and threats associated to the operation, together with hazardous events – assets that can be affected are also identified; b) frequency assessment: involves the study of causes of each dangerous event and the estimate of its frequency – for example, based on operational history and/or consultation with specialists; c) analysis of consequence: a search for potential sequences of events that could occur as a consequence of an accident, leading up to unwanted consequences – part of this step is the study of probabilities of occurrence of these consequences. Usually, resources for mitigation of accidents and contingency measures are also part of the risk assessment/analysis, enabling to estimate the risk level associated to a given operation.

[1] The term "hazard" indicates a potential source of damage, and the expression "hazardous situation" indicates circumstances where persons, property and the environment are exposed to one or more hazards. In this chapter, it was also employed the expression "hazardous event" for indicating hazardous situations.

Qualitative analysis is a process of assessment of impact of risk factors, characterized by the use of subjective indicators as low, medium and high or important, critical and vital. On the other hand, quantitative analysis is characterized by the search for numeric values expressing the probability, the consequence and the contribution of each risk factor (accident scenario, danger, initiating event, equipment failure, human error, etc.), considering specific objectives and planning as a whole.

Generally speaking, quantitative assessment demands a more intense utilization of resources – for instance, information, computer tools, specialists. Sometimes, it is possible, employing simple qualitative tools, to identify the factors that contribute significantly to a hazard, dispensing with detailing quantitatively factors that are insignificant. This way, usually the qualitative analysis precedes the risk quantitative assessment.

From this discussion, this chapter begins with the presentation of the risk assessment process, approaching some qualitative techniques that can be employed in the port planning phases – focused on PHA (Preliminary hazard Analysis[2]) – and the quantitative techniques to be employed in the analysis of events that most contribute to risk – as identified in the qualitative analysis – in the most advanced phase of the project. Subsequently, information is presented for performing the risk analysis in the port planning, and some points deemed as essential are discussed, for the good quality of such analysis.

8.1. Risk analysis process

According to a proposal for rationalization of resources (as time, specialists, computer processing), the risk analysis process of a system can be split in two phases. The first one refers to the global analysis of the operation, when qualitative tools are employed to identify factors that may impact the risk. The second one refers to the quantitative analysis, when factors with significant impact on the risk are detailed – as it will be presented further on, this phase is generally performed in advanced phases of the project, when a larger number of detailed information on the systems being studied is available. The scheme presented in Figure 8.1 illustrates those phases and associates its steps, describing the main activities to be developed in each one.

The risk assessment process can demand analysis with different detail levels depending on its final destination, and on the resources available for performing the analyses. The techniques for development of the activities presented in Figure 8.1. were elaborated in such context and a significant number of approaches can be found, from the simplest to the most complex ones. Such diversity evidences the need for selecting – still in the initial phases of the analysis process – techniques that may result in a better exploration of the available resources, aiming at maximizing generation and concentration of knowledge as regards to safety aspects of the operation. The next topics discuss such selection and present techniques available for risk analysis – initially, for the qualitative analysis and, subsequently for the quantitative analysis.

[2] In this text, the term "system" is employed in a broad sense. In this chapter, it refers to equipment, persons, norms and practices, environment and to any factor that may be object of port planning.

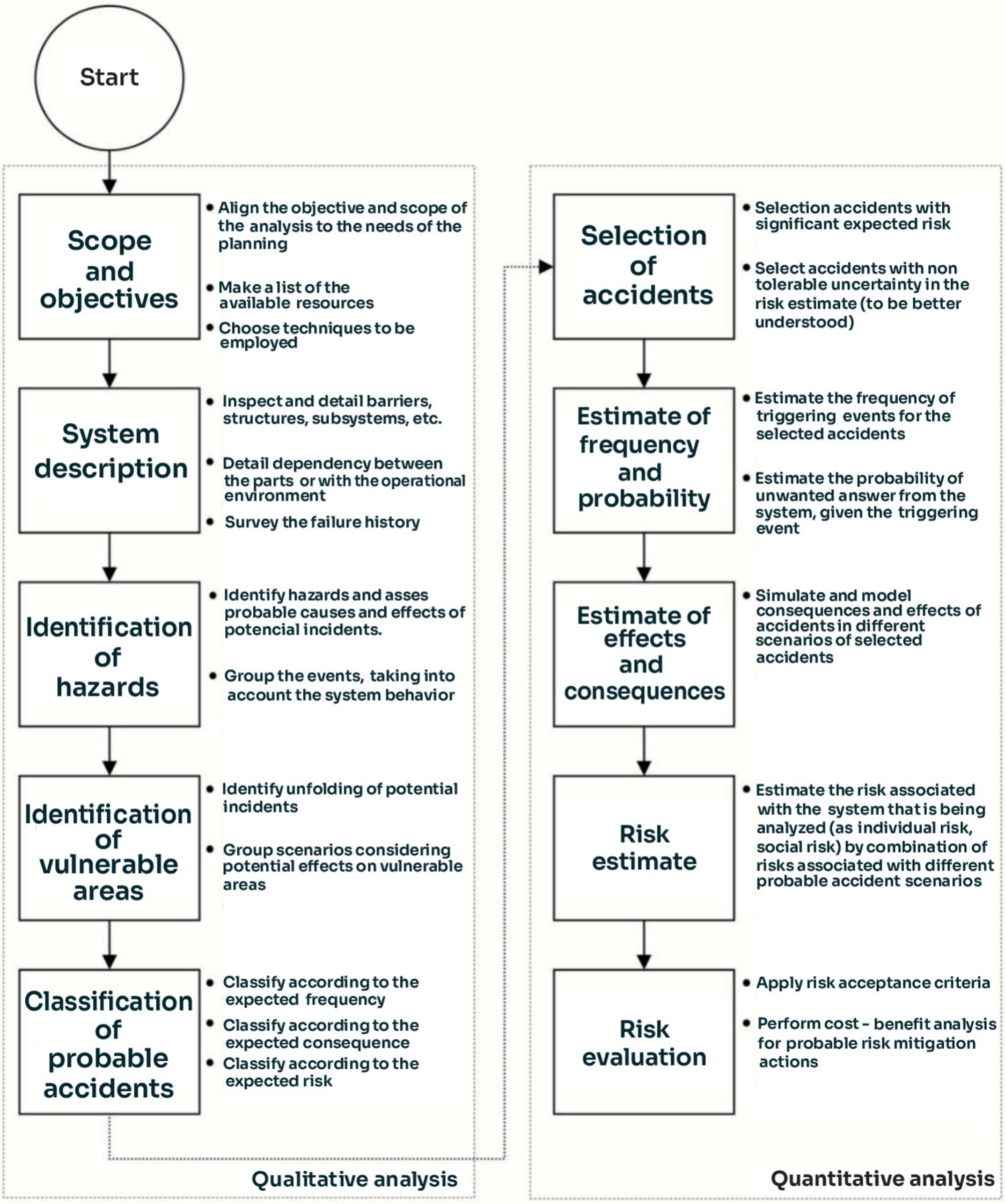

Figure 8.1. Risk analysis process

8.1.1. Risk qualitative analysis

Table 8.1. presents a preview of the main qualitative analysis techniques available, which can be applied to different stages of the risk analysis process. A wider list and more exhaustive descriptions can be found in norm NBR ISO 31010:2012 (ABNT, 2012). This norm, which addresses selection of techniques for each phase of the risk assessment process, can be applied for supporting a probable selection of techniques. As an example of support to such selection, Table 8.1. shows indications of use and a summary of essential resources for each listed technique.

Table 8.1. Qualitative risk analysis techniques

Technique	Description	Use indication	Examples of required resources
Brainstorming	Involve stimulated and encouraged discussions to identify probable kinds of failure, associated risks, criteria for decisions and/or treatment options	Can be employed independently in conjunction with other techniques to encourage creative thinking at any stage of the risk analysis. It is particularly relevant when the problem to be treated demands innovative solutions, or when there is few information available.	Group of specialists with knowledge on organization, on the system or on the process to be analyzed.
(Semi) structured interviews	In a structured interview, questions are prepared and submitted to interviewees, who freely reply (with no intervention). In a semi structured interview, it may occur interaction with the interviewer for exploration of emerging problems.	It can be positive when a meeting of specialists for a brainstorm session is not feasible (for instance, due to logistic issues). It can be employed for identifying hazards and for assessing mitigation and contingency resources	Clear definition of the objectives of the interview. Questionnaires employed in the interview. Careful selection of interviewees
Preliminary Hazard Analysis (PHA)	In a PHA, hazards and events that can cause damage to an activity, system or plant are inductively identified and classified	It is usually performed in the initial phases of the project, when there is few information on the system or on the operational procedures. It is usually employed as a previous assessment of detailed studies, or when circumstances do not allow application of detailed techniques, or for providing information for specification of systems	Information on the system to be analyzed. Relevant details on the project/design of the system to be analyzed
Hazard and Operability Study (HAZOP)	HAZOP is employed for performing the survey of risks and, when possible, proposing solutions for their treatment. This technique is based on questioning how the objectives of the system can be hampered, and on the causes and consequences of it.	Can be applied for identifying project deviations (relatively to the initial intentions), and deficiencies of components and human actions. Usually applied in the detailed design phasis, when there is a process diagram and when alterations are still possible. When applied during the operation, the suggested alterations use to be more costly.	Updated information on the system, process or procedure to be revised. Specifications of the expected performance of the system, process or procedure
Structured "What-if" technique (SWIFT)	It is considered to be a simplification of HAZOP, wherein a group of professionals is stimulated by means of questions on probable deviations and risks	Can be widely applied (as study of systems, components, procedures and organizations). Usually applied for examining effects of changes and how risks are altered or created	Group of specialists and updated information on the system to be studied
Layers of protection analysis (LOPA)	It focus basically on the assessment of prevention of causes identified in pre-selected cause/consequence pairs, that is, on the evaluation of how such prevention can reduce risk to acceptable levels – such technique is called semi-quantitative when the process involves some calculation.	Can be applied to assess protecting layers between a hazard and its probable consequences. It is usually employed for strengthening the specifications of protecting layers, or of integrity levels required from the systems.	Information on risks, that is, on hazards, causes and consequences. Information on mitigation resources.
***Human reliability analysis* (HRA)**	It has as focus the study of the human error and its impacts on the development of systems.	Commonly employed in identification of potential human errors and their causes, and in the study of means for reducing chances of error. In the design stage, it can be employed, for instance, for defining human actions to be taken in case of anomalous behavior of systems.	Description of tasks to be performed by the human element. Expertise in human errors.
Bow tie analysis	A diagrammatic way of describing and assessing the paths of risk, from its causes to its consequences – the resulting graphic can be understood as the junction of a simplified fault tree, resulting from the application of the fault tree analysis technique (FTA) and of a simplified event tree, resulting from the application of the event tree analysis (ETA) technique	Usually applied in identification, study and assessment of barriers between the causes of an accident and its consequences. In general, it is applied when the full execution of FTA and ETA is unfeasible, or when the focus is on ensuring the existence of a barrier for each fault triggering event.	Understanding of information on causes and consequences of a risk, and of barriers and controls that can prevent, mitigate or stimulate it.

Qualitative analysis techniques do not require absolute values for the analyzed variables (for instance, frequency of a hazardous event, severity of a consequence), that is, the quantitative evaluation of each variable. The use of qualitative variables requires also qualitative criteria, with adoption of different categories for separation and grouping of variables, and qualitative definitions establishing a scale for each category. Thus, during the analysis, qualitative decisions are made based on field experience. It is therefore a subjective approach, which allows a high degree of generalization, less restrictive than the quantitative analysis. Therefore, besides expertise and competence of the analyst conducing the risk analysis, experience of the involved group is one of the most important aspects for applying qualitative analysis techniques (see column Examples of required resources in Table 8.1).

Considering the complexity and dimensions of the operations to be performed within a port, as well as the available resources available during port planning (as specialists, available time) and the expected results, it is generally suggested to commence the risk analysis employing the PHA method as qualitative analysis technique. Taking this into account, the next topic concisely addresses general aspects of such technique, and the following one presents the steps of the analysis, considering its utilization.

8.1.1.1. Preliminary hazard analysis (PHA)

PHA has its origin in the military area (Department of Defense, 2000), and is widely recommended for risk qualitative studies in maritime operations (IMO, 2015 and Petrobras, 2015). In a general way, PHA focuses on hazardous materials and areas of the installations. It is a precursory study of hazard evaluation. The analysis commences with a formulation of a list of hazards and hazardous situations, considering the various characteristics of the system being studied. As hazardous situations are identified, also potential causes, effects and feasible corrective and preventive measures are listed. In this process, one or more analysts evaluate the significance of the hazards, and can assign severity categories to different situations. Thus, hazards can be ranked, allowing to prioritize actions for improving safety (emerging from the analysis) with a larger positive impact – see section 8.1.1.2. for a further detailed example of the analysis process. Subsequently, situations for which the utilization of PHA is recommended, expected results from such technique and required resources are addressed.

8.1.1.1.1. Recommendation of use

PHA is usually recommended in preliminary development stages of the system when, in principle, experience provides few or no insight at all on potential safety problems, and when there is few detailed information on the project or on operational procedures. However, when it is necessary to rank hazards and when circumstances do not allow the use of more extensive techniques, PHA can also be suitably applied to the analysis of large enterprises in operation. Besides that, PHA is recommended when it is necessary to select between alternatives of projects..

8.1.1.1.2. Expected results

PHA results in description of hazards related to a system and provides a qualitative (or semi-quantitative) ranking of hazardous situations. These data can be employed, for instance, to priorize actions for reducing or eliminating probabilities of exposure (for instance, of operators and the environment) to hazard.

8.1.1.1.3. Required resources

Use of PHA requires that analysts are given access to the installation design criteria, to specifications of equipment and material and, occasionally, other information sources. PHA can be performed by one or more professionals with knowledge on the system. Less experienced analysts can also perform PHA, in which case, however, the study cannot be exhaustive or detailed, since this technique requires many judgments from the involved professionals. In a general sense, considering the time required for preparing, performing and documenting, PHA can be completed in some weeks, even for more complex systems. (CCPS, 2008).

8.1.1.2. PHA steps

Once the analysis scope is defined, PHA will consist of the following steps (Hammer, 1972; Greenberg and Cramer, 1991; Stephenson, 1991): a) preparation for analysis; b) execution of the analysis and c) documentation of the results.

8.1.1.2.1. Preparation for analysis

In this step, PHA requires that the analysis staff gather all information available on the system, as well as any relevant information – of similar systems, or different systems that utilize the same or similar equipment – and get acquainted with it. The analysis staff must search for experiences from any available source, including hazard studies regarding similar systems, experiences related to similar systems or operations and checklists with relevant questions to the system or specific operation.

For the effectiveness of this step, it must be provided a conceptual description of the system, specifying the design basic parameters, the reactions and chemical products involved, as well as the main kinds of equipment (as pressure vessels, heat exchangers). Operational objectives and basic operational requirements can also help defining or identifying the hazardous events and the operational environment.

8.1.1.2.2. Analysis execution

The main objective of PHA is to identify hazards and accidental circumstances that may result in unwanted consequences. Also, PHA helps identifying project criteria or alternatives that may contribute to eliminate hazard, reduce chances of exposure to identified hazards and/or limit the consequences of probable accidents – depending on the experience of the staff responsible for such judgment. To achieve this, the involved staff must consider:

- Hazardous equipment and materials (fuels, highly reactive chemicals, toxic substances, high pressure systems, fuel storage systems);
- Interfaces between the equipment of the system and safety-related material (interaction between materials, ignition and fire propagation, protection systems;
- Environmental conditions that may influence equipment and materials of the system (extreme environmental conditions, vibrations, flooding, extremely high temperatures, electric discharge, humidity)
- Operation, test, maintenance and emergency procedures (focused on the importance of human error, operations to be performed by the operator, equipment accessibility, layout, staff safety protection);
- Support equipment (storage, testing equipment, training, utilities);
- Safety-related material (mitigation systems, redundancies, fire suppression, personal protective equipment).

Analysts identify the hazards for each part of the system and assess probable causes and effects of potential incidents involving such hazards. Usually, analysts do not seek to develop an exhaustive list of causes, but in a sufficient number to judge the credibility of the incident – the detailed analysis is left to posterior stages of the risk analysis, probably by means of quantitative analysis, as per suggestion outlined in Figure 8.1.

Thus, the staff assesses the effects of each incident – such effects must represent impacts of the worst case associated to the potential accident – and classify each incidental situation according to categories of frequency and consequence that are combined to indicate the hazard categories. Organizations employing PHA must define the categories so that the analysis group can judge properly the hazards. It is suggested that such hazard categories be defined according to their frequencies and to consequences associated to hazardous situations – see section 8.2.3. for suggestions as to port planning.

Finally, the staff lists feasible alternatives for correction and mitigation of the hazard – again, it is emphasized that such task is not based on the full development of incidental scenarios or on a detailed risk assessment of the scenarios, but aims at grounding basic strategies of hazard control to be implemented.

8.1.1.2.3. Documentation of results

Results of PHA are conveniently recorded in a table presenting identified hazards (or hazardous situations), their causes, consequences and potentials, hazard categories and any proposed corrective or mitigation action. Table 8.2. presents the format proposed by norm MIL-STD-882 (Department of Defense, 2000).

Table 8.2. Typical format of APP table

AREA: CONTROL NUMBER:		MEETING HELD ON: STAFF MEMBERS:		
Hazard	**Cause**	**Effects**	**Hazard category**	**Mitigation /contingency actions suggested**

Table 8.2. can be modified, for instance, to record responsibilities for monitoring and executing important items, or for reflecting the current status of implementation of suggested corrective actions (for example, in port planning documents). Information to be included in each box of Table 8.2 are:

- Hazards: name and a brief description of the hazardous event that ensures its clear and unequivocal identification;
- Cause: description of means that can lead to concretion of the hazardous event (that is, an accident) and occurrence frequency of such event;
- Effects: description of the undesirable consequences of the hazardous event and classification of damages to property, persons and to the environment;
- Hazard classification: results from combination of frequency and consequence categories. Hence, it serves as basis for evaluation of risk tolerability;
- Mitigating actions: listing of actions that can be taken for reducing the frequency of occurrence associated to the hazardous event;
- Contingency actions: listing of actions that can be taken for reducing damages caused by the accident associated to the hazardous event.

Once concluded, a PHA table becomes a support tool for decision making, with risk control and safeguard measures. Moreover, the hazardous events listed can be ranked according to their risk level, and the less tolerable ones can be prioritized in following stages of the risk management analysis. It is suggested that causes be categorized according to their frequency, to effects according to their severity and to risks, with the aid of a risk matrix – see section 8.2.3 which contains an example for the case or port planning.

8.1.2. Quantitative risk analysis

Quantitative analysis involves use of numerical data and brings also quantitative results. In a general way, data employed in such analysis originate from three different sources (employed individually or in combination): a) Historical data: when past occurrences are employed to extrapolate probabilities of future occurrences; b) Predictive techniques: when the system logic is studied, and generic data basis are employed to build probabilistic models, and c) Specialists' opinion:when a group of specialists is consulted regarding the expected behavior of the system.

Table 8.3. shows a sample of the main quantitative analysis techniques available, that can be applied to different phases of the risk assessment process – as shown in Figure 8.1. More exhaustive descriptions can be found in norm NBR ISO 31010:2012 (ABNT, 2012).

It is important to emphasize that the quality of the results of quantitative analysis depend on the precision and validity of the data employed. Hence, in a general way, it is import that the results of such analysis are not considered as exact values, but as estimated ones, that may vary depending on uncertainties about input data and the quality of the models developed during the analysis process – the records of such uncertainties must compose the documents of analysis.

Table 8.3 – Risk quantitative assessment techniques

Technique	Description	Utilization	Required resources
Human reliability analysis (HRA)	Focuses on studying human errors and their impacts on the performance of systems. For such purpose, generally HRA techniques as THERP (Technique for Human Error Rate Prediction) are employed.	Besides the points shown in Table 8.1, HRA addresses the quantification of human performance for helping HEP calculation, employed in quantitative risk procedures	Description of tasks to be performed, expertise in human errors and in their quantification.
Fault tree analysis (FTA)	Seeks at showing probable paths that, starting from the combination of basic events, result in an unwanted event (the top event). Such paths are graphically shown in fault trees.	It can be used in the design phase for identifying potential causes of fault, or to choose between different options of project (to reduce or eliminate chances of such faults). In the operational stage, it can be employed to identify the most impacting faults that could lead to the top event	Probabilities of failure of subsystems and components related to basic events.
Event tree analysis (ETA)	Seeks at showing probable scenarios that, originating from a starting event, may lead to different status of the system (wanted or unwanted). Such scenarios are shown graphically in event trees – a tool for distribution of the starting event between probable scenarios.	It can be used in any phase of a system's lifetime: for surveying potential scenarios and sequences, given a starting event and considering the impact of barriers designed for mitigating results of unwanted results. Quantitative results can be employed to assess the adequation of foreseen barriers.	List of triggering events, information regarding foreseen barriers (as probability of failure). Understanding of the triggering event evolution process
Failure mode and effect analysis (FMEA)	Identifies failure modes and mechanisms and their effects. FMEA can be followed by a criticality analysis, defining the significance of each failure mode (in such cases, it is called FMECA)	Can be applied in project, manufacture or operation of systems and components or in processes and procedures for identifying potential faults (for instance, selection of project alternatives, assurance that all kinds of impacting failure were considered in the project, maintenance planning) and in providing quantitative data for other techniques (as FTA).	Information on the system that allows understanding of failure mechanisms (as a function of each component in the system, failure history)
Markov models	Employed for representing complex systems, that present various probable status, when a future status depends only on the current status	With such models one can, for instance, to estimate the probability of the system being in a certain status, or to estimate its availability. Another example of application is estimation of the required quantity of spare parts of a critical component of the system	List of the different status of the system. Description of the process that takes the system from one status to another, including the transition rate
Monte-Carlo analysis	Employed for quantifying probabilities of the status of the system (failure, accident), starting from a large number of simulations and considering the status of the components as random variables.	In a general way, it is indicated for propagation of uncertainty in conventional analytical models (fault trees) or when analytical models do not allow calculations considering field observations.	Model to be quantified, information on modelled variables (their distribution of probabilities)
Bayesian analysis	It is based on the subjective interpretation of the probability. Usually, Bayesian Networks are employed for modeling the systems. Such networks are graphic representations of variables and their probabilistic dependencies.	Useful in any problem where it is necessary to work with complex relationships between parts of the system (for instance, for representing interdependencies), or when it is necessary to update probabilistic data according to evidences	Variables to be modelled, dependence relationships between variables, a priori probabilities (status of the system)

8.2. Information for Risk Analysis in Port Planning

This section presents information for performing risk analysis in port planning. Some points considered as essential for the good quality of such analysis are discussed, mentioning the good practices of the sector.

Such information was organized based on the risk analysis process suggested in Figure 8.1. – relevant information detailed in other chapters was only mentioned in this section. They were discussed in this order: a) Identification of hazards and main hazardous situations in which a vessel navigating a port approach may be involved; b) Identification of vulnerable areas; c) Classification and selection of events that are significant to the risk; d) Attainment and treatment of statistic data for study of hazardous events, and e) Probable measures for treatment of risk.

8.2.1. Hazard identification

Different kinds of hazards can be considered in port planning, all of them typically related to the kind of industry that operate at the terminals, to local geographic characteristics or to the kind of equipment usually employed in the port, either fixed or movable. As an example, we can list local characteristic areas subject to extratropical cyclones or tidal waves, or products to be shipped or stored at terminals – usually, cargoes considered as hazardous are those potentially: a) Toxic; b) Explosive; c) Pollutant; d) Combustible, or e) Corrosive. Ships trading routes, pipes and other means of transfer of such products, their stowage and storage places, as well as their time of stay in the installations must be identified for inclusion in the risk analysis that is part of the port planning.

Specifically as to navigation in port, a ship in movement, even in ballast conditions, represents a hazard for the port infrastructure, its terminals and ships at berths or in transit. On the other hand, such equipment also represents a hazard for the ship. Therefore, a ship navigating in port can lead to hazards to be considered in the risk analysis. In this sense, berths and ships at berths, approach channels, maneuvering basins, anchorages, as well as the surroundings of such areas must be characterized, so allowing the evaluation of their involvement in cases of route deviation or disrespect for planned port limits (for instance, draught), as to losses caused to operators, to the population, to the image of involved organizations, to property or to the environment.

Hazardous events related to navigation are usually caused by abnormal events or deviations from the standard control of a ship, leading to abnormal operational conditions. Such incidents can be:

- Failures on ship's equipment (propulsion, rudder, anchoring and mooring gear);
- Failures on assistance/support equipment (tugboats, buoyage, mooring bollards);
- Unintentional human failures (crewmembers, linesmen, pilots, etc.);
- Loss of ship control due to interaction with the bottom, with structures or other vessels;
- Loss of ship control due to variations in weather and sea conditions;
- Unintentional actions of third parties not involved in the navigation.

The above-mentioned events are potential accident triggers, that is, they can expose a ship to different hazards, and consequently lead to materialization of an accident scenario. The main kinds of accident[3] that may occur in access waterways are: a) Grounding; b) Collision (for example, touching the bottom; c) Collision between two vessels, and d) Sinking (Kristiansen, 2005).

8.2.2. Identification of vulnerable areas

The consequences of the accidents discussed in the previous paragraphs may be more or less severe, depending on the vulnerability of the equipment and material involved. Therefore, a necessary step of risk analysis in port planning is the identification of vulnerable areas, having as reference, for instance, sensible maneuvering points (with smaller margins for errors) or places where hazardous products are stored.

Identification of vulnerable areas must take into account probable losses caused by consequences of potential accidents in terms of lives, image deterioration, loss of property or negative environmental impact. Starting from potential accident scenarios and from classification of vulnerable areas as to their probable impacts or potential losses, it will be possible to classify the risk to which the vulnerable areas are exposed, and in sequence, compare such scenarios with risk acceptance criteria, as exemplified in item 8.2.3.

8.2.3. Classification and selection of significant events for risk

A way to save money and speed up delivery of results is to carry preliminary evaluations and discard, as soon as possible, low impact risk contributors, so enabling the concentration of efforts in detailing factors that most significantly contribute to risk.

To achieve this, it is necessary to classify potential scenarios according to their expected frequency and severity, i.e. according to the expected risk. Starting from such information, it will be possible to compare the results with a risk acceptance criterion for selecting potential accident scenarios to be detailed (because they represent significant contribution to the risk). A qualitative risk matrix can be employed for such assessment.

The qualitative risk matrix can be created from the definition of frequency classes and consequences for potential hazardous events, and from the criteria of risk acceptance. For example, adopting the classes for frequency of occurrence of an event proposed by the International Maritime Organization (IMO, 2015) and by Petróleo Brasileiro S.A. (Petrobras, 2015), the following classes of frequency can be defined:

- Extremely remote: when the occurrence of an event is probable, but there are no records of such occurrence in the port operation history;
- Remote: when the occurrence of an event is not expected in the port that is being planned, but there is a record of it in the port operation story;
- Low probability events: when the event will probably occur once along the lifespan of a group of port plants similar to the one being studied – for instance, that employ similar technology and management systems;

[3] In this text, it is considered the definition presented in NORMAM-09/DPC (Diretoria de Portos e Costas – DPC/Brazilian Navy Directorate of Ports and Coasts)

- Probable: when the event will probably occur once along the lifespan of the port plant being studied;
- Frequent: when the event will probably occur multiple times during the lifespan of the port plant being studied.

Classes of severity consequences must be defined considering the different risk dimensions to be taken into account in the analysis. Usually, the considered dimensions are defined based on kinds of consequences. Consequences most commonly addressed are:

- Safety: consequences on people involved in activities in the installations or on personnel who could be affected outside the facilities;
- Reputation: consequences concerning to perception of third parties as to the public image of those involved in the operation, mainly related do major events with larger impact on the community;
- Properties: consequences on property and activities within the facilities or property and activities that could be affected outside the facilities;
- Environment: consequences concerning alterations to the environment as a consequence of nautical operations (as pollution of local ecosystems).

Taking again the examples proposed by IMO (2015) and Petrobras (2015) and also considering each risk dimension, the following classes of severity can be assigned to consequences of a hazardous event: a) Negligible; b) Marginal; c) Medium; d) Critical, and e) Catastrophic. Table 8.4. contains a proposal for description of each class, based on the risk dimensions presented in the previous paragraphs.

The confrontation of the acceptance criteria for each risk dimension with the possible combinations of frequency and severity allows the development of the qualitative risk matrix. Based on the risk judgment (between not tolerable (NT), medium (M) or tolerable (T)), decisions can be made on how to treat the event that is being assessed. For example:

- Not tolerable (NT): it is necessary to carry out research on corrective measures for reduction of the risk and classification of the hazardous event as acceptable – in a supplementary analysis and considering such corrective measures;
- Medium (M): it is necessary to make a search on corrective measures for reducing the risk to the ALARP (as low as reasonably possible) level – an event initially classified in such risk category will demand an assessment of possible actions to, if technically and economically possible and feasible, have its risk level reduced;
- Tolerable (T): no need for developing corrective measures.

Table 8.4. Severity classes for possible consequences of a hazardous event

Risk	Classes				
Dimension	**Negligible**	**Marginal**	**Medium**	**Critical**	**Catastrophic**
Safety	No injuries, or at maximum first aid cases	Minor injuries	Inner area* severe injuries or outer area* minor injuries	Inner area* fatality or outer area* severe injuries	Inner area* multiple fatalities or outer area* fatality
Image	Insignificant repercussion	Local repercussion	Regional repercussion	Nationwide repercussion	International repercussion
Property	Light damages to equipment (without affecting the operational normality)	Light damages to vessels, systems or port facilities (port operations are resumed in few hours)	Moderate damages to vessels, systems or port facilities (port operations are resumed within one day at maximum)	Severe damages to vessels, systems and port facilities (port operations are resumed within some days)	Catastrophic damages involving loss of vessels or vital port facilities (port operations resumed within several days)
The environment	No environmental damages	Light environmental damages: controllable in short term or with negligible effect	Moderate environmental damages: Controllable in medium time, with restrict effects to the area close to the accident (under control of the risk owner)	Severe environmental damage: a) controllable in the long term, with effects restricted to the area near the accident, or b) controllable in the middle term, with effects beyond the area near the accident (under control of the risk owner)	Catastrophic environmental damage: a) uncontrollable, corrective measures only to mitigate impacts, or b) uncontrollable in the long term, and with effects beyond the area near the accident (under control of the risk owner)
* "Inner area" and "outer area" refer to the port area under analysis and its surrounding area, respectively.					

Starting from the examples presented until now, it is possible to build the qualitative risk matrix shown in Table 8.5. to be applied to each hazardous event, considering individually each dimension of risk.

By applying the risk matrix, it is possible to select the events that contribute significantly to the risk – for a more accurate analysis (building of probabilistic models), or for making proposals of risk improvement (adoption of risk control measures, see item 8.2.5.). Another advantage of this approach is the identification of events for which supplementary studies are required due to uncertainties found (probable incapability of defining frequency classes and consequences of such event).

Table 8.5. Qualitative risk matrix

Consequence severity class	Frequency of occurrence				
	Extremely remote	Remote	Low probability	Probable	Frequent
Catastrophic	M	M	NT	NT	NT
Critical	T	M	M	NT	NT
Medium	T	T	M	M	NT
Marginal	T	T	T	M	M
Negligible	T	T	T	T	M

8.2.4. Statistic data on causes and consequences of hazardous events

Obtaining statistic data for a detailed evaluation of frequencies and consequences of events that are part of probable accident scenarios is essential in risk assessment, especially in quantitative analysis.

Such data are usually obtained either from databanks containing generic data on equipment failures, or by building probabilistic models (as fault trees, see Table 8.3.), or by means of simulations (especially for studying probable consequences of hazardous events).

Besides surveying and researching generic databases, organizing historical information and classifying the causes of navigation accidents presented, for instance, in almanacs edited and published digitally by the Maritime Tribunal[4], helps obtaining probabilistic data on accidents involving maritime and waterborne transport and knowledge about their most recurring causes.

8.2.5. Risk assessment and possible mitigating and contingency measures

In case the risk of any of the analyzed events exceeds the stablished acceptance criteria, then control measures must be proposed. After the proposal of such measures, a new risk assessment must be performed as if such measures had been put into practice, employing methodologies and tools discussed in previous sections. This way, it will be possible to evaluate the impact of such measures in the composition of the operation risks, in order to determine whether the acceptance criteria can be met by means of the adoption of the proposed actions.

Further to that, in port planning, if different control measures are acceptable according to the risk assessment, it is recommended the selection of the most adequate solution – that can be a single action or a combination of actions – according to the following criteria:

[4] Specialized responsible body for launching and/or conducting administrative inquiries regarding navigation facts and accidents and investigations on safety of maritime accidents and incidents, according to the specific legislation in force (Anjos & Gomes, 1992).

- Cost/benefit ratio of the control measure (referring to the reduction of risk found in the supplementary risk analysis);
- Operational repercussions: as, for instance, less increase of operational complexity;
- Global risk: for all the area being assessed.

Possible control measures that can be considered or adopted in nautical access designs are: a) alterations to the geometry of the nautical access; b) establishing environmental operational limits; c) establishment of operational rules; d) adopting navigational aids; e) pilotage services; and f) introduction of specific training programs. The following items discuss such possible measures in a more detailed manner. Together with those measures there are suggestions based on PIANC WG30 (PIANC, 1997) which, besides being superseded by PIANC Report Number 121, 2014 (PIANC, 2014), presents measures that serve as basis for design of nautical accesses in different parts of the world (U. S. Army Corps of Engineers, 2012), being largely accepted by designers and engineers (PIANC, 2014). It must be emphasized, however, that there is no intention to exhaust the subject or to prescribe the adoption of control risk actions, but only to present some suggestions of actions to be discussed in risk assessment sessions (see Figure 8.1.).

At this point, it is interesting to emphasize that the control measures suggested can create new hazardous events. Thus, an analysis taking into account such control measures (in order to evaluate their efficiency in cases of risks classified as not acceptable) must be performed utilizing the same methodology that led to their proposal – which means to update the risk analysis. On the other hand, when the fairways are effectively utilized, new risks may be identified, or the implemented control measures may not have the expected efficiency. Reporting risk situations and mainly incidents or near misses to stakeholders and to risk owners is important, and must be encouraged. It is recommended to avoid seeking for responsibilities in such reports; instead, they must investigate causes, potential consequences and control measures to be adopted and suggested, in order to provide feedback to the risk management process.

8.2.5.1. Alterations to channel geometry (see PIANC, 1997 section 7.1.1.)

Risks can be effectively reduced by means of changes in the fairway dimensions. Once the need for such control measure is detected, it is recommended that a cost/benefit analysis be performed. Corrections during the Concept Design are particularly interesting, as the investment of time and resources (in the part to be altered) is less significant than it would be in the Detailed Design phase. Often, however, the general impact of such measure can only be indicated in the Detailed Design phase. In this case, the general impact must be considered, as measures based on modifications in the dimensions alter completely the risk assessment of the project, thus affecting simultaneously various contributors to the assessed risks.

8.2.5.2. Establishment of limiting operational environmental conditions (see PIANC, 1977, section 7.2.2)

Maritime and environmental conditions for different aspects of the maneuver in a port or terminal have direct impact on the project and on the operation of the channel and other navigable areas. The limits for such conditions can be different for different kinds of ships, and for the specific conditions of each project. The establishment of limits for such conditions has significant consequences on downtime periods and profitability of the port or terminal. Therefore, if the specified limits cannot be confirmed by means of local experience (for instance, in the case of a new design), then their adequacy for the specific case must be carefully assessed by means of simulations involving specialists in navigation in restricted areas.

Some reference values for such limits – that can be Applied *a priori* in the risk assessment process (ABNT, 2012) – are listed in Annex 1. For adopting these reference limit conditions, it is recommended the observation of the following general conditions:

- Applied to the design: it is conservatively assumed that the different environmental limits act simultaneously. However, if it can be proven that such situation is unrealistic, combinations of less extreme values could be used, taking each of the environmental variables at its maximum (that is, the worst case), with the other variables below their respective maxima. These combinations will lead to different design conditions;
- Applied to the operation: maneuvers are suspended as soon as one of the environmental conditions reaches or exceeds its limits, irrespective of the remaining variables having reached their limits or not. The possibility of operating under conditions where only one of the limits is exceeded is limited to the cases in which a detailed study has been carried out for the specific site (and that has indicated such possibility).

8.2.5.3. Establishment of operational rules (see PIANC, 1977, section 7.2.3)

Operational rules, defined in the Detailed Design, are essential to port operations. They summarize the risk control measures considered necessary to the safe operation of the fairway. Operational rules must refer to the following:

- Ship's characteristics, linear dimensions and size, according to each design ship being studied;
- Limiting environmental conditions for safe operation;
- Traffic rules in the fairways (as maximum and minimum speeds, one-way traffic), need for TSS (traffic separation scheme) or VTS (vessel traffic services);
- Tugboat assistance: type, quantity and capacity;
- Pilotage services;
- Contingency plans in emergency situations;
- Other risk control measures as deemed necessary.

Operational rules are defined considering the results of risk assessments, supported in some cases by studies involving simulation of traffic flow. Besides items of operational rules, such studies must include TSS e VTS, when required or necessary, as described in the next topics (8.2.5.3.1. and 8.2.5.3.2., respectively).

At this stage, it is interesting to emphasize that operational rules can be employed not only for increasing safety, but also for reducing fairway costs. For instance, restricting ships movements to high tide in certain situations can result in savings on maintenance and capital dredging. This advantage can be pondered against disadvantages of delays in ships movements until operational conditions are satisfactory, as there is an economic balance between the desired service level and the dimension of fairways. Therefore, the feasibility of imposition of sailing windows must be assessed in economic terms and, if it cannot be acceptable, alterations to the project must be proposed.

8.2.5.3.1. Traffic Separation Scheme (TSS) (see PIANC, 1977, section 7.2.5)

TSS alleviates risks by segregating traffic into lanes where all ships move in the same direction, with a traffic separation zone between the lanes. There may also be inner traffic zones for small crafts to avoid the use of the main traffic lanes. Crossing the TSS is done under a strict set of rules, and often at known crossing points.

8.2.5.3.2. Vessel traffic services (VTS) (see PIANC, 1997 section 7.2.1.)

VTS is a service implemented by the competent authority[5] to improve traffic safety and efficiency, as well as to protect the environment. The system must be capable of interacting with the traffic and to respond to ongoing traffic situations in its area. VTS consist of shore-based traffic management systems of port or coastal areas. The kind of services provided range from provision of information to crafts to extensive traffic management within a port or waterway – in the latter case, it is called vessel traffic management information system (VTMS). Essential elements of a VTS are a) Radar; b) Automatic identification system (AIS); c) Communication (VHF); d) Closed circuit TV (CCTV); e) Meteorological and environmental sensors, and f) a data management system.

Further to information services, VTS can also encompass other services, as assistance to navigation, traffic organization or both. Information services ensure that essential information is always available in time for decision making on board regarding navigation, that is aided and monitored by the navigation assistance systems. Traffic organization systems avoid hazardous situations to develop in the maritime traffic, and provide conditions for a safe and efficient traffic of crafts within the area covered by VTS.

Implications of traffic management – from the operational and channel design perspective – refer firstly to the kind of service available to assist the navigator. For instance, a narrow approach channel to a busy port may require a traffic organization service, while a relatively calm port may need only an information system. Anyway, decision making remains on board – as it is incumbent upon the navigator to be acquainted with the kind of services offered by the VTS in a specific area.

[5] In Brazil, the competent VTS authority is the Maritime Authority

A VTS is particularly appropriate in an area that may include the following situations: a) High traffic density; b) Narrow channels or port configurations, bridges or similar areas where vessels find restrictions to navigation; c) Existing or foreseeable changes in the traffic pattern due to works on port or offshore terminals, or resulting from offshore exploration in the area; d) Traffic of hazardous cargoes; e) Conflicting and complex navigation patterns; f) Difficult hydrographical, hydrological and meteorological elements; g) Shifting shoals and other local hazards; h) Environmental considerations; i) Interference by vessel traffic with other marine-based activities; j) A record of maritime accidents; k) Existing of planned traffic services in adjacent waters and the need for cooperation between neighbouring states, if appropriate.

8.2.5.4. Establishment of Aids to Navigation (see PIANC 121, 2014 section 4.6.)

Navigation itself may be understood as monitoring one's position geographically within a constrained waterway. There are several navigation methods widely employed in maritime navigation:

- Visual navigation, which utilizes optical observations;
- Electronic navigation, which utilizes positioning signals from satellites and other electronic systems;
- Radar navigation, which utilizes radar observations – this is a specific kind of electronic navigation.

Visual navigation is the primordial method. Aids to navigation facilitate the application of such method, and are necessary in the absence of visual natural leads, or if traffic density indicates its application. Next topics discuss positioning systems and aid to navigation apparatus in the context of planning and designing approach channels.[7]

8.2.5.4.1. Channel markings (buoyage) (see PIANC 121, 2014 section 4.6.1.)

Channel markings, also called buoyage, are prescribed for both visual and radar navigation, and may be located either along the sideline of the channel (as buoys) or the channel center line (for instance, leading lights). The properties of channel markings may be summarized as follows:

- Leading lines along the center line of the channel act as a very powerful tool for lateral positioning, but poor for longitudinal positioning;
- Leading lines crossing the channel are accurate tools for longitudinal positioning;
- Single markers are usually employed for longitudinal positioning, but may be effective for lateral positioning when used in wide, long channels;
- Paired markers act for both longitudinal and lateral positioning. Alternatively, center line markers may be used;
- A single marker on a curve turning point may act as position reference around the turn;
- Single markers may be used for warning purposes. For instance, warning about a wreck or a rock.

[6] The guidelines for designing aids to navigation result from international agreements. Thus, the recommendations presented in this text do not prevail on specific recommendations from the technical bodies in charge with the/responding for current regulations.

[7] Shoals may be sandbanks or rocks near the water surface, often covered and hidden, at small depths, that constitute hazards to navigation.

By combining kinds of markers, one may design a safe to navigate channel. The required Aids to Navigation are related to channel properties, which include width and curvature, weather and traffic conditions. Therefore, a curvy channel requires more complex markings. There is a very strong connection between channel dimensions, alignment and markings.

Reference points must be included, for helping lateral and longitudinal positioning and turning in all curves. For such purpose, vessel sizes, speed and bridge visibility must be considered. A minimum requirement of channel marking is that at least one marker should be visible on either side of the channel (by eye or radar). With this rule and knowledge of visibility conditions in the area of interest, one can calculate maximum distances between markers, that is, the maximum spacing between markers must be less than the minimum visibility required. On the other hand, utilization of electronic navigation instruments must also be considered when determining maximum and minimum distances between navigation markers.

Theoretically, the more channel markings provided, the easier it is to navigate. However, one must appreciate that an excessive number of markings may cause confusion. The ideal solution for channel marking according to channel dimensions is usually found by simulations in the Detailed Design phase. As ships use a variety of aids to navigation in addition to channel markings, the designer should pay special attention to possible channel crossings, to avoid creating confusing navigational situations with too many marks.

Another possible way to mark a channel is to position a marker in all vertices of sidelines ('corners'). If straight parts are longer than the maximum spacing allowed, there is always an option to place additional markers along the straight sideline. This is a common marking technique in curved channels.

An alternative to both straight and curved channels is the use of center line buoys, particularly in two-way channels. In this case, fewer buoys are needed, which avoids the factor of paired buoys creating additional channel obstructions and restrictions to small crafts. In general, however, paired markings are more effective in straight sections of a channel, comparing to single markers positioned on sideline vertices. As previously mentioned, paired markers are effective for both lateral and longitudinal positioning.

Summarizing, each channel is an individual case and so it should be studied. There is no universal optimal solution, but a variety of marking solutions and techniques. It is, therefore, recommended that proposed marking systems (or at least their sensible points) be always studied in simulation. Designers should necessarily consult an Aids to Navigation expert while planning the aids to navigation equipment of a channel. The final configuration of the marking project has to be approved by the safety of navigation competent authority.

8.2.5.4.2. On-board navigation systems (see PIANC 121, 2014, section 4.6.2.)

The basic objectives of on-board navigation systems are to recognize and monitor both the absolute geographic position of the vessel within the area and its relative position to known fixed and moving objects – natural or man-made ones. In such respect, the next paragraphs present a brief discussion on visual, electronic and pilotage navigation.

Visual navigation (see PIANC 121, 2014, section 4.6.2.1.)

The primary form of visual navigation is manually plotting on a paper chart, using two or more compass bearings of geographical features. The use of sextants for taking vertical and horizontal angles can be considered impractical. Fixing a relative position can be facilitated through observation of various forms of leading marks, including geographical features and channel buoys. Night vision equipment and binoculars are probably the only optical aids found nowadays.

Electronic Aids to Navigation (see PIANC 121, 2014, section 4.6.2.2.)

International or national rules define equipment requirements according to the type and size of the ship. Electronical aids to navigation include: a) radar; b) electronic chart system (ECS); c) electronic chart display and information system (ECDIS); d) global navigation satellite system (GNSS), a standard-generic term for satellite navigation systems; e) differential GPS (DGPS); f) electronic navigation (e-Navigation); g) automatic identification system (AIS); h) portable pilot unit (PPU).

AIS systems and other aids to navigation are being combined, the AtoN being equipped with an AIS transmitter, so it may be seen as an AIS target on an ECDIS screen. Remote monitoring of aids to navigation is also possible with such method, enabling the verification of position and status of the aid to navigation. This remote monitoring system has the potential to promote considerable savings on channel maintenance.

Virtual aids to navigation (Virtual AtoN) is a new concept involving AIS and Aids to Navigation that, instead of using a physical aid to navigation, employs a virtual aid, represented on the ECDIS screen via AIS. This is accomplished by transmitting the virtual aid to navigation from a shore-based station to all ECDIS users. It is a quick and handy way to mark, for instance, a danger or a lost buoy, recommended only as temporary marking, as it must be considered that vessels that do not use ECDIS cannot see the virtual aid to navigation.

Navigation performed by pilot

When navigation is performed by a pilot the positioning it is done without plotting on the chart, but based on a detailed knowledge about the site. This, in one hand, ensures fast decision making, although, in the other hand, still requires the crew to keep plotting on the chart as a way of verifying the position and auditing the navigation.

8.2.5.5. Pilotage services (see PIANC, 1997, section 7.5.)

Traffic of crafts in fairways occurs under responsibility of a varied number of groups of mariners. Most of such traffic is usually assisted by pilots qualified and certified by a competent pilotage authority.[8] These professionals combine ship maneuvering abilities with local knowledge of specific conditions of each pilotage area. Besides that, they keep detailed knowledge about technical, regulatory and environmental characteristics of their specific area of operation.

The competent pilotage authority is responsible for defining areas in which navigation is compulsorily assisted by pilots. The following subsections address specific topics related to the pilot contribution.

8.2.5.5.1. Safety of navigation (see de PIANC, 1997, section 7.5.6.)

The pilots' primary aim, having regard to the limitations of the channels and the vulnerability of port installations, is to ensure optimum expedition, consistent with maximum safety of the ships navigating under their advice. By their training and experience, pilots can assess the safety of a certain activity, and render advice in simulation studies. In extreme cases, when acceptance criteria are not explicitly defined, or control measures are not available, pilots are customarily the only reliable consulting source available to the risk assessment staff. They can be the sole information source for the conclusion of the assessment.

Risk owners must pay special attention to the number of pilots qualified to perform such activities. If such number is too small, the demand for services may lead them to work under fatigue. On the other hand, an excessive number of pilots hinders them to keep their qualification and proficiency in their activity, as their knowledge and skills depend on routine repetitions of their activities (learn-by-doing). In both cases, the risk levels of fairways may increase.

8.2.5.5.2. Employment of more than one pilot (see PIANC, 1997 section 7.5.5.)

Special situations may demand simultaneous action from more than one pilot on board. Such requirement may occur as a consequence of:

- Long lasting navigations, requiring rotation by shifts to avoid that pilots work under fatigue;
- Dimensions and draughts of vessels relatively to a certain fairway, resulting in reduced safety margins and, consequently demanding additional risk control measures;
- Vessels' characteristics demanding deployment of additional pilots in strategic positions on the vessel besides the bridge or its wing to allow visualization of the fairway limits or of mooring fenders (as in vessels whose bridge wings do not reach the side line, container ships with cargo stowed excessively high on the main deck, vessels or platforms with structures or industrial plants on the main deck).

In such situations, all pilots involved must have qualification compatible with the vessel and approach fairways.

[8] In Brazil, the pilotage competent authority is the Maritime Authority.

8.2.5.5.3. Pilots variability (see PIANC, 1997, section 7.5.2.)

Although being difficult to evaluate, variation in the skills of the staff of pilots who operate in a certain fairway must be taken into account by the risk owner and, therefore, included in the risk assessment. The skills of those who are part of the operations can be affected, for instance, by experience or training level (these professionals may or may not be interested in taking part in simulations and training).

8.2.5.5.4. Pilotage exemptions (see PIANC, 1997, section 7.5.5.)

The competent pilotage authority, in compulsory pilotage areas, can evaluate if certain masters can be exempt from employing pilots, considering their transit frequency in these fairways on the same vessel, the vessel's characteristics and the fairway dimensions relatively to the vessel. In such cases, the competent authority must issue certificates attesting the capacity and knowledge of these masters. It is recommended that specific risk assessments be performed based on the number of vessels with such exemption in the fairways.

8.2.5.5.5. Pilot boarding areas (see PIANC, 1997, section 7.5.3.)

It is recommended that specific risk assessments be performed taking into account the time required for pilot boarding and landing and for master/pilot information exchange.

8.2.5.6. Specific training (see PIANC, 1977, section 7.5.6)

The traffic of vessels in a fairway is a consequence of decisions made by the mariners conducting such vessels (masters and pilots) and executed by other persons, which poses on the operation the uncertainty caused by human behavior.

Most of the accidents in fairways is caused by human errors. As a way to identify the human factors responsible for most of the accidents and ensure compliance with international and local rules and good practices, it must be considered to require additional training for the staff associated with the utilization of the fairway – especially pilots, VTS operators and tugboat masters must be included. Training is particularly relevant in case of new built channels, or when a work may alter significantly the previous conditions and design, or when a new kind of vessel is scheduled to call at the port.

Training areas may include, for instance, a) New traffic management regulations originating from risk assessments; b) Navigation and maneuvering methodologies for new types of vessels and support equipment; c) Use of tug escorting techniques; d) Implications of minimum underkeel clearance, knowledge about revised echo sounding and buoy standards, etc.; e) Emergency procedures due to failures on vessel's or tugboats' equipment, and f) Simulations with new types of vessels and new operational conditions.

REFERENCES - CHAPTER 8

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APPENDIX I - CHAPTER 8

Limiting operating environmental conditions – reference values

The limiting operating environmental conditions presented in this appendix were searched and defined for low risk conditions – to a large extent, these data are based on the contents presented in PIANC 121, 2014.

In applications where the values of environmental risk variables exceed the ones indicated in this appendix, it is recommended that detailed studies be performed for risk assessment and control. Reference values for environmental risk variables were defined according to the following port areas: a) channels; b) port accesses; c) stopping areas; d) maneuvering areas; e) anchorages; f) mooring areas and buoy systems, and g) port basins and mooring quays. Figure 8.2. shows the relative positioning between such areas in a hypothetical port.

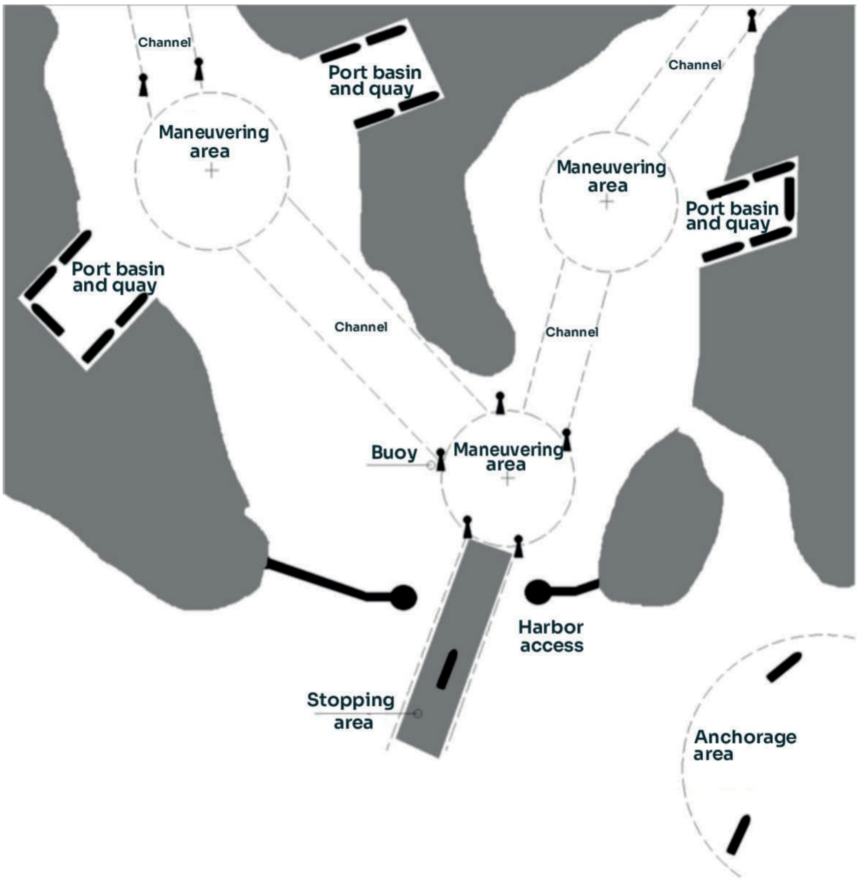

Figure 8.2. Schematic of typical positioning of parts of a port

In the following sections, the variable $V_{W,1min}$ represents wind speed at a height of 10m above the sea level, as a 1-minute average; $V_{F,1min}$ is the current speed at a depth corresponding to half the ship's draught as a 1-minute average, and e H_s is the significant wave height.

I.1. Channels (See PIANC 121, 2014, section 4.3.2.)

The limits for navigation conditions in channels are recommended to be selected in such a way that the drift angle β shown in Figure 8.3 does not exceed the values specified in Table 8.6. when the vessel is sailing at the lowest permissible speed. The reason for this is that, given the same environmental condition, higher speeds tend to result in smaller drift angles. The channel conditions differ according to their relative depth ratios h/T, where h is the depth and T is the vessel's draught. It justifies the recommendation of different values for the maximum drift angle β.

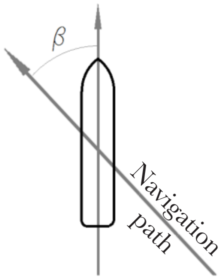

Figure 8.3. Drift angle β

Table 8.6. Drift angle β *versus* channel relative depth

Channel relative depth condition		***Maximum β (in degrees)***
***h*/*T* ≤ 1.2**	• Normal stretches • Singular points	5 10
1.2 <*h*/*T* < 1.5	• Normal stretches • Singular points	10 15
***h*/*T* ≥ 5**	• Normal stretches • Singular points	15 20

The drift angle β is calculated assuming that its sine is the sum of the sines of the drifting angles for the forces that act separately, for example:

$$\text{Sin}\beta = \text{Sin}\beta_{\text{wind}} + \text{Sin}\beta_{\text{currents}} + \text{Sin}\beta_{\text{waves}} + \text{Sin}\beta_{\text{tugs}}$$

This sum is algebraic and therefore each drift angle is considered with its pertinent plus or minus sign relative to the direction of the specific action. If there is no specific criteria for the minimum vessel speed Vs, this can be taken as the smallest one of the value specified in Table 8.7.

Table 8.7. Variation of ship's speed in navigation areas

Navigation Area	Vs	
	m/s	knots
Outer areas (by kind of lane):		
• Long (≥ 50lpp)	4-7.5	8-15
• Short (< 50lpp)	4-6	8-12
• Anchorage	1-1.5	2-3
• Maneuvering area	2-3	4-6
• Terminal area	1-1.5	2-3
Passing in access to the port area	2-4	4-8
Internal port areas:		
• Anchorage	1-1.5	2-3
• Channel	3-5	6-10
• Maneuvering areas	2-3	4-6
• Piers or approaching to berth	1-1.5	2-3

I.2. Harbor entrances (see PIANC 121, 2014, section 4.3.3.)

In the risk assessment, it is convenient not to consider in isolation the maneuverability of a vessel when accessing a port. It is also recommended to consider also the channel stretch, from its external limits to its internal limits. The following aspects are recommended to be taken into consideration:

- Approach routes are pre-set, and are not always aligned to winds, waves or currents. Therefore, it is recommended to consider those main components of transverse forces and drift angles whose values are close to the maximum ones admissible, as well as to determine environmental limits as a function of the required service level. Unless specific measures or model results are available, the following transverse or lateral environmental conditions are recommended:

  – Wind speed $V_{W,1min} \leq 15m/s$ (29 knots);
  – Current speed $V_{F,1min} \leq 1m/s$ (2 knots);
  – Wave significant height $H_s \leq 3m$.

- In small-craft ports of refuge (fishing or pleasure boats), as well as ports designed for operating under severe environmental conditions, approaching routes may allow the crafts to arrive at the harbor with their stern into the storm or at a small angle with the channel (sailing with the storm on a quarter), with 15-to-20 degree angles between the craft's heading and the wave direction. Limiting environmental conditions for such bad weather entry routes can be established by analyzing the service levels required and, if such criteria are not yet available, by means of the following operational limits:

  – Wind speed $V_{W,1min} \leq 16m/s$ (32 knots);
  – Current speed $V_{F,1min} \leq 2m/s$ (4 knots);
  – Significant wave height $H_s \leq 5m$.

I.3. Stopping areas (see PIANC 121, 2014, section 4.3.4.)

The operational criteria for stopping areas are the same as for the adjacent areas (connecting areas) of the channel. If the stopping area is not in line with the channel, the direction of the different actions on the vessel will be different from those in the channel. In this case, it is recommended that the limiting operating conditions be conservatively assumed as omnidirectional.

In some cases, the configurations of the port or maneuvering area would not allow the stopping maneuver of a ship of interest to be carried out from beginning to end in an autonomous and controlled manner. In such cases, the ship's stopping area has to be located outside the port area – so that the ship can stop before entering the port area. The ship can thus proceed and perform its final turning or approaching maneuver to the quay with assistance of tugboats. In such cases, the limiting operating environmental conditions may have to be based on the limitations of the auxiliary crafts (pilot boat, tugs), which take the ship to its mooring berth. Unless detailed model results for each area are available, limiting operating environmental conditions may be set according to the following values (such conditions are assumed to be omnidirectional):

- Wind speed $V_{W,1min} \leq 10m/s$ (20 knots);
- Current speed $V_{F,1min} \leq 1m/s$ (2 knots);
- Significant wave height $H_s \leq 2m$.

I.4. Maneuvering areas (see PIANC 121, 2014, section 4.3.5)

The operational limits come from the resulting environmental forces on the ship and the drift angle caused by such forces. In these cases, the following operational limits are recommended:

- Maneuvers without tugboat assistance

  - Wind speed $V_{W,1min} \leq 10m/s$ (20 knots);
  - Current speed $V_{F,1min} \leq 0{,}5m/s$ (1 knot);
  - Significant wave height $H_s \leq 2m/3m$ (depending on the type of maneuver).

- Maneuvers with tugboat assistance

  - Wind speed $V_{W,1min} \leq 10m/s$ (20 knots);
  - Current speed $V_{F,1min} \leq 0{,}1m/s$ (0,2 knot);
  - Significant wave height $H_s \leq 1{,}5m/2m$ (depending on the type of tugboat).

When maneuvering areas are located in zones with no geometric restrictions in one direction (for instance, some river ports), the operational limits in the longitudinal direction (for instance, river) can be higher, according to the particular conditions of the project.

I.5. Anchorage areas (see PIANC 121, 2014, section 4.3.6.)

The limiting environmental conditions recommended for operations in anchorage areas are listed in Table 8.8. They depend on the vessel, type of anchorage and scheduled operation. Wind speed is determined for general-type ships. Should they have relatively large areas of exposure to winds (as methane carriers, container ships, car carriers, oils tankers in ballast) it is recommended that the limiting operational wind speeds be 20% less than those presented in Table 8.8.

Table 8.8. Limiting environmental conditions for operations in anchorage areas

Activity		$V_{W,1min}$	$V_{F,1min}$	H_s
Approaching and berthing areas		17m/s	2m/s	2.5m
Vessel at anchorage	With one anchor ahead	24m/s	2m/s	3.5m
	With two anchors down	30m/s	2m/s	4.5m
Anchoring against ebb/flood tide with one anchor ahead and one astern	Longitudinal forces	24m/s	2m/s	3.5m
	Transverse forces	Anchorage not operative		
Loading and unloading operations		Depends on the loading/unloading equipment		

I.6. Mooring areas and buoy systems (see PIANC 121, 2014, section 4.3.7.)

The environmental conditions recommended as operational limits for mooring areas and buoy systems are presented in Table 8.9. The reference values vary as a function of the vessel's ability to freely rotate to an orientation with the minimum resistance or whether its orientation is fixed.

Table 8.9. Operational limits for mooring areas and buoy systems

Activity		**Mooring areas with free orientation**			**Mooring areas with fixed orientation[(2)]**
		Mooring to a single buoy	**Mooring to a mini single buoy[(1)]**	**Mooring to single dolphins**	
Approaching and mooring	$V_{W,1min}$	17m/s	17m/s	17m/s	10m/s
	$V_{F,1min}$	2m/s	2m/s	2m/s	0.5m/s
	H_s	2.5m	2m	2m	2m
Vessel at the anchorage	$V_{W,1min}$	30m/s	24m/s	30m/s	22m/s
	$V_{F,1min}$	2m/s	2m/s	2m/s	1m/s
	H_s	4.5m	2m	3.5m	2m

NOTE 1: Mooring at mini single buoys or small buoys usually occurs with fishing and pleasure crafts.
NOTE 2: Mooring areas with fixed orientation usually refers to buoy systems.

I.7. Basins and quays (see PIANC 121, 2014, section 4.3.8.)

The limiting operational conditions for ships navigating and maneuvering (including stopping and turning) in basins or near quays are the same as those established for such maneuvers in other port areas, irrespective of the location being a more sheltered area.

For operating at the quay, it is recommended that three conditions be specifically considered: a) ship maneuvering to berth; b) loading and unloading operations, and c) ships berthed at quays or piers. The limiting environmental conditions for these three cases will depend on other factors besides the vessel that is being maneuvered. Berthing limits depend on tugs available and on the fender system at the quay. Interruption of loading/unloading operations depends mainly on the cargo characteristics and on the handling equipment employed.

The limiting environmental operating conditions for vessels berthed at quays or piers depend on the structure limits, on the availability of towing equipment for unberthing the ship under extreme conditions and on the capability of the ship to navigate under control to other quays, anchorages or outer navigation areas. Further to that, other considerations and factors may also play an important role in some cases, as, for instance, comfort limits for passengers of a cruise vessel under the action of waves. Unless detailed results of specific models are available, the limiting environmental operating conditions for quays or piers can be set a priori according to the values listed on Table 8.10.

Table 8.10. Operating limits for quays or piers

<table>
<tr><th colspan="3">Description</th><th>VW,1min</th><th>VF,1min</th><th>Hs</th></tr>
<tr><td colspan="3">Fishing crafts
(Forces transverse to the quay)</td><td>22m/s</td><td>1.5m/s</td><td>0.6m</td></tr>
<tr><td colspan="2" rowspan="3">Oil tankers</td><td>< 30,000DWT</td><td>20m/s</td><td>0.7m/s</td><td>1m</td></tr>
<tr><td>30,000 DWT-200,000DWT</td><td>20m/s</td><td>0.7m/s</td><td>1.2m</td></tr>
<tr><td>> 200,000TPB</td><td>20m/s</td><td>0.7m/s</td><td>1.5m</td></tr>
<tr><td colspan="2" rowspan="2">Bulk carriers</td><td>Loading</td><td>22m/s</td><td>0.7m/s</td><td>1m</td></tr>
<tr><td>Unloading</td><td>22m/s</td><td>0.7m/s</td><td>0.8m</td></tr>
<tr><td colspan="2" rowspan="2">Liquefied gas carriers</td><td>< 60,000m^3</td><td>16m/s</td><td>0.5m/s</td><td>0.8m</td></tr>
<tr><td>> 60,000m^3</td><td>16m/s</td><td>0.5m/s</td><td>1m</td></tr>
<tr><td colspan="3">General cargo merchant ships, open sea fishing crafts and reefer ships</td><td>22m/s</td><td>0.7m/s</td><td>0.8m</td></tr>
<tr><td colspan="3">Container ships, Ro-Ro and ferries</td><td>22m/s</td><td>0.5m/s</td><td>0.3m</td></tr>
<tr><td colspan="3">Liners and cruise ships[1]</td><td>22m/s</td><td>0.7m/s</td><td>0.3m</td></tr>
<tr><td colspan="3">Fishing crafts</td><td>22m/s</td><td>0.7m/s</td><td>0.4m</td></tr>
<tr><td rowspan="7">Vessels at the quay</td><td rowspan="2">Oil tankers and liquefied gas carriers</td><td>Actions longitudinal[3] to the quay</td><td>30m/s</td><td>2m/s</td><td>3m</td></tr>
<tr><td>actions transverse[4] to the quay</td><td>25m/s</td><td>1m/s</td><td>2m</td></tr>
<tr><td rowspan="2">Liners and cruise[2] ships</td><td>Actions longitudinal[3] to the quay</td><td>22m/s</td><td>1.5m/s</td><td>1m</td></tr>
<tr><td>Actions transverse[4] to the quay</td><td>22m/s</td><td>0.7m/s</td><td>0.7m</td></tr>
<tr><td rowspan="2">Pleasure crafts</td><td>Actions longitudinal[3]to the quay</td><td>22m/s</td><td>1.5m/s</td><td>0.4m</td></tr>
<tr><td>Actions transverse[4] to the quay</td><td>22m/s</td><td>1.5m/s</td><td>0.4m</td></tr>
<tr><td colspan="2">Other crafts</td><td colspan="3">Limitations imposed by the design loads</td></tr>
<tr><td colspan="6">NOTE 1: Conditions regarding passengers embarking or disembarking.
NOTE 2: Conditions regarding to limits for comfort of passengers on board.
NOTE 3: Wind, current or waves taken as acting longitudinally, when their direction lies within the sector of $\pm 45^o$ relative to the longitudinal axis of the vessel.
NOTE 4: Wind, current or waves taken as acting transversally, when their direction lies within the sector of$\pm 45^o$ relative to the transverse axis of the vessel.</td></tr>
</table>

APPENDIX
Ship Simulation Methods and Techniques

Introduction

This purpose of this appendix is to address methods and possibilities of application of various ship maneuver simulation techniques, as well as to provide the reader with sufficient evidence that the described models can be considered realistic, provide appropriate examples of the real world and be used in assessment of safe navigation in a port fairway.

First it presents an overview of the methods and different techniques for developing maneuvering models to predict ship maneuverability, initially in deep waters and with no influence of environmental forces, according to criteria recommended by the International Maritime Organization (IMO) (MSC 1053; MSC Resolution 137(76)). The behavior of the ship's hull is emphasized. The ship's behavior in deep waters must be clearly understood and studied, so that it can be employed as a basis for a future extrapolation to restricted waters. A summary of deep water results is usually included on the pilot card on which the ship's main dimensions and characteristics are included.

The second part addresses a broader view of the concept of simulation models and their ability to be adopted in a port environment.

The third part of this appendix presents basic theoretical aspects for developing mathematical ship maneuvering models.

A large part of this text was elaborated having as reference the main chapters of the report Capability of mathematical ship maneuvering simulation models for approach channels and fairways in harbors, *Bulletin* 77 (PIANC, 1992) and resolutions IMO MSC 1053 and MSC 137(76).

In a port area, environmental forces resulting from restricted waters, curves, currents (often with high gradients), waves varying both in height and direction, swell, bank effects, side walls, interaction with other vessels, etc., exert a strong influence on the ship.

In the publications MSC 1053 and MSC 137(76), IMO proposes a standard procedure for assessing the maneuverability of a vessel. This is because of the fact that the maneuvering capability of a commercial ship did not deserve much attention in the design of such type of ship, which, according to IMO, was a consequence of a lack of a standard in terms of ship maneuverability. For this reason, many ships with poor maneuverability were built, whose designers relied on human ability to counterbalance the vessel's inherent defects. Thus, IMO proposes that vessels be designed to meet maneuver standards ensuring that no undue burden will be imposed on masters and pilots for compensating ship maneuverability deficiencies. It is convenient to emphasize that such standards proposed by IMO refer to maneuvers in deep waters.

Part I – Maneuverability Prediction

I.1. Predictive methods for a design ship maneuverability (IMO 1053,Chapter 3)

In order to assess the maneuverability of a ship at the design stage, the prediction should be made based on its main dimensions, shape, lines plan and other information available at that stage.

According to IMO (MSC 1053), there are many methods to predict the maneuverability of a design ship, varying the maneuver prediction accuracy and thereby the execution costs. From the practical point of view, three prediction methods are significant.

The first, which is also the simplest, employs existent experience and data, assuming that the design ship maneuverability is approximately the same as that of similar existing ships.

The second method utilizes results from tests with a scale physical model. Tests with physical models are considered to be the most reliable prediction method. However, precision requirements are not as rigorous as they are in the case of resistance to forward motion. The document IMO MSC 1053 points out that it happens due to a lack of standards for maneuvering tests with scale models. Comparisons between model and full scale tests have usually been less frequent than forward motion resistance tests. The IMO document emphasizes that such tendency strengthens in cases of hull shapes that may present problems as to handling and maneuvering characteristics.

According to the third method, the prediction of results is made by employing a mathematical model.

I.2. Maneuvering tests with the design ship

Sea trials in deep waters are mandatory. According to IMO resolution MSC 137(76), the sea trial must be performed with the ship in full load conditions, in calm environmental conditions and in deep waters. The standard set of maneuvering tests consists of turning circle, zigzag curves and crash stop.

I.3. Tests with scale physical models (IMO 1053, 3.2. and PIANC, 1992, item 1.4., p. 6, second paragraph)

Two approaches are employed for predicting a vessel's maneuvering characteristics by means of scale models.

I.3.1. Free model tests

In this case, a scale model of the vessel equipped with steering and propulsion equipment is put in a test taken, in a lake or in a facility wherein it can move freely. By means of a control input, its steering and propulsion equipment (for instance, rudder and propeller) are put into action to reproduce the test maneuvers in the ship's scale to achieve direct results for maneuvering characteristics.

The tests can be performed in two ways: (1) Conducted by a human element, either on board the ship or by means of an onboard camera and remote control from shore and (2) Employing an automatic pilot system, in which the model follows a course predetermined by a control system, which generates rudder and engine orders to the model.

It must be emphasized that, in physical models of reduced–scale length, the scale physical similarity imposes that the speed of the model be established by equal Froude numbers for the model and the ship This implies a time scale, which becomes an important factor in human behavior. The conduction of a physical model by a human element is subject to such factor. As mentioned in the IMO document, in most of the cases such time scale will be equal to 5 or more, given a length scale equal to 25 or more. The human element will have to perform his actions in a lapse of time five (or less) times inferior.

The use of physical models with automatic pilot system is not prone to that problem. However, it must be considered that it is quite costly and will not necessarily provide comprehensive information.

The advantage of physical models regarding mathematical models is that there are fewer doubts about the validity of the model, and therefore it is more useful in situations where mathematical modeling is not sufficient – or the physics of the involved problem are represented by complex and slow mathematical models as viewed from the informatics perceptive and sometimes not very reliable.

Thus, we could say that the most straightforward maneuverability assessment method is to perform representative maneuvers with a scale model. A relatively large model must be employed, which also tends to reduce the scale effects on the results. We must remember that the problem with reduced scale tests is not associated only with the hull, but also with the rudder and propeller effects.

I.3.2. Tests with captive models (IMO 1053, item 3.2.2.)

The model is fixed to equipment that imposes predetermined movements to it, as well as to its steering and propulsion equipment. When in forced motion, the hydrodynamic forces acting on the model and its steering and propulsion equipment are recorded.

Generally speaking, the mathematical model is used in the form of polynomials to associate hydrodynamic forces with hull speed, rotation of propeller and rudder angle. The coefficients of these polynomials are also called hydrodynamic derivatives.

The analysis of the measurements provides the mathematical model coefficients, which can be employed for predicting the response of the ship to any control input.

Tests with captive models include towing tests in long and narrow tanks, as well as turning tests in premises with a rotary arm. Initial tests are performed with the use of a PMM capable of producing oscillating sway and yaw movements while the model is towed along the tank, thus allowing ship maneuvering tests to be performed on the horizontal plane in a long and narrow tank. Testing with captive models are subject to scale effects, similar to the effects found in free running tests. However, corrections are performed more easily through result analysis.

The “rotating arm” consists of an arm with a fixed point installed in the center of a circular tank, which extends to the edge of the tank. The model is attached to the arm, which is free to rotate around the fixed point. The point along the arm where the model is placed, rotation of the arm and angle formed between the model and the arm may vary. Hydrodynamic coefficients (hydrodynamic derivatives) related to the vessel’s turning rate and the drift angle are determined by this method.

From the analysis of forces measured on the model as a function of the movements imposed by the PPM and/or by the oscillating arm, the hydrodynamic coefficients of the forces acting on the hull, propeller and rudder (forces as a function of hull speeds, propeller rotation and rudder angle) are identified. These are basic elements of a mathematical model that can be executed on a computer to simulate the behavior of a vessel when maneuvering.

When testing captive models, it must be considered the possibility of taking into account the rolling motion or not.

I.4. Mathematical model (IMO 1053, item 3.3.)

A ship maneuver mathematical model is a “set of equations” that can be employed to describe the behavior and maneuvering dynamics of a ship. As already mentioned, it is common to employ polynomial forms for describing the different hydrodynamic forces as a function of ship’s speed, propeller rotation and rudder angle, which are the independent variables of the formulation. The coefficients of these polynomials are determined by adopting experimental techniques, such as those described in the captive model tests tests with captive model, as well as results of tests with free running models and even results of tests with the real ship.

As various maneuverability tests in deep waters with different ships and different loading conditions (draught and trim) are performed, a database is being formed with results of tests with captive models, free running models and sea trial results. A data bank is then available with, for instance, coefficients of polynomials representing hydrodynamic forces on the hull, on the propeller and on the rudder as a function of the hull, propeller and rudder geometric characteristics. Mathematical models can be then developed that provide expressions for the hydrodynamic derivatives as a function of hull, propeller and rudder geometry. This set of data, when duly programmed, allows the numeric calculation of ship’s reactions to actions of propeller and rudder. Thus, there is a first maneuver simulator for a ship equipped with propeller and rudder in deep waters. The development of mathematical models and laboratory tests for representing the action of waves, winds and currents allows to incorporate also environmental actions on the vessel to the maneuver mathematical model and to the maneuver simulator. Going a little further, tests can be developed to allow effects of finite depth, bank effects and interaction with other vessels to be considered.

Since the maneuver simulator can provide a vessel’s instantaneous position and attitude, one can employ graphic tools to generate the visualization of the vessel moving on waves and showing its surrounding scenario.

The method employed for programming the mathematical model in a maneuver simulator must not necessarily follow a polynomial representation. Functional relationships between forces and independent variables can be inserted in a ship maneuvering simulator by means of graphic tables of graphical representations.

At IMO, the mathematical model is also called hydrodynamic force model, as it is based on hydrodynamic forces with a system composed of coefficients including mutual interferences.

According to IMO (MSC 1053), when using a mathematical model to describe the behavior dynamics of a ship, the following details must be observed: 1. when and where to use it; 2. how to use it; 3. accuracy level of the predicted results; 4. description of the mathematical model.

I.4.1. Assessment of ship maneuverability employing mathematical models (PIANC, 1992, *Bulletin* 77, p. 6)

Mathematical models are quite usual nowadays in the evaluation of ship maneuverability. Most of them are based on scale model tests, and often include results of full-scale tests in order to determine different coefficients of the model. The great advantage of a mathematical ship maneuvering model as compared to a scale physical model is that it is not affected by the time scale, as it is incorporated in vessels maneuver simulators. The ship and bridge geometry, the various equipment on board, the environment in full scale, etc., are modelled in the simulator, so as to allow the master or the pilot to give orders to the "ship" and observe the responses. It is also possible to fit the simulator with an automatic pilot system. In the same way as with physical models, it is possible to perform maneuvers with automatic pilot systems in which the vessel follows a predetermined course. The difference between runs performed in man handled models and in automatic pilot models is the repetitiveness. Runs performed in automatic pilot models are, in principle, fully repeatable in the same conditions. This is not possible with manually controlled models due to an implicit random human factor.

Mathematical models describing the physical process of ship maneuvering are considered to be adequate or not, depending on the type and extension of the model and on situations of the local environment. Most of the mathematical models are based on tests with physical models for determining the different coefficients in the model, as it was previously presented. Different mathematical models can represent the physics of the maneuverability of the same vessel, and so there may be a difference in accuracy between different models. Therefore, the proper choice of a certain model will depend on the problem to be solved.

Comparison between results of mathematical models and prototypes (design ship in full scale) can only be made under well-known and not too much complicated environmental conditions. In a general way, such comparison is limited to deep water tests and some results of sea trial, as turning circle, zigzag, spirals and acceleration and deceleration tests. Most of the mathematical models can present good results in such cases. Due to risks inherent to tests with ships in confined environments, comparisons of results in such conditions with results of tests with mathematical models are not made. In such cases, mathematical models can be checked by comparing scale physical models. These comparisons may present evidences confirming the reliability of mathematical models.

Mathematical models are reliable and indispensable tools for designing port and fairways. They may be mathematical models fitted with automatic pilot systems or not, processed in simple micro simulators or real scale bridge simulators. When human action is important or there is a certain probability of occurrence of accidents like running aground, real scale bridge simulators must be employed. As physical models are subject to the time scale problem, they are less adequate. However, their use is important, either for generating data for development of mathematical models or when a physical problem requires complex modeling or its understanding is still insufficient.

I.4.2. Assessment of ship maneuverability in confined waters in a port environment

Same as in assessment of ship's maneuverability in deep waters, several models can be employed in simulation of ship maneuvers in ports and fairways. Physical and mathematical models stand out among them, although tests with the ship itself may also be performed.

I.4.3. Assessment with the design ship

Tests with the ship in shallow waters are costly and dangerous. The best known were performed with the tanker Esso Osaka. Tests with this ship and similar ones allowed the development of mathematical expressions for extrapolating to shallow waters the results of measurements performed in deep waters. In Brazil, the first shallow water maneuvering test in real scale was performed with the Login owned ship Tambaqui in 2015.

However, full real scale comparison to assess ship behavior in a port environment is almost unavailable or non-existent. Near port entrances the waters are shallow, their depth may vary substantially, there are currents often with strong gradients and waves vary both in height and direction. There may also be suction effects due to banks, side walls, interaction with other ships, etc. That is, the ship's behavior is not fully known regarding the environment in which it is navigating. The ship is the least of the problems. The environmental effects on the ship, with shallow waters and depth variations, currents and waves are the major problems, as the ship responds strongly to them.

I.5. Uncertainties (IMO 1053, item 3.5.)

I.5.1. Accuracy of model test results (IMO 1053, 3.5.1.)

Experience with reduced physical models shows that they can present more directional stability due to wave effects than the actual ship. The use of large models minimizes this problem. Thus, for reducing scale effects, models comparable in size to those employed in resistance and propulsion tests must be used. On the other hand, satisfactory results can be achieved in tests with smaller scale captive models.

I.5.2. Accuracy of predicted results using a mathematical model (IMO 1053, 3.5.2.)

The mathematical model that can be employed to predict the maneuvering performance of a ship depends on the type and amount of available data.

If data on maneuvering behavior and physical model test results are not available, and assuming that results of resistance and auto propulsion tests are known, it will be necessary to employ approximate formulae to determine the hydrodynamic coefficients of the mathematical model.

On the other hand, when a database of experimental results is available, such data can be utilized for elaborating a mathematical model. Usually, a sufficient amount of experimental data for elaborating the mathematical model is not available, and it becomes necessary to employ a combination of different experimental data and expressions that estimate the necessary data for formulating the model.

I.6. Predictive overview of ship maneuverability (IMO 1053, APPENDIX 2)

In Document IMO 153, Appendix 2, some important observations are listed. Some of them are here in commented.

- The mathematical model of ship maneuvering motion can be employed to check if the maneuverability standards recommended in resolution MSC 137(76) are met in fully loaded conditions and from results of a sea trial performed in different loading conditions, such as in ballast and half laden.
- IMO subdivides maneuvering models in two types: response model and force model. The first one relates the vessel's response to the action imposed on the control system. The second one, called hydrodynamic force model, translates the hydrodynamic forces, including their mutual interferences. Changes in the ship's maneuvering behavior resulting from alteration to ship's hull form are taken into consideration by altering the hydrodynamic derivatives and interference coefficients.
- The Appendix to the IMO text shows schematically the method for predicting a ship's behavior in maneuvers employing a hydrodynamic force model and emphasizes that a hydrodynamic force method is quite effective for understanding the relation between maneuverability and ship's hull form.
- The diagram of the method in the IMO document is shown in Figure A1. Generally speaking, it can be said that there are many expressions for representing hydrodynamic forces; however, the fundamental ideas that originated them are the same. Hydrodynamic forces acting on a vessel are usually represented by polynomials as a function of surge, sway and yaw speeds.
- The main difficulty in predicting the behavior of a maneuvering vessel is determining the hydrodynamic derivatives, which is the most important part of the development of a maneuvering model.
- Hydrodynamic derivatives may be directly estimated from tests with models, by means of data based on data accumulated along the time, by means of theoretical calculation and by means of semi empirical mathematical expressions as a function of parameters as vessel's length, beam, mean draught, trim and block coefficient.

– The maneuver performance accuracy predicted by the hydrodynamic force model depends on the accuracy of the results estimated by means of the forces. When estimating hydrodynamic derivatives, it is important to keep the consistency of relative precision between the different hydro dynamic forces for ensuring the precision as a whole.
– It is not yet possible for theoretical models to provide calculation of hydrodynamic forces with sufficient precision. Thus, empirical mathematical expressions and databases are often used or incorporated into the calculations.

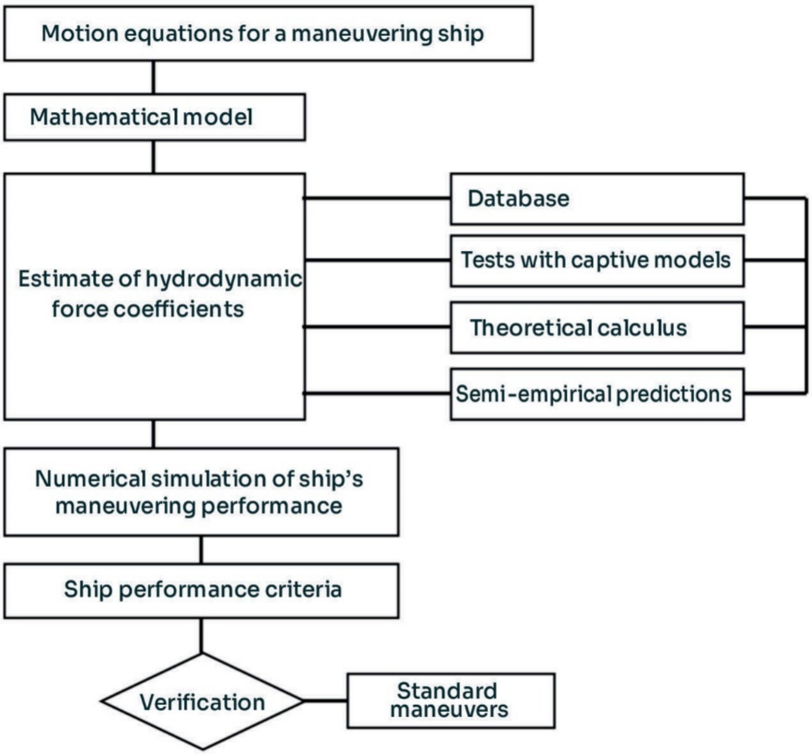

Figure A1. Development of ship maneuverability equations

I.7. Manned physical models (PIANC, 1992, *Bulletin* 77, item 3)

I.7.1. Types

Bulletin 77 (PIANC, 1992) classifies manned physical models used in port design in two broad categories:

i. Remote-controlled models with a human operator distant from the model;
ii. Manned models, with an operator on board.

In remote-controlled models, an operator situated at a convenient observation point controls the model and follows its movements and track. Another option is to use a closed-circuit TV camera mounted in the control cabin, allowing the operator to have a view of the waterway from a monitor.

Manned models are generally large and their crew consist of one or two men. The pilot/master has a realistic view of the environment, positioned in the control cabin, and all control functions are carried out on board.

In both cases, data regarding position, course, rudder, rotation, etc. may be stored on board or sent ashore for storage.

I.7.2. The use of physical models steered by human beings

Section 3.2. of *Bulletin* 77 (PIANC, 1992) indicates in which cases this physical modeling may be employed. Next, we present the observations mentioned in the referred publication.

– In conjunction with large-scale hydraulic models
  Occasionally, a large physical model for studying hydraulic characteristics and navigation problems may be employed for avoiding scale distortion.

– When the physics of a system are incompletely understood
  Mathematical models translate our comprehension of the processes they represent. Thus, when a fairway hydraulic system or a ship hydrodynamics are not well understood, physical models may be the only means of assessing a ship's behavior in complex situations.

– When computational simulation is not wholly adequate
  In these cases, physical models or physical models in conjunction with computer simulation (for instance, complex berthing maneuvers) may be used.

– For demonstration purposes
  Occasionally, a client may prefer the use of a physical model for demonstration to parties interested in the study to be carried out. Often, such demonstration form allows a best understanding than computer simulation results. Some mariners learn more easily lessons from physical ship models operating in an environment or fluvial waterway with which they are acquainted.

– For training purposes
  Manned large models may be quite effective for training masters and pilots in ships operations and maneuvers.

I.7.3. Advantages e disadvantages of employing models steered by human beings

Bulletin 77 (PIANC, 1992), section 3.3., lists vantages and disadvantages of employing physical models steered by human beings in comparison to mathematical models. It presents also advantages and disadvantages of employing manned models in comparison with remote-controlled models. Such comparisons are transcribed below.

I.7.3.1. In comparison with mathematical models

The advantages of physical models are

- They allow observation and measurements to be made model undergoing cross currents, near sandbanks, (curve or irregular), in situations where the physical problem is not fully understood, etc.;
- Remote-controlled models can be combined with fairway physical models, when these are already built. In case of manned models, such combination may not be feasible, since they are usually too large;
- Shorter testing time with scale models provides a certain advantage, as a large amount of data can be collected in a short period of time.

Disadvantages are

- The use of the Froude number for determining the model time-scale implies that the time for performing an operation with the model is equal to the ship time-scale multiplied by the square root of the scale, that is, for our observation, the operation occurs is fairly fast and human factors must be considered;
- The viscous force scale is defined by the Reynolds number, and the scale employed in tests with models is defined by the Froude number. It means that the viscous forces are not correct in the tests. However, viscous effects are less important at low speeds, which usually is the case when operating a vessel in confined waters;
- Tests with scale models of ships do not allow the introduction of dimensional distortion. Thus, one must find a compromise for the model to be large enough to give reasonable results, but not so large as to incur too heavy and costly a waterway model.

I.7.3.2. Manned models compared with remote-controlled models (PIANC, 1992, Bulletin 77, item 3.3.2.)

The advantages below apply to manned models in comparison to remote-control models:

- The pilot/master on board the model is in a better condition to perceive the model's reactions to wind, currents, rudder and propeller effects, and to realistically control the craft.

– Being on board a manned model, the pilot/master are situated at level with the bridge wings and the control cabin. Given the geometric similarity between the model and the ship, the pilot/master has the same visual angle and hence the same perspective as on the bridge.
– In a remote-controlled model, the viewpoint of the pilot/master is usually positioned upwards, well above the model, which alters their perception of what is actually occurring. This can be partially overcome by means of a closed-circuit TV system.
– The pilot/master has a 360-degree angular vision, which allows them to carry out maneuvers right up to the moment of berthing, to berth stern first, to go astern in a channel, etc.

The disadvantages of manned models compared to remote-controlled models are listed below.

– Since a manned model must usually be larger than a remote-controlled model, it becomes difficult or too costly to combine it with current and wave hydraulic models.
– Manned models present a minor inconvenience of visual perception, as the eyes of the piolt/master, in the model scale, are too far apart (binocular vision). Experience has shown that it can be overcome if the pilot/master considers the ratio between the ship's length and the distance to go.
– In some manned models operating in the open, it is necessary to operate in a place that affords good shelter from winds, otherwise the model will be exposed to the local real winds, for which there is no control of strength or direction.

Part II – Ship Maneuvering Simulation Models

The analysis of operations involving a ship maneuver in port areas is extremely complex, implying different variables in the dynamics is considered of a floating body undergoing different environmental efforts (waves, wind, current, shallow waters) and to actuation/control elements (engine, rudder, thrusters, tugboats, mooring and towing ropes, fenders, interaction with other vessels, etc.), often under manned control.

It is known that a maneuver simulator that acceptably represents the behavior of a complex port system and can be employed for defining operational conditions within the limits of safety should be endowed with validated known mathematical models, and that all considered and/or discarded phenomena must be explicit, both in the ship's hydrodynamics and in the environmental areas. The capacity of ship maneuvering simulators depends on the reliability of their governing mathematical models and on the quality of the environment being simulated.

In port projects, a ship maneuvering simulator can be used mainly for the following purposes:

– Development of new piers;
– Development of new approach channels;
– Verification of maneuverability during the design phase of new type ships;
– Verification of vessel's maneuverability due to changes in approach fairways;

– Training for adaptation to changes in approach fairways or to a new type of ship;
– Investigation of ship's behavior in new operational windows;
– Risk deterministic assessment in function of human failures;
– Assessment of limiting environmental conditions;
– Replication of accidents or incidents occurred;
– Traffic density assessment in geographical points that characterize constraints to navigation;
– Assistance in choosing the positioning of aids to navigation;
– Training under reduced visibility conditions, employing electronic navigation instruments;
– Assessment of adequate position and number of tugs to the maneuver.

II.1. Mathematical model modules a port maneuver simulator must contain

The maneuver simulator must be suitable for application to different practical problems, as verifying the possibility of reduction of operational restrictions at a terminal, assessment of the feasibility of operating a new vessel (for instance with a larger draught), dimensioning of dredging areas and depths in approach channels and maneuvering basis, risk assessment, among others.

To meet such purpose, the maneuvering simulator must include modules in its mathematical model for the following functions:

– Responses of the hull hydrodynamics to different speeds, including stern movements;
– Effects of the machine dynamics;
– Effects of the propeller dynamics;
– Effects of thrusters and auxiliary thrust devices;
– Effects of rudder;
– Effects of current;
– Effects of wind;
– Effects of waves (first and second orders);
– Effects of shallow waters;
– Effects of bank and channel;
– Effects of interaction between crafts;
– Effects of tugboat force;
– Interaction of tugboats as independent crafts to control;
– Action of fenders, mooring ropes, mooring buoys, piers and other topics regarding berthing/unberthing of ships.

II.1.1. Responses of hull hydrodynamics to different Froude numbers

Ship maneuvering operations in port services involve speeds that are not included in any of the standard tests recommended by the International Maritime Organization or by classification societies. Operations at low speed include several combinations of speeds relative to the hull drifting angle with the ship moving ahead, astern, laterally and/or turning.

The simulator supplier must present technical documentation informing how it is established the relation between the behavior of the hull for those different speed ranges and how the mathematical validation of their ship models is done, so that they can be employed in the low-speed range of ship operations when in channels, maneuvering basins and approach channels, as well as during berthing/unberthing and anchoring maneuvers.

II.1.2. Effects of engine dynamics

This module presents how the alteration of the propeller rotation rate is done by means of the torque provided by the main engine. The model must include the difference between the water resistance torque on the propeller and the engine output torque that allows the acceleration (or deceleration) of the shaft that transmits the engine force to the propeller.

The engine torque must be modelled in all "four quadrants", that is, for all four possible combinations of the vessel going ahead or astern with forward or astern rotation of the propeller as presented in Figure A2.

Figure A2. The four quadrants of the propeller a) ship going ahead and propeller rotating in the design direction; b) ship going ahead and propeller rotation inverted; c) ship going astern and propeller rotation inverted; d) vessel going astern and propeller rotating in the design direction (Harvald, 1977, apud PIANC,1992, *Bulletin* 77)

II.1.3. Effects of propeller dynamics

The thrust generated by the propeller T and the torque Q applied to it depends on the propeller shape, area of blades, number of blades, diameter D, ratio pitch/diameter P/D, rotation n and surge velocity V_a. Thrust and torque are usually expressed in the dimensionless forms $K_T = T/(\rho n^2 D^4)$ and $K_Q = Q/(\rho n^2 D^5)$. Such dimensionless forms are available for most of the propeller systems in open waters, as a function of the progress coefficient $J = V_a/(nD)$, as shown in Figure A3., in this case a four blade B Series Wageningen propeller of developed area/disk area ratio A_D/A_0 equal to 0,55.

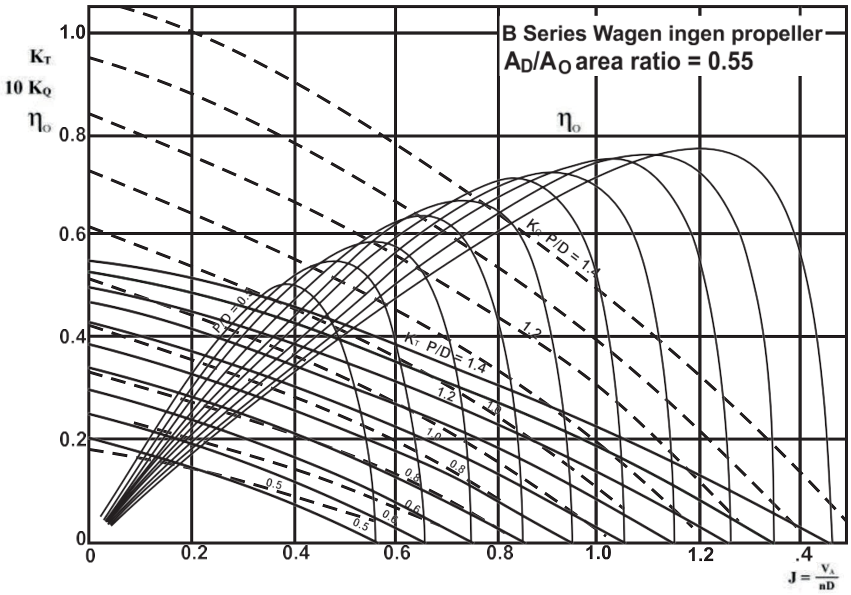

Figure A3. K_T, K_Q, J diagram of a B-Series four blade, 0.55 area rate Wageningen propeller (Bernitsas et al., 1981; Harvald, 1983)

As for the engine dynamics, the propeller dynamics must be modelled in all "four quadrants", that is, for all four possible combinations of a vessel going ahead or astern with propeller rotation ahead and astern, as presented in Figure A4.

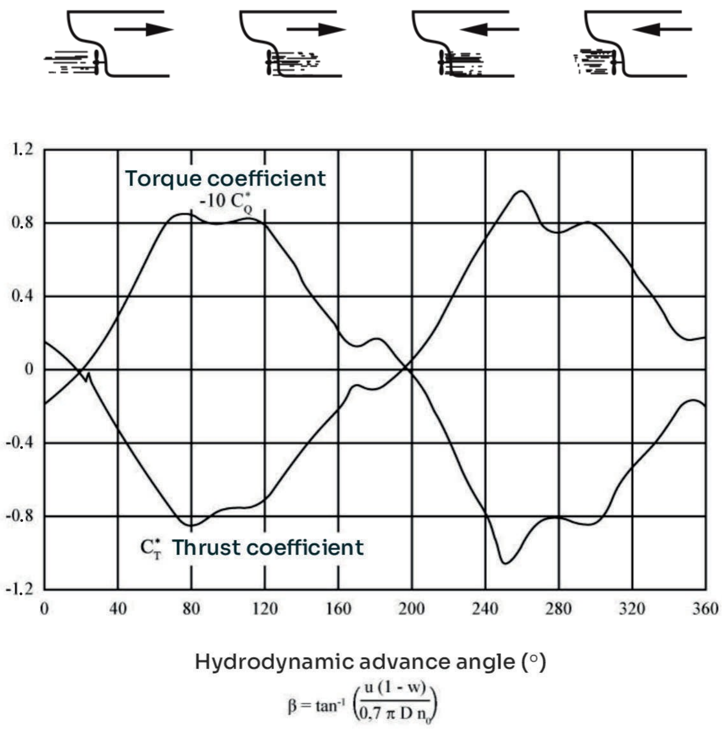

Figure A4. Propeller thrust and torque in the four quadrants (Harvald, 1977, apud PIANC, 1992, *Bulletin* 77)

The simulator developer must document how the propeller lateral force is inserted in the mathematical model as, besides generating longitudinal force, the propeller may also cause a lateral force due the direction of its rotation. Such force becomes important when the propeller inverts its rotation, which plays an important role both turning and in maneuver to stop the ship. Its effects on the "four quadrants" must be considered and duly documented.

In the model, as well as in the ship, the effective propulsion force must be calculated by taking into consideration the reduction of propulsion force by means of the propulsion force reduction coefficient t.

Propulsion must also take into account the underkeel clearance effect, since the flow around and under the vessel is altered. This can be corrected by providing the due alterations to the wake coefficient w and to the propulsion force reduction t.

II.1.4. Effects of thrusters and auxiliary thrust devices

The forces of bow-thrusters, stern-thrusters and azimuths regarding the maneuverability of the ship at slow and dead slow speeds must be carefully assessed and documented, as well as how the speed of the ship, or a current, reduces the lateral force and the turning moment generated by them.

II.1.5. Rudder effects

A conventional rudder in a ship is a wing of small aspect ratio. The forces on the rudder are then modelled as lift and drag forces. The speed of the water flowing on the rudder is due to the ship motion (forward speed, drift and turning) and to the propeller discharge current, whose contribution may be the most important one. It is known that, in vessels with low inertia, oscillating the rudder from port to starboardside may reduce the stopping distance.

The rudder must be controlled by the steering gear: hydraulic piston or electric motor. The time from hard port to hard starboard rudder, or vice versa, must be included in the simulation.

As the rudder force depends on the propeller discharge current, the rudder action module must be integrated to the propeller and engine "four quadrants" region.

II.1.6. Current effects (PIANC, 1992, *Bulletin* 77, item 4.4.3.)

The forces and movements on the ship generated by the action of the current depend on the ship/current relative speed and direction, on the hull shape and on the underkeel clearance.

When the ship moves in calm waters, the perception of an observer on board is similar to that of the vessel having been put into a current. To avoid difference between these two situations, it is important to treat the current as seen relatively to the ship. By doing so, the hydrodynamic coefficients determined in maneuvering standard tests can be utilized, using the ship's speed – relative to the water, or on the water surface – for calculating the forces.

Bulletin 77 (PIANC, 1992) recommends that the effects of currents by the bow and by the stern be modelled, pointing out that they are significantly different. Currents by the bow improve the steering, while the ship's speed over ground and inertia forces do not increase. When the current comes by the stern, the water speed in the rudder area decreases and the magnitude of the lift force provided by the rudder also decreases. In the rudder area, the water speed is lower than the ship's speed over ground. When the current is strong and the pilot/master increases the speed, the drop in the lift force provided by the rudder causes a change to the ship's behavior, as in such conditions, the diameter of the turning circle and the stopping distance will increase significantly.

A second concern regards to the probable presence of strong current gradients in the area where the ship navigates. In São Marcos Bay, for instance, there are strong current gradients. When a ship passes from a strong current area to calm waters and vice versa, its bow and stern may become exposed to quite different incident flows, and the pressures acting on the bow and stern will be significantly altered and in different forms, which may result in a great hydrodynamic moment that may exceed the restoration moment available when the rudder is put at its maximum angle.

Bulletin 77 (PIANC, 1992) comments that, in case of strong water speed gradients, a refined spatial resolution of the current must be used, and the force and moment exerted by the current may be modelled as if the vessel were performing a rotation.

When applied to oil tankers and bulk carriers, the results of forces and moments of the model of currents as a function of depth ratio must adhere to the results of the document *Prediction of wind and current loads on VLCCs* (OCIMF, 1994).

As an example, see below figures showing graphics of the longitudinal force coefficients for a current acting on an oil tanker at depth ratios 3.0, 1.5 and 1.2 (Figures A5., A6. e A7.). Figures A8., A9. and A10. present coefficients of longitudinal and lateral forces and moments due to action of wind on an oil tanker.

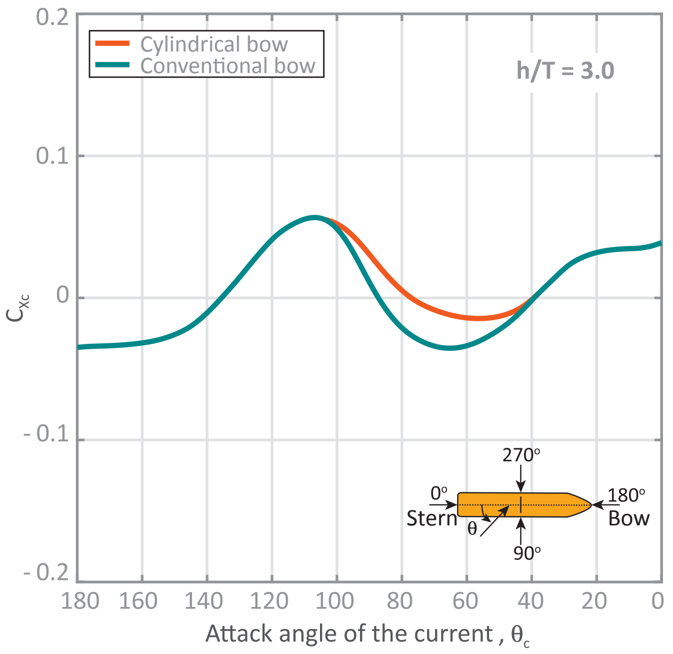

Figure A5. Longitudinal force coefficient C_{Xc} due to current for a loaded oil tanker for depth/draught ratio = 3 (OCIMF, 1977)

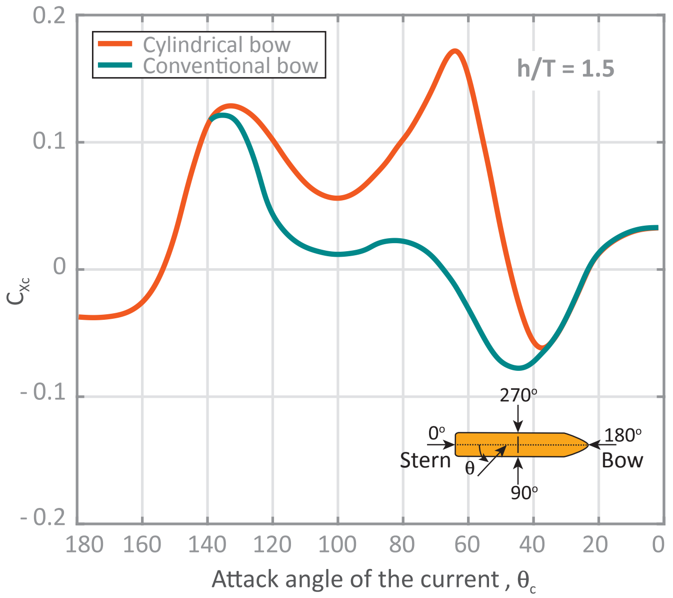

Figure A6. Longitudinal force coefficient C_{Xc} due to current for a loaded oil tanker for depth/draught ratio = 1.5 (OCIMF, 1977)

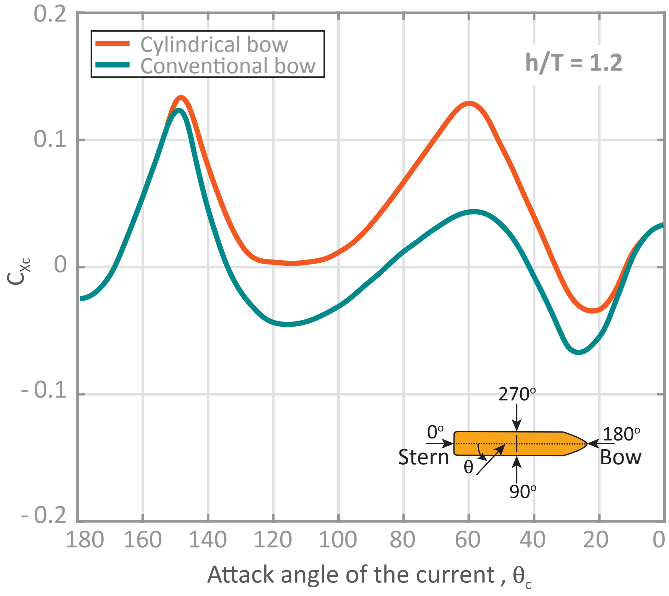

Figure A7. Longitudinal force coefficient C_{Xc} due to current for a loaded oil tanker for depth/draught ratio = 1.2 (OCIMF, 1977)

II.1.7. Wind effects (PIANC, 1992, *Bulletin* 77, item 4.4.1.)

The mathematical model for forces and aerodynamic moments acting on the ship due to action of the wind is usually generated by means of experiences with a scale model in a wind tunnel. Forces and moments are presented in form of dimensionless coefficients as a function of the wind attack angle, draught and trim, since they depend on the exposure of lateral and frontal areas. In case of container vessels, the wind action depends on the number of containers stacked on deck.

The mathematical model for wind forces relatively to oil tankers, bulk carriers and gas carriers must meet the OCIMF *Prediction of wind and current loads on VLCCs* (1994) standard, recommended by IMO. An example of such coefficients for ships is presented in Figures A8., A9. and A10.

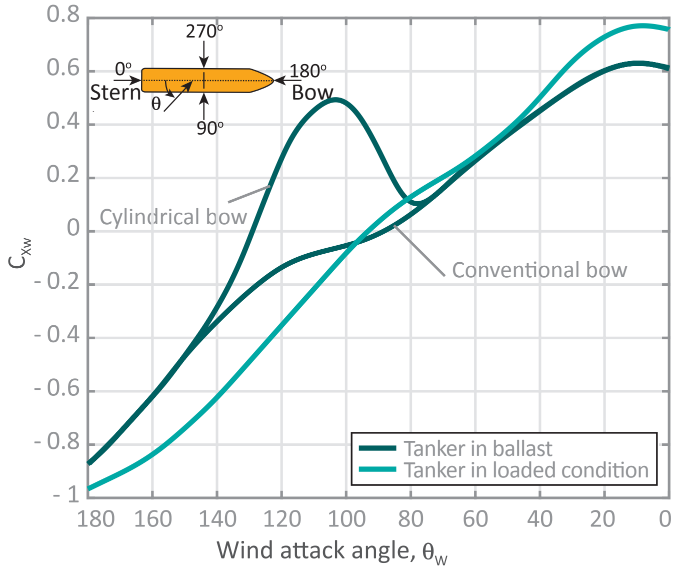

Figure A8. Longitudinal force coefficient C_{Xw} due to wind for an oil tanker in ballast (OCIMF, 1977)

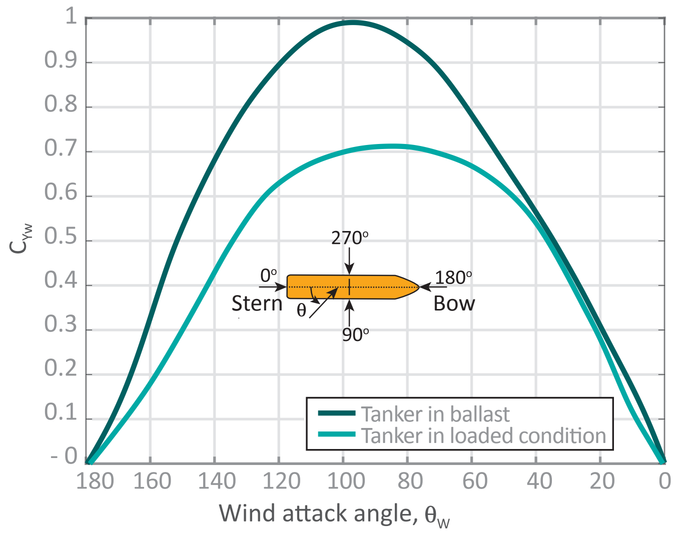

Figure A9. Lateral force coefficient C_{Yw} due to wind for an oil tanker in loaded and ballast conditions (OCIMF, 1977)

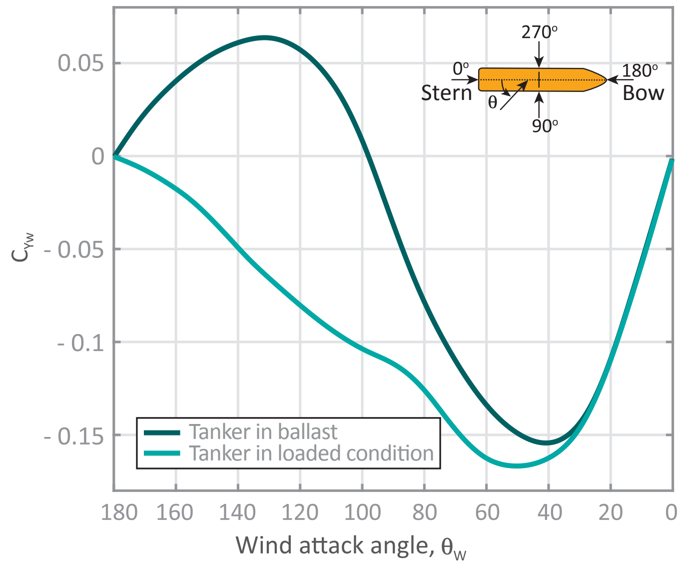

Figure A10. Turning moment coefficient C_{XYw} due to wind for an oil tanker in laden and ballast conditions (OCIMF, 1977)

Force and moment coefficients due to wind can be determined from regression analysis of a great number of experiments with scale models in wind tunnels, with different angles of attack. An example of this procedure can be seen in Isherwood (1972, apud *Bulletin* 77, PIANC, 1992) and in BSRA (1967, 1969, 1971, 1973, apud PIANC, 1992, *Bulletin* 77).

As highlighted in *Bulletin* 77 (PIANC, 1992), some types of vessels are specially affected by winds due to their freeboard, big superstructure or deck cargo. Examples are container carriers, gas carriers, cruise ships, car carriers, as well as tankers and bulk carriers in ballast conditions. Wind has turbulences of different magnitudes and time scales. Gusts with change of direction and speed are not easy to control. For a vessel of great inertia such gusts may be insignificant, but for smaller vessels or if the wind force is significant, they can be a nuisance, as the pilot/master has to react in advance to all gusts to avoid losing control of the ship.

Wind forces must be included in all simulation models. It is recommended to simulate wind gusts for improving the realism of the simulation.

II.1.8. Wave effects (PIANC, 1992, Bulletin 77, item 4.4.2.)

By employing a linear analysis for describing sea waves, it can be said that, due to its random nature, the sea is composed of superposition of regular waves with a wide range of frequencies. Due to their frequency, some of these waves have a small effect on ships, while others will cause important forces and moments, depending on the size of the ship, the weight distribution and the hull shape.

Waves of long or short periods do not generate forces capable of causing significant effects on the behavior of merchant ships. However, in intermediate frequencies, heave, roll and pitch movements may increase and make it difficult to steer the ship if the wave frequency gets near the natural frequency of one of these movements.

Waves act in a different way on the side of the ship that is exposed to them and on the opposite side, generating different pressure distributions, causing an average drift force that makes the ship move as if it were under wind effects. It is essential to consider the average drift force in the simulations.

Furthermore, one must observe that, when employing tugboats, waves may render it difficult for the tugs the operation of passing the towline to the ship, and their pulling efficiency is reduced.

It is important to take into consideration the ship's speed on waves, as well as the direction of incident waves, always having in mind that the frequency of oscillating forces acting on the ship is the encounter frequency. Furthermore, it must be emphasized that waves coming from forward and waves coming from astern cause quite different effects on the ship. At low speeds of the ship, the effect of waves coming from astern is very important.

For merchant ships of medium and large sizes, wave forces do not have necessarily to be included in the simulations. However, for smaller ships, it is recommended that forces and instantaneous moments generated by waves be taken into consideration.

II.1.9. Shallow water effects (PIANC, 1992, Bulletin 77, item 4.4.4.)

The depth of the area where the ship is moving is an important factor. The ship's behavior is considerably altered as a function of the depth/draught ratio (h/T, where h is the water depth and T is the vessel's draught), called depth ratio. Depths are classified according to that ratio as follows:

– Deep water $h/T > 3.0$

– Medium deep water $1.5 < h/T < 3.0$

– Shallow water $1.2 < h/T < 1.5$

– Very shallow water $h/T < 1.2$

In medium deep water, the effect of the bottom can already be noticed. In shallow waters, it may become more intense yet, altering the maneuvering capacity of the ship. In very shallow waters, the flow underneath the keel is almost blocked, increasing the damping forces and the added mass, which impairs considerably the maneuvering capacity.

The mathematical model must represent the most relevant consequences of shallow waters: increased directional stability and worse turning ability (lower drift angles). The turning circle diameter is larger, as seen in Figure A11., presented in *Principles of Naval Architecture* (PNA) originally from Crane (1979). Usually, the stopping distance is slightly larger (larger added mass and reduction of propeller thrust), and more powerful tugboats are required for counteracting the larger damping. Depth effects can be modelled employing different sets of hydrodynamic derivatives for different depths, taking into consideration the underkeel clearance.

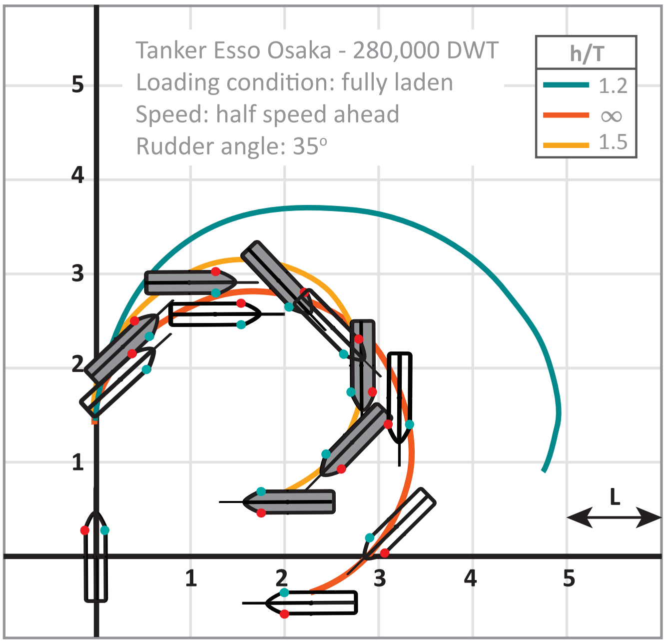

Figure A11. Influence of depth on the turning circle of the Esso Osaka in loaded conditions and engine half ahead (Crane, 1979, apud PNA, vol. 3)

Figure A12, taken from Bogdanov et al. (1987, apud PIANC, 1992, *Bulletin* 77), presents the significant increasing of the lateral force coefficient with h/T varying between h/T = 1.5 and h/T = 1.2. It shows that one must be careful when determining lateral force in small depths. It is risky to extrapolate values of lateral force, for smaller depths. Laboratory tests must be performed, or tests already performed must be employed for different h/T ratios in order to estimate hydrodynamic coefficients.

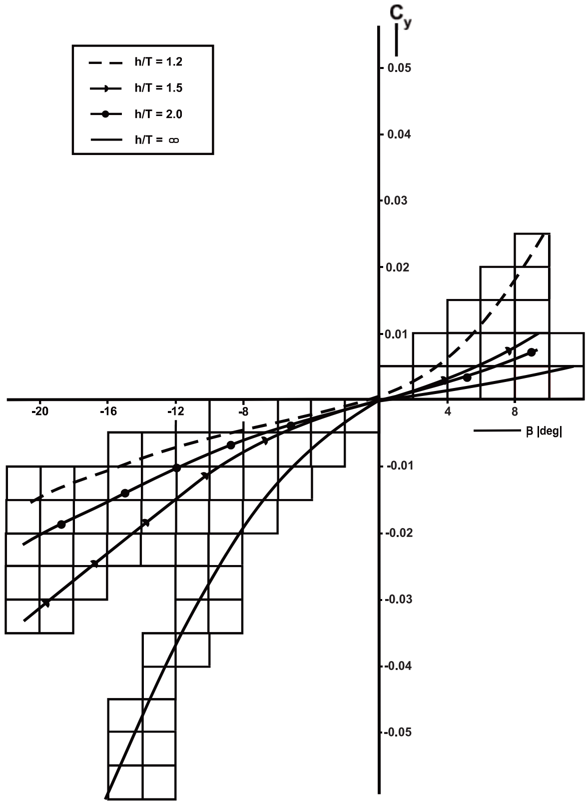

Figure A12. Coefficient of lateral force on an oil tanker: depth and drift angle effects (Bogdanov et al.,1987, apud PIANC, 1992, *Bulletin* 77)

As shown in *Bulletin* 77 (PIANC, 1992) there are some mathematical expressions experimentally obtained e that relate deep waters coefficient to shallow water coefficient. The Hirano publication (1985, apud PIANC, 1992, *Bulletin* 77) is mentioned here as an example, which, from experimental data, obtained mathematical expressions that can be included in a mathematical model. Hirano introduced the "effective aspect ratio in shallow waters" as a function of h/T value and deep water aspect ratio 2T/L to estimate functions that predict the hydrodynamic derivatives in shallow water.

II.1.10. Bank effects (PIANC, 1992, Bulletin 77, item 4.4.5.)

When a ship passes near a bank, the flow around its hull is altered, which may cause the ship to lose symmetry. The flow speed between the ship and the bank increases, and according to the Bernoulli principle, the pressure decreases, causing a suction effect on the vessel towards the bank. With the pressure distribution along the hull altered, besides the suction force a hydrodynamic moment takes place on the ship, which forces it to turn. The pressure center is usually positioned abaft of the gravity center, generating a moment that forces the bow away from the bank. Such effect is known as bow cushion. However, it depends on the hull shape and on the underkeel clearance. Similar effects occur when a ship passes near a quay, sandbank, berthed ships or cliffs in a fairway. Figure A13., presented in PNA originally from Abkowitz (1964), shows a flow diagram around a ship in a channel when approaching a bank.

Bank effects depend both on the distance from the ship to the bank and on its speed. As such distance decreases, the suction force increases. For low speeds, the suction force is proportional to the square of the speed. However, as speed increases, the force varies with a higher potence of the speed, above 2. This occurs for Froud depth numbers above 0.2.

Bank effects must be included in the simulation if the ship is to navigate at a distance from the bank that is twice as short as the beam of the vessel.

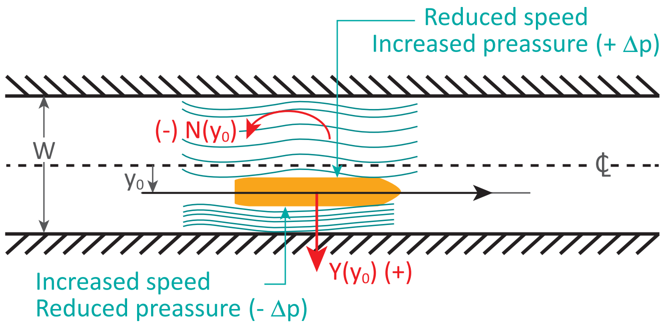

Figure A13. Diagram of waterflow around a ship near a bank in a channel
(PNA vol. 3, Figure 105; Abkowitz, 1964)

In a straight channel, the suction force and the turning moment can be compensated by applying an attack angle to the rudder and a drift angle to the ship. If the channel width changes, such continuous compensation will not be possible any more. For keeping the ship away from the bank, a continuous control of the rudder will be required, which, as a matter of fact, is also required in channels with varying widths.

Bank effects may be incorporated in ship maneuvering simulations by means of mathematical expressions developed from model tests. Even so, it is difficult to know precisely the bank position. It is also difficult to extrapolate results of model tests to a real situation where the bank shape is different. Near sudden width changes, hydrodynamic forces induced by a short bank may be incorporated as a function of the ship position (see Figure A14., taken from Ashburner, 1980, apud PANC, *Bulletin* 77).

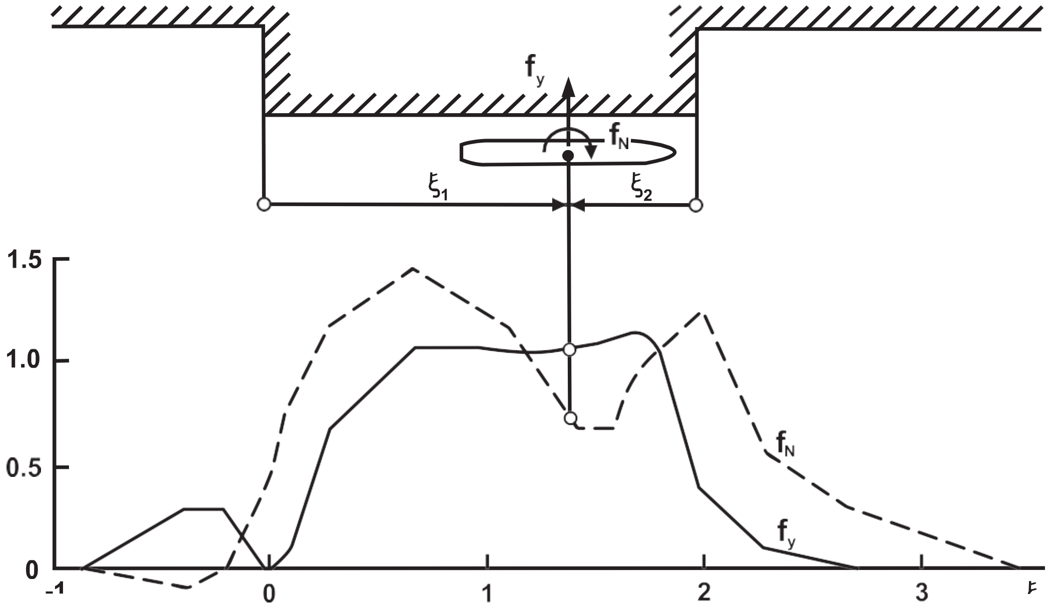

Figure A14. Variation of force and moment acting on a ship as it passes near a small bank (Ashburner e Norrbin, 1980, apud PIANC, 1992, *Bulletin* 77)

II.1.11. Ship/ship interaction (PIANC, 1992, *Bulletin* 77, item 4.4.6.)

As explained in the previous item, a ship navigating near an obstacle presents alteration in the flow around its hull, which generates suction forces in the area of constrained flow and a moment on the hull. When two ships are sailing next to each other, a similar phenomenon occurs. In cases of two lane traffic and intense traffic regions where slower ships are being overtaken, the interaction between two ships is quite relevant. Attraction and repulsion forces, as well as moments, may appear on both hulls.

Dand (1981, apud PIANC, 1992, *Bulletin* 77) presents a case of a small ship A passing by a large ship B, sailing in a head-on encounter (see Figure A15). While ship A approaches ship B, the former is subjected to a repulsion force until it is fully on the side of ship B, when it then becomes subjected to a suction force, which reaches its maximum value when A reaches the stern of B.

Initially, a moderate bow-out yawing moment acts on ship A until it is changed to an important bow-in moment when ship A is sailing along the middle of ship B. When ship A reaches the stern of ship B, the moment changes again to a bow-out moment.

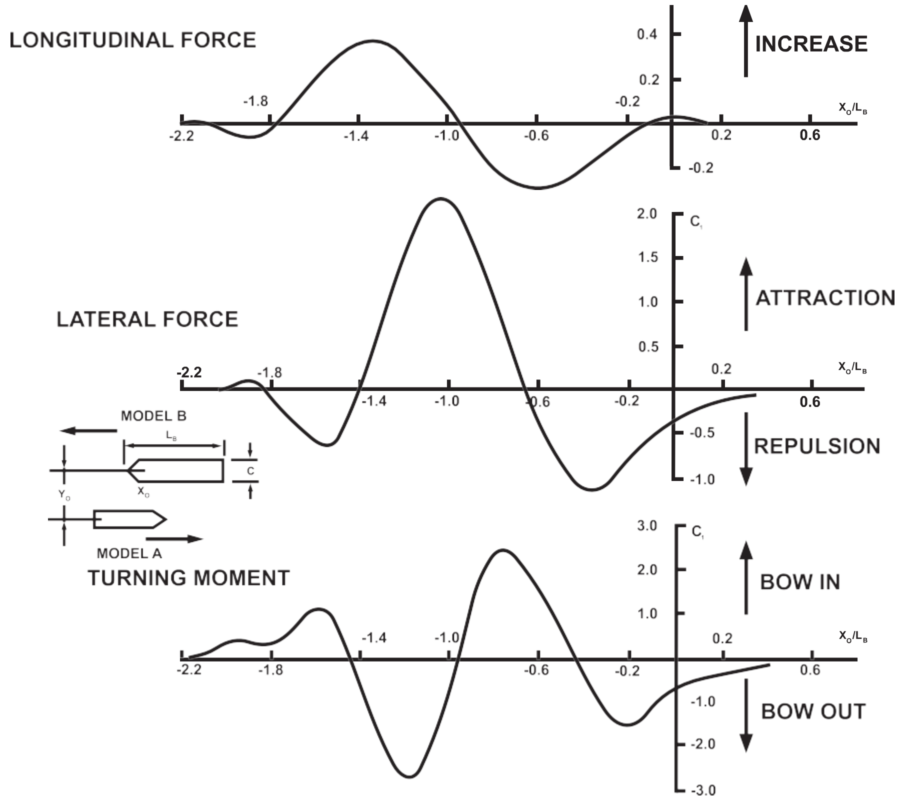

Figure A15. Forces and moment acting on a ship due to the passage of another ship (ship/ship interaction), from Dand (1981) in PIANC, 1992, *Bulletin* 77

Norrbin (1975, apud PIANC, 1992, *Bulletin* 77) showed, by means of theoretical and experimental treatment, that interaction forces increase sensibly as underkeel clearance decreases.

Using a potential flow model, Dand (1981, apud PIANC, 1992, *Bulletin* 77), could successfully reproduce interaction forces measured with ship models. Although the theoretical model yields good results, it is not appropriate to a real time simulation. However, a dimensionless representation of forces and moments as a function of the distance between the ships, their dimensions, speeds and underkeel clearances can be sought, so that interaction forces between ships are included in mathematic ship maneuvering models.

II.1.12. Tugboats

According to *Bulletin* 77 (PIANC, 1992), tugboats are employed to:

– Enable the ship to turn in a a confined area;
– Counteract environmental forces at times when the ship's speed must be kept low, and use of engine and rudder is limited;
– Restrain or stop the ship;
– Assist while berthing and unberthing.

The number of tugs required for an operation depends upon the ship dimensions, environmental conditions and presence of bow or stern thrusters.

In Brazil, most of the tugs are of the ASD (Azimuth stern drive) type, a reverse tractor tugboat that, due to the configuration of its equipment, can operate both as reverse tractor and as a conventional tugboat.

In Brazilian port operations, for safety reasons, the towrope is always from the tug, which employs a towing winch and does not use the device known as towing hook.

The type of propulsion of a tugboat is very important for its performance. The diagrams of Figure A16., taken from the book *Utilização de Rebocadores nos Portos*, translated by Calenzo into Portuguese language from the original Tug Use in Port, show the thrust in different directions for:

a. Voith Tractor Tug;
b. Tractor Tug equipped with ducted azimuth thrusters;
c. Reverse Tractor Tug equipped with ducted azimuth thrusters;
d. Conventional Twin Screw Tug equipped with ducted CPP and bow thruster;
e. Conventional Twin Screw Tug equipped with ducted CPP.

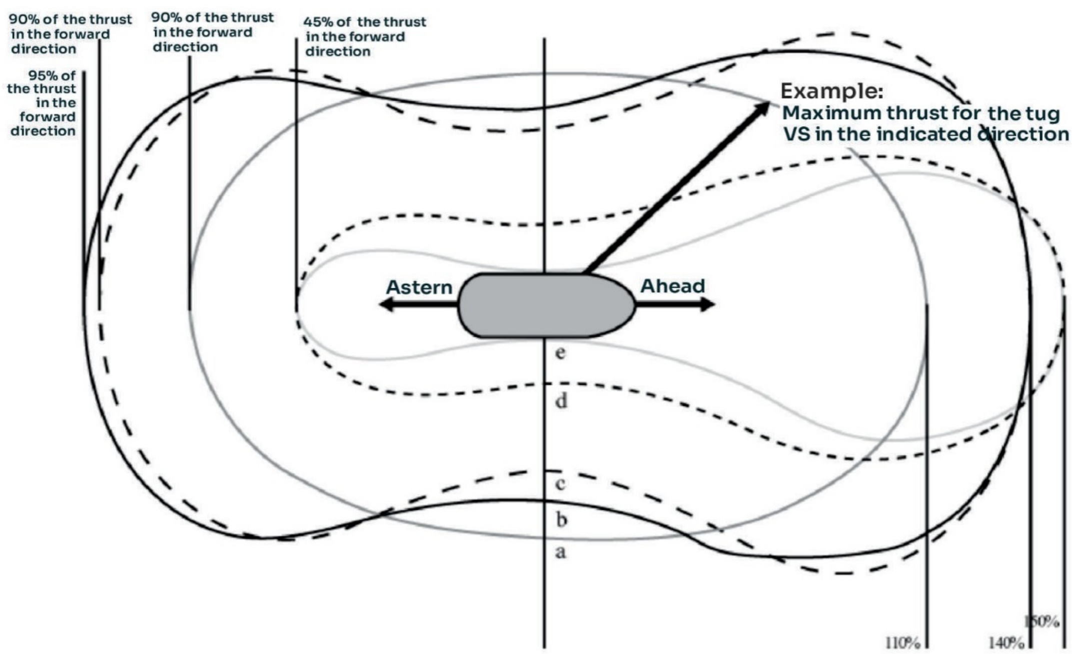

Figure A16. Plotting of bollard pulls of different tugboats as a function of direction (Hensen, 2007)

The location of the towing winch on deck and its type influences the force balance on the tug and the way towing maneuvers can be performed.

The tug towing capacity is specified in terms of traction at zero speed, known as static traction, or Bollard Pull. Such capacity decreases when the tug is developing a speed. Especially while towing laterally to a moving ship, the available force is significantly reduced with rising speed, as the angle between the ship and the tug must remain smaller (otherwise, the tug would be left behind). The maximum force is also limited by the capsizing moment exerted by the rope traction force on the tugboat.

The way the tug is connected to the ship depends on local tradition, available room and the kind of assistance required. Tugboats can also be employed for pushing or restraining a ship, as a "hydrodynamic parachute" assistance method known as indirect towing.

II.1.13. Interaction of tugs as independent crafts to be controlled

Hydrodynamic interactions can occur between the hull of a ship and the tug, which can be dangerous for the tug. Also, the discharge from the tug propeller can hit the ship and create a force resisting to pull.

The above considerations are examples that the simulation of tugboat assistance can be very complex. However, not all points are of equal importance for a specific simulation project.

It is recommendable that tugboat masters cooperate in simulations, as the interpretation of the pilot orders by the tugboat master is an important factor.

More elaborate models treat tugboats with a complex mathematical model, like the one used for the ship. This is the case of maneuver simulators that interact with one another.

For a more complete approach on the subject and its application to simulator projects, we recommend the book *Tug Use in Ports*, by pilot Captain Henk Hensen.

II.1.14. Action of fenders, mooring ropes, mooring buoys, anchors, piers and other topics related to ship berthing/unberthing

The ship's speed is suddenly reduced in case of a collision with a quay, dolphin, another vessel or bank. For modeling the ship's speed reduction and deceleration, a force representing the reaction of the structure to the ship must be introduced.

The impact force will cause a deflection or a deformation to the structure struck by the ship. Such deflection and/or deformation will depend on the structure's mass and stiffness. The penetration of the ship into the structure will depend on the obstruction offered by the structure. Light obstructions will allow large penetrations.

While the structure deformation is in the elastic regime, the energy stored in the structure elastic deformation will produce a reaction force that will push the vessel outwards.

The fenders are projected for absorbing as much energy as possible and for generating a limited reaction force.

Thus, impact forces can be modelled by means of a mass-spring-damper, in which the impact force is calculated as a function of the vessel's penetration into the obstruction.

Another aspect to be addressed is the water behavior around the ship. The ship's movement creates a long wave, and the pressures originating from such fluid movement will cause alterations to the pressure fields acting on the hull, which will give rise to a lateral force and a moment that changes with time.

Figure A17. Shows schematically two kinds of structure utilized for berthing a vessel. In the case of a closed structure, when the vessel moves, it pushes the water towards the wall. The water will then have to flow under the keel or near the bow or astern. In very shallow waters, the amount of water flowing under the keel is small, and the level of water trapped between the vessel and the wall rises, causing a damping force.

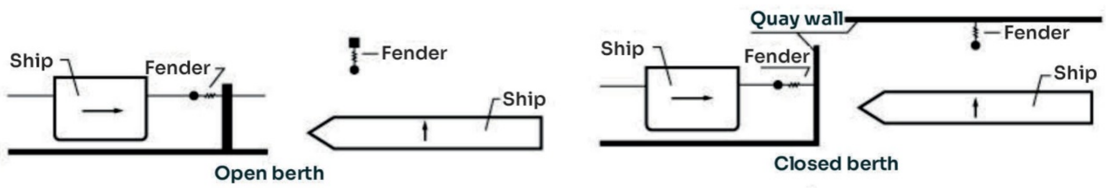

Figure A17. Schematic of open structure and closed structure utilized for berthing a vessel (PIANC, 1992, *Bulletin* 77)

Thus, the mathematical model of impact forces must take into consideration:

– The stiffness and damping of the struck structure;
– The long wave forces due to the sudden deceleration of the ship;
– The damping effects near a closed structure.

Bow anchors are employed for keeping the vessel moored to the sea bed, as well as for assisting in a maneuver by imposing an external force on the ship by means of the anchor chain fixed to the bottom of the sea. Besides these applications, the bow anchor can be employed as an emergency measure for stopping the ship.

The heavy iron anchor chain hangs in a catenary curve from the hawse hole to the seabed. Part of the chain can rest laying on the sea bed, which adds to the holding force of the anchor. Such conformation of the mooring line is a function of the distance between the anchor and the hawsepipe, of the water depth, of the weight of the chain and anchor and of the tension on the line. When the distance between the anchor and the hawsepipe grows, the tension on the chain and the force to the ship increases. If the tension on the chain exceeds the holding power, the ship will drag its anchor. The holding power depends on the anchor weight, its holding capability and on the local seabed characteristics.

The anchor chain tension calculation can be made by solving the catenary equation. The ratio between computational time and real time, however, requires a more schematic representation of the anchor system.

Mooring lines are usually made of synthetic fibers (nylon, polypropylene, polyester), or steel wire, each one having its own elastic properties. Their function is to keep the vessel moored. Mooring lines can be represented by (nonlinear) springs.

Usually, the simulation is finished in a position where the ship is as close as possible to the berth to allow the connection of the mooring ropes. Since berthing of large ships take a long time and is not a critical operation relatively to the fairway or port design, it is justifiable to complete the simulation without performing the whole berthing maneuver. It must be emphasized, however, that it is possible to simulate berthing/unberthing maneuvers to/from quays and mooring/unmooring maneuvers to/from single buoys with the type of mathematical model herein described, on a full mission simulator. There are also specific simulators for berthing maneuvers, which main purpose is to determine the number of mooring lines required for keeping the ship safely berthed.

II.2. Ship maneuvering simulators as regards to kind of interaction and model response time

As regards to interaction with human control, simulation methods can be divided in two groups: noninteractive and interactive.

In noninteractive simulation, the whole navigation process is mathematically modelled, but there is no human interference on the ship control process. This method can be employed either in vessel traffic studies or in studies of ship maneuverability under external environmental influences employing an automatic pilot. In such case, there is no need for running the simulation in real time, which is the reason why noninteractive simulation is often called fast time simulation.

In interactive simulation, the interference with the simulator occurs by means of a human operator. Ship's path, speeds and movements are never alike. Usually, interactive simulation means simulation in real time. However, the time scale may be enlarged in some cases.

II.3. Types of simulators as to their installation environment

As to the installation environment, simulators can be divided into:

– Micro simulators;
– Mini simulators;
– Full mission simulators;
– Multi- bridge simulators.

Micro simulators are characterized by the installation in a single computer or laptop, and can be operated by mouse and keyboard. Due to the capacity of the computers currently available, it is possible to install any maneuvering model and use it in all levels of training, design and research.

II.3.1. Mini simulators

Mini simulators are typically connected to a computer network that allows, for instance, using a computer for representing the navigation equipment, another one for visualizing the scenario and another one for controlling the ship.

They are ideal for implementing in places where the available physical space is reduced.

Vessel controls can be mounted in mini consoles and adapted to the type of vessel to be utilized in the training.

The visual projection can be made by means of video screens of different sizes.

II.3.2. Full mission simulators

The characteristic of these simulators is a bridge like the ones found in real vessels, where most of the instruments are real and emulated. They also have a visual projection room that, depending on the available space, can allow a 360-degree vision.

II.3.3. Simulators with multiple interactive bridges

In these simulators there is at least a full mission bridge that interacts with the other crafts, which have independent controls. For instance, in a berthing maneuver it is possible to put the tugboat crews interacting with the ship.

Part III – Basic Theoretical Aspects in Maneuvering Theory

III.1. Introduction

The aim of this appendix Part III is to present basic theoretical aspects to help comprehension of maneuver mathematical models. There was no intention to go in-depth on the theories of the contents presented. Emphasis was given to representation of hydrodynamic forces on the ship hull and of forces created by the rudder and propeller.

The development of the equations that follow was based on books by Greenwood (1988) and Fossen (2011), publications by Gertler and Hagen (1967), Abkowitz (1964), Eda (1971) and volumes 2 and 3 of PNA, edited by Lewis.

III.2. Ship dynamics

Initially, two orthogonal coordinate systems are defined: one fixed ashore (OXYZ), another one solidary to the ship (oxyz), with its axis ox pointing at the ship's forward longitudinal direction, the oy axis pointing at the starboarsided and the oz axis pointing at the ship's bottom. The fixed system ashore has its OXY plane on the free water surface at rest and its OZ axis pointing vertically at the bottom. In its initial rest condition, the systems have their axis in parallel (OX and ox, OY and oy, OZ and oz). The ship gravity center has coordinates xG, yG, zG in the ship solidary system. The ship linear speed relative to the solidary system is the linear instant speed of the origin point of the sy system solidary to the body, and has the components u, v, w. The ship's speed relative to the fixed system ashore has the components U,V,W. Knowing the values of u,v, w at an instant, it is possible to determine U, V, W and then the ship's advances ΔX, ΔY, ΔZ in a time increment Δt, where t is the time.

The body angular spatial orientation is described by Euler angles (ϕ, θ, ψ),, observing the use of a sequence of rotations. For example, ψ around oz axis, θ around oy and ϕ around ox. Figure A18. presents the rotation around the axis according to the values of Euler angles.

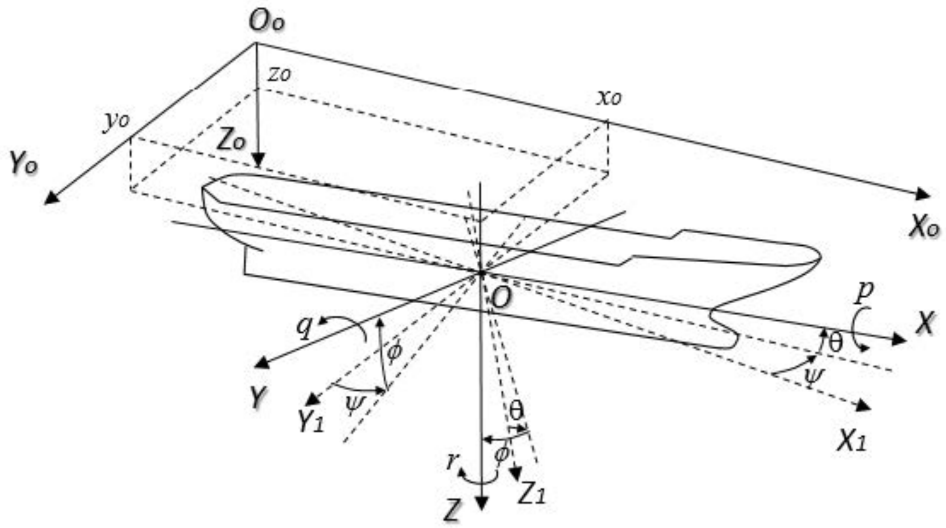

Figure A18. Euler angles

Rotation rates around each axis per unit of time ($\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$) at each moment relate to p, q, r through the Euler angles, p, q, r being the components of the ship's angular speed in the solidary system. Thus, once p, q, r are known, $\Delta\phi$, $\Delta\theta$, $\Delta\psi$ can be obtained and thence, the new set of values for the Euler angles.

The values of u, v, w, p, q, r are obtained by integrating to time the force and moment equations formulated from Newton's second law: for an element of mass δm, by applying a force **f**, such element will have an acceleration **a**. Newton's second law is expressed by **f** = δm**a**. Printings in boldface indicate vectors. Once integrated the linear displacement quantity equation and the angular movement quantity equation relatively to a point, the body displacement equations are obtained by means of the body whole volume, as follows

$$m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})] = X \quad (1)$$
$$m[\dot{v} - wp + ur + x_G(qp + \dot{r}) - y_G(r^2 + p^2) + z_G(qr - \dot{p})] = Y$$
$$m[\dot{w} - uq + vp + x_G(rp - \dot{q}) + y_G(rq - \dot{p}) - z_G(p^2 + q^2)] = Z$$
$$I_{xx}\dot{p} + (I_{zz} - I_{yy})qr - (\dot{r} + pq)I_{zx} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy} + m[y_G(\dot{w} - uq + vp) - z_G(\dot{v} - wp + ur)] = K$$
$$I_{yy}\dot{q} + (I_{xx} - I_{zz})rp - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{zx} + (qp - \dot{r})I_{yx} - m[x_G(\dot{w} - uq + vp) - z_G(\dot{u} - vr + wq)] = M$$
$$I_{zz}\dot{r} + (I_{yy} - I_{xx})pq - (\dot{q} + rp)I_{yx} + (q^2 - p^2)I_{xy} + (rq - \dot{p})I_{zx} + m[x_G(\dot{v} - wp + ur) - y_G(\dot{u} - vr + wq)] = N$$

External forces are given by:

$$X = X_I + X_H + X_P + X_R + X_C + X_A + X_W + X_{OUT} \quad (2)$$
$$Y = Y_I + Y_H + Y_P + Y_R + Y_C + Y_A + Y_W + Y_{OUT}$$
$$Z = Z_I + Z_H + Z_P + Z_R + Z_C + Z_A + Z_W + Z_{OUT}$$
$$K = K_I + K_H + K_P + K_R + K_C + K_A + K_W + K_{OUT}$$
$$M = M_I + M_H + M_P + M_R + M_C + M_A + M_W + M_{OUT}$$
$$N = N_I + N_H + N_P + N_R + N_C + N_A + N_W + N_{OUT}$$

where

where m is the ship mass;

I_{xx}, I_{yy}, I_{zz} are the mass inertia moments of the ship;

I_{xy}, I_{xz}, I_{yx}, I_{yz}, I_{zx}, I_{zy} are the products of inertia;

and employing G for representing X, Y, Z, K, M, N we get

G_I – forces and moments of hydrodynamic inertia;

G_H – other non-inertial forces and hydrodynamic moments of reaction to ship movement as a function of the ship's speeds;

G_P – forces and moments due to action of propeller;

G_R – forces and moments due to action of rudder;

G_C – forces and moments due to action of currents;

G_V – forces and moments due to resistance of air and to action of wind;

G_W – forces and moments due to action of waves;

G_{OUT} – forces and moments due to other factors, as anchor chains, towing, interaction with other vessels, bank effects, depth, etc.

The dots on letters u, v, w, p, q, r indicate a derivative relative to time, that is , $\dot{u}$, $\dot{v}$, $\dot{w}$, $\dot{p}$, $\dot{q}$, $\dot{r}$ are instant accelerations of the ship in surge, sway, heave, roll, pitch and yaw.

Inertia hydrodynamic forces of potential origin are given by:

$$
\begin{aligned}
X_I &= X_{\dot{u}}\dot{u} - Y_{\dot{v}}vr + Z_{\dot{w}}wq \\
Y_I &= Y_{\dot{v}}\dot{v} - Z_{\dot{w}}wp + X_{\dot{u}}ur \\
Z_I &= Z_{\dot{w}}\dot{w} - X_{\dot{u}}uq + Y_{\dot{v}}vp \\
K_I &= K_{\dot{p}}\dot{p} + (N_{\dot{r}} - M_{\dot{q}})qr + (Z_{\dot{w}} - Y_{\dot{v}})vw \\
M_I &= M_{\dot{q}}\dot{q} + (K_{\dot{p}} - N_{\dot{r}})rp + (X_{\dot{u}} - Z_{\dot{w}})wu \\
N_I &= N_{\dot{r}}\dot{r} + (M_{\dot{q}} - K_{\dot{p}})pq + (Y_{\dot{v}} - X_{\dot{u}})uv
\end{aligned} \tag{3}
$$

Where $X_{\dot{u}}$, $Y_{\dot{v}}$, $Z_{\dot{w}}$, $K_{\dot{p}}$, $M_{\dot{q}}$, $N_{\dot{r}}$, $Y_{\dot{v}}$ are masses and additional inertia moments of hydrodynamic origin.

In the notation employed, letters X, Y, Z, K, M and N indicate factors representing the fluid action towards surge, sway and heave, or roll, pitch and yaw moments, respectively. Subscript letters indicate the acceleration to which the ship must be submitted for generating the action. It must be observed that such factors appear multiplying accelerations and also speeds. This is a consequence of nonlinear effects and of the formulation of forces being performed in a ship solidary system.

The equation system presented in (2) and (3) is a system with six degrees of freedom. However, it can be considered that heave and pitch movements are governed by the action of waves. Thus, for certain types of ships, in which the roll motion may be affected by maneuver effects, the equation system can be reduced to just four equations:

$$
\begin{aligned}
& m[\dot{u} - vr - x_G r^2 + z_G pr] = X \\
& m[\dot{v} + ur + x_G\dot{r} - z_G\dot{p}] = Y \\
& I_{xx}\dot{p} - \dot{r}I_{zx} + r^2 I_{yz} + prI_{xy} - mz_G(\dot{v}p + ur) = K \\
& I_{zz}\dot{r} - rpI_{yx} - p^2 I_{xy} - \dot{p}I_{zx} + mx_G(\dot{v} + ur) = N
\end{aligned} \tag{4}
$$

In case of vessels in motion, roll motion is practically decoupled from the displacements in the horizontal plan (surge, sway and yaw), and the modeling of shiphandling equations can be reduced to a system with three degrees of freedom:

$$
\begin{aligned}
& m(\dot{u} - vr - x_G r^2) = X \\
& m(\dot{v} + ur + x_G\dot{r}) = Y \\
& I_{zz}\dot{r} + mx_G(\dot{v} + ur) = N
\end{aligned} \tag{5}
$$

In the introduction part of this chapter, some tests were described for establishing relationships between forces acting on a ship model as a function of its speeds. Tests called pure drift, pure sway and pure yaw were presented, so that, by measuring the forces acting on the hull, it would be possible to write them as a function of the speeds and accelerations imposed on the model. These are cases of simple tests. More sophisticated tests can be elaborated by combining, for example, surge, sway and yaw forward speed simultaneously, for establishing a functional relationship between forces and motions (velocities and accelerations).

Focusing on the case of a ship in motion in which the only existing actions are due to the hydrodynamic reactions of the hull to a propeller and a rudder, and adopting a system solidary to the ship with origin in its diametral plane, as well as ignoring the action of the air, then motion equations can be written as follows:

$$m(\dot{u} - vr - x_G r^2) = X_I + X_H + X_P + X_R \quad (6)$$
$$m(\dot{v} + ur + x_G \dot{r}) = Y_I + Y_H + Y_P + Y_R$$
$$I_{zz}\dot{r} + mx_G(\dot{v} + ur) = N_I + N_H + N_P + N_R$$

Hydrodynamic inertia forces of potential origin can thus be given by:

$$X_I = X_{\dot{u}}\dot{u} - Y_{\dot{v}}vr \quad (7)$$
$$Y_I = Y_{\dot{v}}\dot{v} - X_{\dot{u}}ur$$
$$N_I = N_{\dot{r}}\dot{r} + (Y_{\dot{v}} - X_{\dot{u}})uv$$

For building a maneuvering model for this ship, physical tests and mathematical models must be employed for determining the factors $X_{\dot{u}}$, $Y_{\dot{v}}$ and $N_{\dot{r}}$, in order to write expressions that result $X_H = f_1(u, v, r)$, $Y_H = f_2(u, v, r)$ and $N_H = f_3(u, v, r)$ and expressions that, taking into consideration the interaction hull/propeller/rudder, describe $X_P = f_4(n, V_s)$, $Y_P = f_5(n, V_s)$, $N_P = f_6(n, V_s)$ and $X_R = f_7(\delta, V_s)$, $Y_R = f_8(\delta, V_s)$, $N_R = f_9(\delta, V_s)$, in which n, V_s and δ are, respectively, the rotation of the propeller, the ship's speed and the rudder angle.

III.3. Ship maneuvering linear model and experimental determination of the coefficients

In the case of a ship moving ahead in calm, deep waters without action of winds, trying to keep a straight path, but subject to small alterations to its route that are compensated by rudder actions, the motion equations can be simplified. Assuming the propeller lateral force to be negligible, we get

Force equation in the ox direction

$$mu = X_I + X_{\dot{H}} + X_P + X_R \quad (8)$$

Force equation in the oy direction

$$m(\dot{v} + ur + x_G\dot{r}) = Y_I + Y_H + Y_R \quad (9)$$

Moment equation around oz axis

$$I\dot{r} + mx_G(\dot{v} + ur) = N_I + N_H + N_R \quad (10)$$

By adopting for $X_I + X_H$ the expression

$$X_I + X_H = X_{\dot{u}}\dot{u} + X(u, v, r) = X_{\dot{u}}\dot{u} + X_{uu}u_0(u_0 + mu) \quad (11)$$

Where u_0 is a mean speed and $u = u_0 + \Delta u$, the longitudinal speed u varies around u_0,, which would be the advance speed should the ship be moving at a steady speed in a straight line.

One can separate the equation of forces in ox into an equation for average speed

$$X_P + X_R + X_{uu} u_0 \left| u_0 \right| = 0 \tag{12}$$

and another one for the oscillatory term

$$(m - X_{\dot{u}})\dot{u} - X_{uu} u_0 m u = 0 \tag{13}$$

As for sway and yaw motions, it is admissible that hydrodynamic reactions $Y_I + Y_H$ and $N_I + N_H$ are due to inertia effects of fluid particles and wing effects, described by a linear approximation

$$\begin{aligned} Y_I + Y_H &= Y_{\dot{v}}\dot{v} + Y_v v u_0 + Y_{\dot{r}}\dot{r} + Y_r u_0 r \\ N_I + N_H &= N_{\dot{v}}\dot{v} + N_v v u_0 + N_{\dot{r}}\dot{r} + N_r u_0 r \end{aligned} \tag{14}$$

and also that the lateral force and the moment induced by the propeller are null. Thus, the sway and yaw equations are written as

$$(m - Y_{\dot{v}})\dot{v} - Y_v v u_0 - (Y_{\dot{r}} - m x_G)\dot{r} - (Y_r - m)u_0 r = Y_R \tag{15}$$

$$(I_{zz} - N_{\dot{r}}\dot{r} - (N_r - m x_G) r u_0 - (N_{\dot{v}} - m x_G)\dot{v} - N_v v u_0 = N_R \tag{16}$$

where Y_R and N_R are the lateral force and yaw moment caused by the rudder action.

For expressing the equations in a dimensionless form, the force equations are divided by $0.5\rho L_{pp}^2 U^2$, the moment equation is divided by $0.5\rho L_{pp}^3 U^2$ and so the equations are then written in the form

$$\begin{aligned} &(m' - X'_{\dot{u}})\dot{u} - X'_{uu} m u' = 0 \\ &(m' - Y'_{\dot{v}})\dot{v}' - Y'_v v' - (Y'_{\dot{r}} - m' x'_G)\dot{r}' - (Y'_r - m')r' = Y'_R \\ &(I'_{zz} - N'_{\dot{r}})\dot{r}' - (N'_r - m' x'_G)r' - (N'_{\dot{v}} - m' x'_G)\dot{v}' - N'_v v' = N'_R \end{aligned} \tag{17}$$

It is important to observe that it is assumed that $u_0/U \approx 1$.

From such expressions, it can be seen that the equation in the longitudinal direction is independent from the other two, as well as that the last two form a system of two coupled non-homogeneous linear differential equations.

Such equations represent the application of Newton's second law to the components of forces and accelerations in two directions in the horizontal plan, and the extension of the second law for the case of the moment relative to a vertical axis perpendicular to the linear motion plan, around which the body moves. It is usual to call them motion equations, as by means of their integrations, the evolution of the body's motions along the time can be obtained.

III.4. Tests for modeling hydrodynamic forces on the hull

Ship horizontal motion equations employing linear approximations for describing the variation of forces with different velocities have eight hydrodynamic coefficients to be determined for allowing the assessment of a vessel's maneuverability. Usually, there are two ways for estimating such coefficients. The first one is to estimate them by means of empiric expressions, picked up from experiments with similar crafts, systematizing the variations of form. The other one implies in employing laboratory tests with a reduced ship model. Ways of obtaining coefficients by means of laboratory tests are presented in this section. Some captive tests are shown below, in which the model remains tethered by mechanisms that impose forced movements to it and measures forces and movements. The development of the equations that follow are based on class notes of professor John V. Wehausen, University of California, Berkeley, where he taught from 1956 to 1984 and thereafter remained active.

III.4.1. Towing test

This test consists of towing a model along a tank at a constant forward speed U, keeping a steady fixed heading angle (see Figure A19.). Several runs are performed with the model, varying the velocity and the attack angle. As the major interest is in ship maneuvers at normal velocities, there is no need for working with large heading angles. Besides that, a search is carried out for derivatives of lateral force functions and yaw moment against the attack angle around the origin, that is, for small angles.

This test measures the lateral force Y and the yaw moment N acting on the model with length L, for speed U and incidence angle ψ, in a fluid of density ρ and dynamic viscosity μ in presence of free surface, that is, under gravitational effects with acceleration g. Thus, it can be written

$$Y/(1/2\rho U^2L^2) = f_1(R_e, F_r, \psi) \qquad (18)$$
$$N/(1/2\rho U^2L^3) = f_2(R_e, F_r, \psi)$$

where $R_e = \varrho UL/\mu$ and $F_r = U/\sqrt{gL}$ are the Reynolds and Froude numbers, respectively.

The similarity between the model and the ship can only be trusted if, simultaneously, the model Reynolds number $R_{e,m}$, is equal to the ship Reynolds number $R_{e,n}$, and the model Froude number $F_{r,m}$, is equal to the ship Froude number, $F_{r,n}$, and then:

$$Y_m/(1/2\varrho_m U_m{}^2L_m{}^2) = Y_n/(1/2\varrho_n U_n{}^2L_n{}^2) \qquad (19)$$
$$N_m/(1/2\varrho_m U_m{}^2L_m{}^3) = N_n/(1/2\varrho_n U_n{}^2L_n{}^3)$$

Admitting that the environmental conditions acting on the ship and on the model respect geometric, kinematic and dynamic similarities, the results of tests could then be extrapolated to the real ship if, simultaneously

$$U_mL_m = U_nL_n \qquad (20)$$
$$U_m/\sqrt{L_m} = U_p/L_p$$

Which is only possible if $L_m = L_n$ e $U_m = U_n$. However, such deadlock can be overcome, once experience has showed that the results are weakly dependent on the Reynolds number. That is, they do not suffer significant alterations due to variations of the Reynolds number if the tests are performed with large models and if due care is taken to have the flow in the limit layer in the model similar to the flow in the limit layer in the ship by means of providing turbulence stimulators.

For this test, it is known that

$$v = - U \sin\psi \tag{21}$$

and

$$v' = v/U = - \sin\psi \tag{22}$$

Thus, it can be written:

$$Y' = Y/(1/2\rho U^2 L^2) = f_1(R_e, F_r, v') \tag{23}$$

$$N' = N/(1/2\rho U^2 L^3) = f_2(R_e, F_r, v')$$

Expanding these functions in Taylor series around position $\psi = 0$ and considering the linear approximation, we get the hydrodynamic derivatives:

$$Y'(v') = Y'(0) + (dY'/dv')v' \tag{24}$$

$$N'(v') = N'(0) + (dN'/dv')v'$$

Employing the notation Y_v' for the derivative of Y' relatively to v', we get:

$$Y_v' = \frac{dY'}{dv'} = \frac{dY/(1/2\rho U^2 L^2)}{dv/U} = \frac{1}{1/2\rho U L^2}\frac{dY}{dv} \tag{25}$$

$$N_v' = \frac{dN'}{dv'} = \frac{dN/(1/2\rho U^2 L^3)}{dv/U} = \frac{1}{1/2\rho U L^3}\frac{dY}{dv}$$

and since

$$\frac{dY}{dv} = - \frac{dY}{U d\psi} \tag{26}$$

$$\frac{dN}{dv} = - \frac{dN}{U d\psi}$$

the values of Y_v' and N_v' can be obtained.

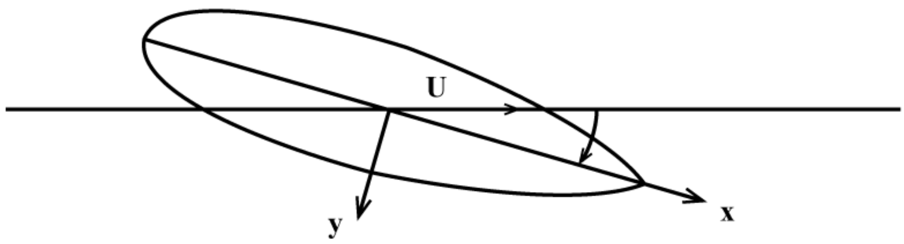

Figure A19. Towing test with fixed drift angle – "pure drift"

III.4.2. Test with rotating arm

The execution of this test requires a special apparatus. Schematically, a round tank of radius R_b and a long arm of length R_b must be available. The arm is put in a horizontal plan with one end connected to the end of a vertical rod, located in the axis that passes by the center of the tank. The connection of the arm to this point allows it to turn around the rod, remaining perpendicular to it. A wheel fixed to the arm runs along a rail on the lateral of the tank. The ship model is fixed to a point along the arm at a distance R from the center of the tank so that, when the model longitudinal axis is positioned in perpendicular to the arm and the arm turns around its end located at the vertical axis that passes by the center of the tank, the model will be at a velocity ≠ 0 and v = 0. As a consequence, $\dot{v} = 0$. As the arm turns at constant velocity, then $\dot{r} = 0$. The tangential velocity, the model motion velocity in the solidary system, is given by $u = R\Omega$, in which Ω is the angular velocity of the arm, which is the yaw velocity of the model r.

Figure A20. shows a circular cylindric tank scheme, with a rotating arm linked to it. A photo of a tank with a rotating arm of the Stevens Institute Davidson Laboratory is shown in PNA third volume, Figure 33 on page 233.

Like it was presented in the previous item, the dependency of forces and moments on Reynolds and Froude numbers must be analyzed. In this case, keeping the Froude number constant means keeping constant the value of u. Thus, by varying R and Ω in such a way that u remains constant, the following functions are being experimentally generated

$$Y = f_1(\Omega) \tag{27}$$

and

$$N = f_2(\Omega) \tag{28}$$

with which their derivatives are determined for $\Omega = 0$, thus getting the derivatives:

$$Y_r = \frac{dY(\Omega)}{d\Omega} \tag{29}$$

$$N_r = \frac{dN(\Omega)}{d\Omega}$$

and

$$Y_r' = \frac{dY'}{dr'} = \frac{d\dfrac{Y}{1/2\rho U^2 L^2}}{d\dfrac{rL}{U}} = \frac{dY}{dr}\frac{1}{1/2\rho U^2 L^3} = Y_r \frac{1}{1/2\rho U^2 L^3} \tag{30}$$

$$N_r' = \frac{dN'}{dr'} = \frac{d\dfrac{N}{1/2\rho U^2 L^3}}{d\dfrac{rL}{U}} = \frac{dN}{dr}\frac{1}{1/2\rho U^2 L^4} = N_r \frac{1}{1/2\rho U^2 L^4}$$

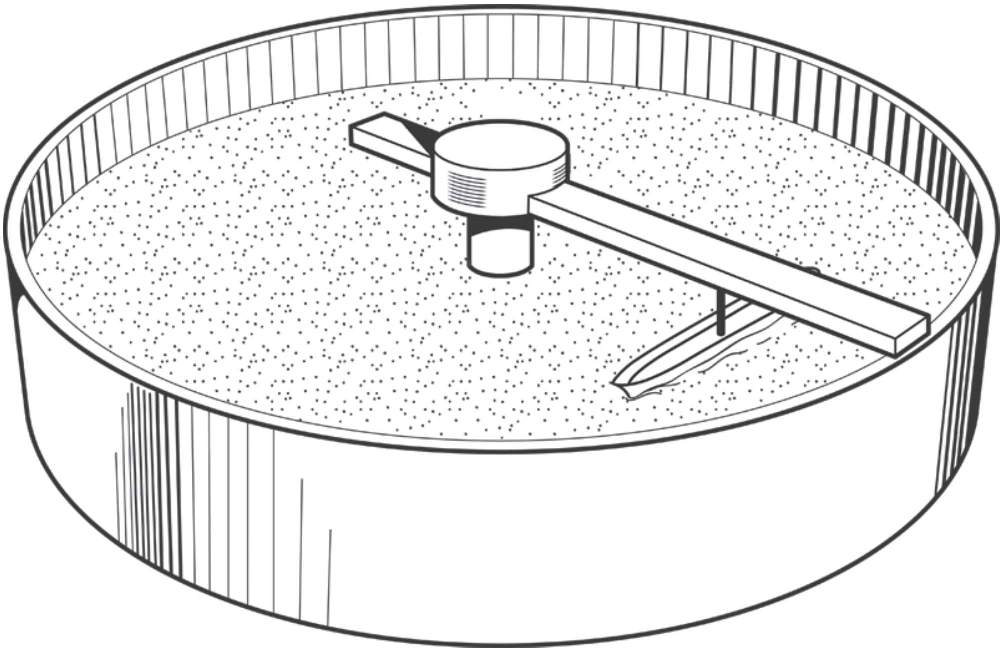

Figure A20. Rotating arm

III.4.3. Planar Motion Mechanism – PMM

The previous tests allow only to establish four out of eight hydrodynamic derivatives required for determining the ship's directional stability. PMM is a mechanism that enables obtaining all eight required derivatives for a full assessment of the ship's directional stability. Figure A21. shows a schematic of a PMM.

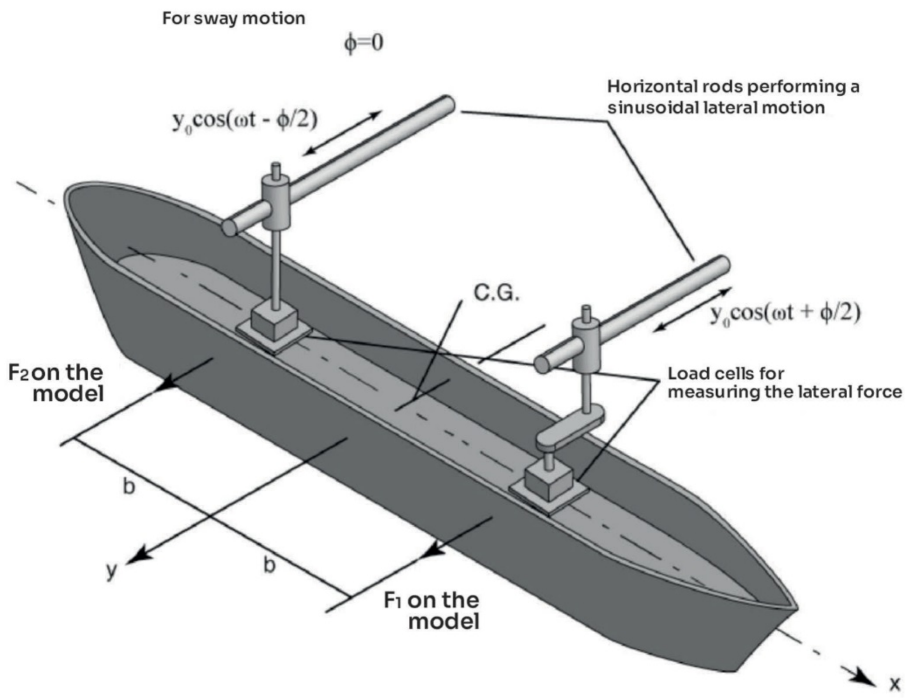

Figure A21. PMM (planar motion mechanism) scheme

Such mechanism consists of two horizontal rods mounted transversely to the model longitudinal axis, at a distance 2 b between them. Two vertical rods fixed to each of the horizontal rods are connected to the model, at two different points of its longitudinal axis. Each vertical rod is fixed to a unique point, one of them ahead and the other astern of the gravity center of the model. Each horizontal rod can move independently and harmonically. Horizontal movements are then applied laterally do the ship, in the form

$$y_A = y_0 \mathrm{Sin}(\omega t + \phi_A) \tag{31}$$

$$y_R = y_0 \mathrm{Sin}(\omega t + \phi_R)$$

to each one of the rods as the model moves forward and the forces acting on each rod are measured, Y_A and Y_R. According to the phase angles of the movements, while the model moves forward longitudinally, it is possible to keep it:

case 1 - parallel to the longitudinal axis, executing a harmonic transverse movement;

case 2 – touching the path as a tangent, executing a harmonic transverse movement;

case 3 – oscillating periodically around a point at the longitudinal axis, with such point moving longitudinally without executing transverse motion.

III.4.4. Pure sway

In this case, null phase motions are kept on both rods

$$\phi_A = \phi_R = 0 \tag{32}$$

The center of the system moves with $x = Ut$, $y = y_0 Sin(\omega t)$, describing a movement schematically shown in Figure A22. (pure sway). The model path and its positioning during the test are schematically presented in the pure sway figure.

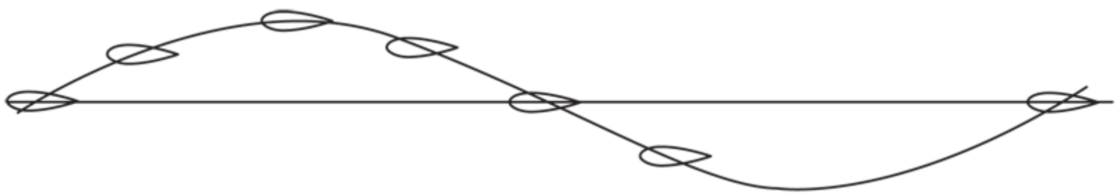

Figure A22. Path scheme of a model executing a pure sway test

The totals of force and moment applied by the PMM to the model are

$$Y_T = Y_A + Y_R \tag{33}$$

$$N_T = (Y_A - Y_R)b$$

In such conditions, we have $r = \dot{r} = 0$ and the lateral and the angular motion equations are

$$(m - Y_{\dot{v}})\dot{v} - Y_v v = Y_T = Y_A + Y_R \tag{34}$$

$$- (N\dot{v} - x_G m)\dot{v} - N_v v = N_T = (Y_A - Y_R)b$$

Introducing in such equations the speed v and acceleration $\dot{v}$ expressions

$$v(t) = \omega y_0 Cos(\omega t) \tag{35}$$

$$\dot{v}(t) = - \omega^2 y_0 Sin(\omega t)$$

we get:

$$- (m - Y_{\dot{v}})\omega^2 y_0 Sin(\omega t) - Y_v \omega y_0 Cos(\omega t) = Y_A + Y_R \tag{36}$$

$$(N_{\dot{v}} - x_G m)\omega^2 y_0 Sin(\omega t) - N_v \omega y_0 Cos(\omega t) = (Y_A + Y_R)b$$

With the records of $Y_A(t)$ and $Y_B(t)$ and using the orthogonality property of sinus and cosine functions, it is possible to determine the hydrodynamic coefficients.

It is also possible to observe the values of forces measured at instant $t_1 = n\pi/\omega$, with n = 0, 1, 2, ... integer, and the values of forces measured at instant $t_2 = (n\pi + \pi/2)/\omega$ and then determine the hydrodynamic derivatives:

$$Y_v = -\frac{Y_T(t_1)}{v} = -\frac{Y_A(t_1) + Y_R(t_1)}{y_0\omega} \tag{37}$$

$$N_v = -\frac{N_T(t_1)}{v} = -b\frac{Y_A(t_1) - Y_R(t_1)}{y_0\omega}$$

$$Y_{\dot{v}} - m = -\frac{Y_T(t_2)}{\dot{v}} = -\frac{Y_A(t_2) - Y_R(t_1)}{y_0\omega^2}$$

$$N_{\dot{v}} - x_G m = \frac{N_T(t_2)}{\dot{v}} = -b\frac{Y_A(t_2) - Y_R(t_2)}{y_0\omega^2}$$

III.4.5. Pure yaw

In this case, both rods are kept moving in phases of equal modules, but opposite signs

$$\phi_A = -\phi_R = \alpha \tag{38}$$

The center of the system moves with

$$x = Ut \tag{39}$$

$$y = y_0 \mathrm{Cos}(\alpha)\mathrm{Sin}(\omega t)$$

The tangent to the path of the central point is:

$$\frac{dy}{dx} = \frac{dy}{dt}\frac{dt}{dx} = y_0\omega\mathrm{Cos}(\alpha)\mathrm{Cos}(\omega t)\frac{1}{U} \tag{40}$$

And the inclination of the ship's longitudinal axis, its heading ψ, is given by:

$$\tan\psi = \frac{y_A - y_R}{2b} = y_0\frac{\mathrm{Sin}(\omega t + \alpha) - \mathrm{Sin}(\omega t - \alpha)}{2b} = \frac{y_0}{b}\mathrm{Sin}\alpha\mathrm{Cos}\left(\frac{\omega x}{U}\right) \tag{41}$$

To make such inclinations equal

$$\tan(\psi) = \frac{y_A - y_R}{2b} = \frac{dy}{dx} \tag{42}$$

and then

$$y_0\omega \mathrm{Cos}(\alpha)\mathrm{Cos}(\omega t)\frac{1}{U} = \frac{y_0}{b}\mathrm{Sin}(\alpha)\mathrm{Cos}\left(\frac{\omega x}{U}\right) \tag{43}$$

or

$$\tan(\alpha) = \frac{\omega b}{U} \tag{44}$$

As the ship's longitudinal axis is always tangent to the path, then $v = \dot{v} = 0$.

The model pathway and its positioning during the test are schematically presented in Figure A23.

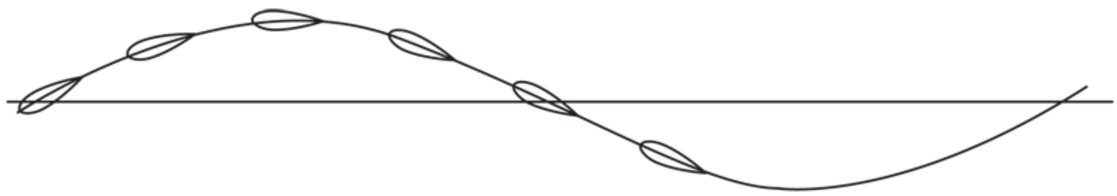

Figure A23. Schematic of pathway of a model performing a pure yaw test

Assuming that ψ angle is small

$$\psi = \tan(\psi) = \frac{y_0}{b}\mathrm{Sin}(\alpha)\mathrm{Cos}\left(\frac{\omega x}{U}\right) \tag{45}$$

$$r = \dot{\psi} = -\frac{\omega y_0}{b}\mathrm{Sin}(\alpha)\mathrm{Sin}(\omega t)$$

$$\dot{r} = -\frac{\omega^2 y_0}{b}\mathrm{Sin}(\alpha)\mathrm{Cos}(\omega t)$$

and, as y_0 is small, then

$$u = \sqrt{U^2 + (y_0\omega \mathrm{Cos}(\alpha)\,\mathrm{Cos}(\omega t))^2} \approx U \tag{46}$$

Thus, the motion equations are given by:

$$(Y_{\dot{r}} - x_G m)\,\frac{\omega^2 y_0}{b}\,Sin(\alpha)Cos(\omega t) + (Y\{r\} - mU)\,\frac{\omega y_0}{b}\,Sin(\alpha)Sin(\omega t) = Y_A + Y_R \tag{47}$$

$$(I_{zz} - N_{\dot{r}})\,\frac{\omega^2 y_0}{b}\,Sin(\alpha)Cos(\omega t) + (N_r - x_G mU)\,\frac{\omega y_0}{b}\,Sin(\alpha)Sin(\omega t) = (Y_A + Y_R)\,b$$

As previously presented, the orthogonality property of sine and cosine functions can also be employed for determining the hydrodynamic coefficients or for observing the values of forces measured at instant $t_1 = n\pi/\omega$, with n = 0, 1, 2 … integer, and the values of forces measured at instant $t_2 = (n\pi + \pi/2)/\omega$ and thereafter determining the hydrodynamic derivativese

$$Y_{\dot{r}} - x_G m = b\,\frac{Y_A(t_1) + Y_R(t_1)}{y_0\omega^2 Sin(\alpha)} \tag{48}$$

$$N_{\dot{r}} - I = b^2\,\frac{Y_A(t_1) - Y_R(t_1)}{y_0\omega^2 Sin(\alpha)}$$

$$Y_r - Um = b\,\frac{Y_A(t_2) + Y_R(t_2)}{y_0\omega Sin(\alpha)}$$

$$N_r - Ux_g m = b^2\,\frac{Y_A(t_2) - Y_R(t_2)}{y_0\omega Sin(\alpha)}$$

III.4.6. Angular harmonic oscillation

In this test, the rods move with a 180-degree lag between them. Thus, when one of them moves in the positive sense, the other one proceeds in the negative sense. The model keeps the center of the system moving in a straight line along the tank, while its heading angle oscillates periodically.

Figure A24. “Oscillatory motion” shows the movement of a model during the test.

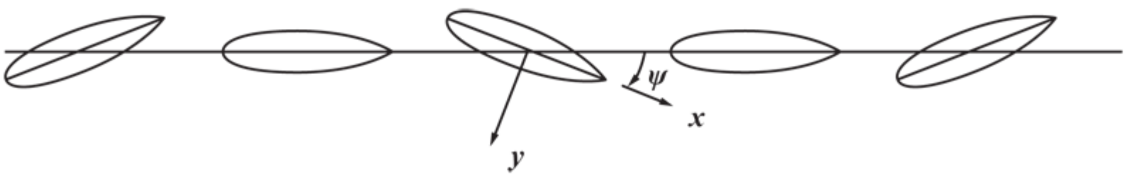

Figure A24. Schematic of the oscillatory motion test

This test can be performed by a “harmonic oscillator”, another device that does not require the use of a PMM.

In either case, the forces acting transversally and longitudinally to the movement of the small kart that tows the model are measured, as well as the moment around the center of the system..

$$\psi = \psi_0 \mathrm{Sin}(\omega t) \tag{49}$$

In this case, the modules of the heading and incidence angles are equal, and transverse and longitudinal speeds are given by:

$$u = U\mathrm{Cos}(\psi) \tag{50}$$

$$v = -\ U\mathrm{Sin}(\psi)$$

In such conditions, the motion equations are given by:

$$-\ (m - Y_v)U\mathrm{Cos}(\psi)\dot{\psi} + Y_v U\mathrm{Sin}(\psi) - (Y_{\dot{r}} - mx_G)\ddot{\psi} - (Y_r - mU)\dot{\psi} = -\ X_0\mathrm{Sin}(\psi) + Y_0\mathrm{Cos}(\psi) \tag{51}$$

$$(N_{\dot{v}} - mx_G)U\mathrm{Cos}(\psi)\dot{\psi} + N_v U\mathrm{Sin}(\psi) + (I_z - N_{\dot{r}})\ddot{\psi} - (N_r - mx_G U)\dot{\psi} = N$$

Same as in the above cases, one can explore the orthogonality of sinus and cosine functions, as well as to use the instants when sinus and cosine annul each other, and thus determine for the instant $t_1 = 0$

$$(m - Y_{\dot{v}})U\omega\psi_0\ \ -\ (Y_r - mU)\omega\psi_0 = Y_0(t_1 = 0) \tag{52}$$

$$-\ (N_{\dot{v}}\dot{v} - mx_G)U\omega\psi_0 - (N_r - mx_G U)\omega\psi_0\ \ = N(t_1 = 0)$$

and for instant $t_2 = \pi/(2\omega)$

$$-\ Y_v U\mathrm{Sin}(\psi_0) + (Y_{\dot{r}} - mx_G)\omega^2\psi_0 = -\ X_0(t_2)\mathrm{Sin}(\psi_0) + Y_0(t_2)\mathrm{Cos}(\psi_0) - N_v U\mathrm{Sin}(\psi_0) - (I_{zz} - N_{\dot{r}})\omega^2\psi_0 = N(t_2) \tag{53}$$

These four equations involve all eight derivatives. If hydrodynamic derivatives Y_v, Y_r, N_v and N_r have already been determined by towing and rotating arm tests, this test enables obtaining the additional hydrodynamic derivatives of acceleration, mass and inertia.

III.5. Hydrodynamic forces due to the rudder

A first approach for taking into consideration the force and moment created by the rudder can be formulated by despising the effect of the hull on the rudder. In such conditions, it will occur a flow at a speed equal to the speed of the ship. The rudder is deflected by an angle δ. By employing sustaining and dragging curves acting on a rudder obtained from laboratory tests, it can be assumed that the lateral force acting on the rudder for small angles is given by:

$$Y_R = C_L(\delta)\left(\frac{1}{2}\rho U^2 A_R\right) \approx \frac{dC_L(\delta = 0)}{d\delta}\,\delta\left(\frac{1}{2}\rho U^2 A_R\right) \tag{54}$$

dividing by $(1/(2)\rho L^2 U^2$, the force in the dimensionless form is then given by:

$$Y'_R = \frac{dC_L(\delta = 0)}{d\delta}\, v' \frac{A_R}{L^2} = Y'_{R,v} v' \tag{55}$$

Figure A25. (built from Figure 131 of PNA third volume) shows the behavior of the sustaining force coefficient for different rudder angles.

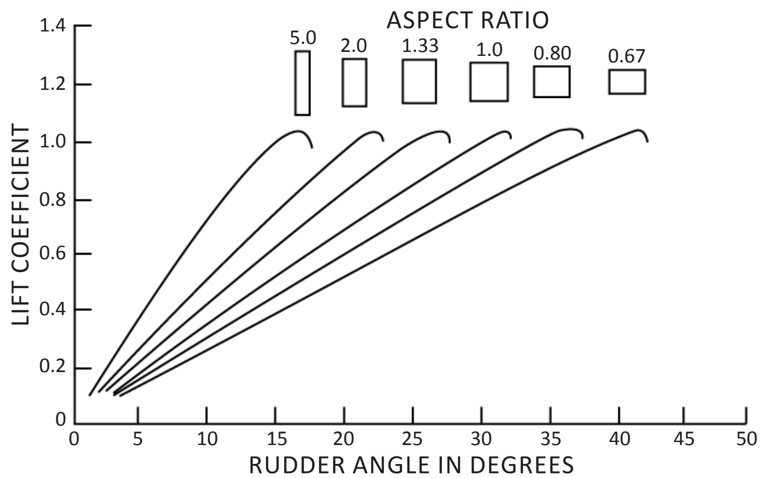

Figure A25. Sustaining force coefficient for different rudder angles (PNA vol.3, Figure 131)

Assuming that the pressure center on the rudder is located at a distance b from the center of the ship, the moment induced on the vessel by the rudder, in the dimensionless form, is given by:

$$N'_R = \frac{b}{L} Y'_R = b' \frac{dC_L(\delta = 0)}{d\delta} \frac{A_R}{L^2} \tag{56}$$

The dragging force on the rudder is given by:

$$X_R = C_D(\delta)\left(\frac{1}{2}\rho U^2 A_R\right) \tag{57}$$

The behavior of the dragging coefficient $C_D(\delta)$ can be observed in Figure A26, built from PNA third volume, Figure 132, for a rudder of profile section NACA 0015, $R_e = 2{,}7 \times 10^6$, shown in PNA (original by Whicker and Fehlner, 1958).

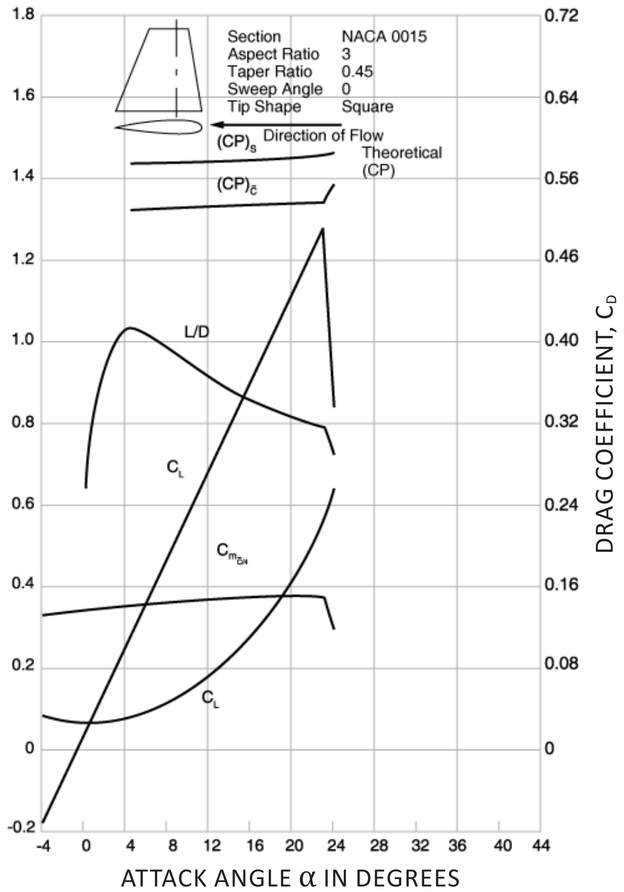

Figure A26. Drag coefficients for a rudder of profile section NACA 0015, $R_e = 2.7 \times 10^6$, presented in PNA (original by Whicker and Fehlner, 1958)

In principle, this model does not take into consideration the presence of the ship. It is necessary to include the ship influence on the rudder. In this case, tests of forces acting on the ship can be performed, employing a model fitted with a rudder. The model is towed along the tank, keeping a null heading angle. If the rudder angle is kept null, there will be neither lateral force nor yaw moment acting on the rudder. The model is then towed at different rudder angles, and longitudinal, lateral forces and yaw moment are then recorded. Thus, functions $X_R(\delta)$, $Y_R(\delta)$ and $N_R(\delta)$. are created. Obtaining the derivatives of these functions relatively to the rudder angle ($Y_\delta(\delta)$, $Y_\delta(\delta)$ and taking their values for $\delta = 0$, the hydrodynamic derivatives of the lateral force and of the moment relatively to the rudder angle are obtained. Thus, we get the forces and moments due to rudder action for a linear approximation of the lateral force and yaw moment

$$Y_R(\delta) = Y_\delta(0)\delta = Y_\delta\delta \tag{58}$$

$$N_R(\delta) = N_\delta(0)\delta = N_\delta\delta \tag{59}$$

These coefficients could be determined similarly to the way it is done in cases of rudder tests without the presence of the ship.

These kinds of test allow to analyze the results and generate force correction functions given the interaction hull/rudder. Thus, the forces on the pure hull, the forces on the rudder and a correction factor for including the effect of the interaction hull/rudder are obtained.

Actually, the problem is more complex, since the intention is to represent forces for large rudder angles, as well as to include the presence of the propeller, which will be addressed further on.

Another important aspect with this example is to differ modular and holistic approaches. In a modular approach, hydrodynamic derivatives of pure hull, pure rudder and factors representing the interaction hull/rudder are determined. In a holistic approach the model is fitted with rudder and propeller, and tests with the full model are performed.

III.6. Propeller action

Previously, equations of linear motion in the directions ox and oy and of angular motion around the oz axis were formulated. Neither the force component transverse to the ship nor, consequently, the moment around oz due to the propeller were considered (see equations (11) e (12)).

The rudder force towards ox can be calculated from the curve of the coefficient of force generated by the propeller $K_T = f(J)$, in which $K_T = T/(\rho n^2 D^4)$, $J = V_a/(nD)$, T is the force generated by the propeller, V_a is the speed of the water entering the propeller, n is the rotation of the propeller and D is its diameter. The form of function K_T (J) suggests that it can be represented by a second-degree parabola (see Figure A27.)

$$K_T = T/(\rho n^2 D^4) = b_1 + b_2 J + b_3 J^2 \tag{60}$$

From this parabola, and employing the wake coefficient w and the propulsion force reduction coefficient t, one can get the expression:

$$X_P = a_1 n^2 + a_2 n V_s + a_3 V_s^2 \tag{61}$$

where a_1, a_2, a_3 are dimensional coefficients given by:

$$a_1 = \frac{b_1 \rho D^4}{(1 - t)} \tag{62}$$

$$a_2 = \frac{b_2 \rho D^3 (1 - w)}{(1 - t)}$$

$$a_3 = \frac{b_3 \rho D^2 (1 - w)^2}{(1 - t)}$$

III.7. Full linear maneuvering model

Equations (12), (13), (15), (16), (58), (59) e (61) together form a linear model for representing a ship maneuverability. By reason of their development, they are valid for a ship moving with small heading angles, small rudder angles, approximately constant speed with small variations

III.7.1. Nomoto approach

In this section, sway and yaw coupled equations are reduced to two second order differential equations, decoupled and presented in Nomoto notes. From such equations, the ship directional stability concept is shown. These equations are important for the formulation of an autopilot.

The linearized sway and yaw equations form a pair of coupled first order differential equations. They will be changed into two decoupled second order equations, one for the sway motion, another one for the yaw motion.

For showing the procedure to be employed, two differential equations must be considered

$$a1\dot{x}(t) + a2x(t) + a3y(t) + a4\dot{y}(t) = a5z(t) \quad (63)$$

$$A1\dot{x}(t) + A2x(t) + A3y(t) + A4\dot{y}(t) = A5z(t) \quad (64)$$

By multiplying equation (63) by A1 and subtracting from equation (64) multiplied by a1, a equation EQ1 is obtained.

By deriving this equation EQ1 relative to time, an equation EQ2 is obtained.

By multiplying the equation EQ1 by $- a2/(A1\ a2 - a1\ A2)$, subtracting from equation EQ2 multiplied by $- a1/(A1\ a2 - a1\ A2)$ and adding (63), equation (65) is obtained, which is a third order differential equation for y decoupled from x

$$(A1\ a3 - a1\ A3)\ddot{y} + (A1\ a4 - a1\ A4 + A2\ a3 - a2\ A3)\dot{y} + (A2\ a4 - a2\ A4)y = (A2\ a5 - a2\ A5)z(t) + (A1\ a5 - a1\ A5)\dot{z}(t) \quad (65)$$

This procedure can be applied to maneuver equations for sway and yaw, employing

$$\begin{aligned}
v' &= x \quad (66)\\
r' &= y\\
a1 &= (m' - Y'_{\dot{v}})\\
A1 &= - (N'_{\dot{v}} - m'x_G')\\
a2 &= - Y'_v\\
A2 &= - N'_v\\
a3 &= (Y'_{\dot{r}} - m'x_G')\\
A3 &= I_{zz}' - N'_{\dot{r}}\\
a4 &= - (Y_r' - m')\\
A4 &= - (Nr' - m'x_G')\\
a5z(t) &= Y_R' = - Y_\delta'\delta\\
A5z(t) &= N_R' = - N_\delta'\delta
\end{aligned}$$

Thus proceeding, we get a third order differential equation for yaw decoupled from sway

$$A\ddot{r}' + B\dot{r}' + Cr' = D\delta + E\dot{\delta} \tag{67}$$

Similar procedure leads to a third order differential equation for sway decoupled from yaw:

$$A\ddot{v}' + B\dot{v}' + Cv' = F\delta + G\dot{\delta} \tag{68}$$

where A, B and C are

$$A = (m' - Y_{\dot{v}}')(I'_{zz} - N_{\dot{r}}') - (Y_{\dot{r}}' - m'x_G')(N_{\dot{v}}' - m'x_G') \tag{69}$$

$$B = -(m' - Y_{\dot{v}}')(N_r' - m'x_G') + Y_v'(I'_{zz} - N_{\dot{r}}') + (Y_r' - m')(N_{\dot{v}}' - m'x_G') + N_v'(Y_{\dot{r}}' - m'x_G')$$

$$C = Y_v'(N_r' - m'x_G') - (Y_r' - m')N_v'$$

The study of directional stability is performed for the case where the ship advances with no action of the rudder for correcting its course. In such cases, equations (67) and (68) are reduced to:

$$A\ddot{r}' + B\dot{r}' + Cr' = 0 \tag{70}$$

$$A\ddot{v}' + B\dot{v}' + Cv' = 0$$

The solutions are of the form $v = V_0e^{\sigma t}$ and $r = R_0e^{\sigma t}$ which, for determining σ, in both cases lead us to equation

$$A\sigma^2 + B\sigma + C = 0 \tag{71}$$

Os valores de σ são dados por

$$\sigma_{1,2} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{72}$$

the values of σ1.2 one can be used to verify if the system is stable or not. As A and B are always positive, the sign of C indicates if the ship is stable or not.

III.7.1.1. Second-order Nomoto equation

Following the notation employed by Nomoto et al. (1957, apud PIANC, 1992, *Bulletin* 77) and defining $T_1' = 1/\sigma_1$ and $T_2' = 1/\sigma_2$, we get

$$\frac{A}{C} = T_1' T_2' \tag{73}$$

$$\frac{B}{C} = T_1' + T_2'$$

Employing such relationships, we come to the second order Nomoto equation for r' (yaw)

$$T_1' T_2' \ddot{r}' + (T_1' + T_2')\dot{r}' + r' = K_r'\delta + K_r'T_{3r}'\dot{\delta} \tag{74}$$

where

$$K_r' = \frac{N_v'Y_\delta' - Y_v'N_\delta'}{Y_v'(N_r' - m'x_G') - N_v'(Y_r' - m')} \tag{75}$$

and

$$T_{3r}' = \frac{(m' - Y_{\dot{v}}')N_\delta' + (N_{\dot{v}}' - m'x_G')Y_\delta'}{N_v'Y_\delta' - Y_v'N_\delta'} \tag{76}$$

It is a second order non homogeneous differential equation with constant coefficients. In its right-hand side are the terms describing the action of rudder as a function of the instantaneous position and of the speed of rudder movement.

Based on the hydrodynamic derivative values for ships in general, some tendencies can be observed:

– The K_r' denominator is the C parameter whose value is greater than 0 employed as directional stability criterion. Depending on the ship, its value can be positive or negative.
– Always $Y_v' < 0$ and $N_r' < 0$
– Always $Y_\delta' > 0$ and $N_\delta' < 0$
– Usually $N_v' < 0$
– It is expected that $(Y_r' - m') < 0$ and $N_r' - m'x_G' < 0$ since x_G' is small.

With such behavior, it is known that

– D tends to be negative
– E tends to be negative
– K_r' depends on the ship being stable or unstable
– T_{3r}' tends to be positive

A similar development leads to the sway motion equation

$$T_1' T_2' \ddot{v}' + (T_1' + T_2')\dot{v}' + v' = K_v'\delta + K_v'T_{3v}'\delta \tag{77}$$

where

$$K'_v = \frac{(Y_v' - m')N_\delta' - (N_r' - m'x_G')Y_\delta'}{Y_v'(N_r' - m'x_G') - (Y_r' - m')N_v'} \quad (78)$$

and

$$T'_{3v} = \frac{(Y_{\dot{r}}' - m'x_G')N_\delta' + (I_{zz}' - N_{\dot{r}}')Y_\delta'}{(Y_v' - m')N_\delta' - (N_r' - m'x_G')Y_\delta'} \quad (79)$$

III.7.1.2. First order Nomoto equation

It can be shown that the motion equation for r (yaw), in the form presented by Nomoto, can be approximated by

$$T'\dot{r}' + r' = K_r'\delta \quad (80)$$

where

$$T' = T_1' + T_2' - T_{3r}' \quad (81)$$

III.8. Nonlinear formulations

In the previous section, the problem of representing ship maneuvers by a linear model was addressed, and laboratory techniques for obtaining hydrodynamic derivatives were shown. While the focus of the studies remains on the analysis of behavior around a given forward speed and sway and yaw motions are small, such results enable the execution of a directional stability analysis, the design of an automatic pilot, the simulation of the path of stable ships with small rudder deflections and other studies. However, if the focus is on simulation of ship motions for all speed ranges with the action of rudder and propeller at different combinations of ship's speed, propeller rotation and rudder angle, representation of hydrodynamic forces on the hull and hydrodynamic forces created by propulsion and steering equipment, more sophisticated and non-linear models are required, for better representing such forces.

Similar tests to the ones described above may be employed, since they are executed with broader amplitudes.

III.8.1. Expressions of hydrodynamic forces on the hull

The most commonly employed formulations for representing transverse and moment hydrodynamic responses can be classified in cubic and quadratic formulations. In maneuvers at normal speeds about the ship's design speed, models containing cubic, quadratic terms and even terms of higher orders are employed.

Basically, it can be said that in a quadratic formulation, forces and hydrodynamic moments follow the following model

$$X_I + X_H = X_{\dot{u}}\dot{u} + X_{uu}u|u_0| + X_{vr}|v||r| \quad (82)$$

$$Y_I + Y_H = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_v v u_0 + Y_r r u_0 + Y_{v|v|}v|v| + Y_{r|r|}r|r|$$

$$N_I + N_H = N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_v v u_0 + N_r r u_0 + N_{v|v|}v|v| + N_{r|r|}r|r|$$

Introducing these expressions in the motion equations, employing the suppression of dimension already shown, that is, dividing the force equations by $0,5\rho L_{pp}^2 U^2$ and the moment equations by $0,5\rho L_{pp}^3 U^2$ and rearranging the terms, we get:

– For longitudinal force equations

$$(m' - X_{\dot{u}}')\dot{u} - X_{uu}'u'|u'| + (X_{vr}' - m')|v'||r'| - m'x_G'r'^2 = X'_P + X'_R \quad (83)$$

– For lateral force equations

$$(m' - Y_{\dot{v}}')\dot{v}' - Y_v'v' - Y'_{v|v|}v'|v'| - (Y_{\dot{r}}' - m'x_G')\dot{r}' - (Y_r' - m'u')r' - Y'_{r|r|}r'|r'| = Y'_P + Y'_R \quad (84)$$

– For moment equations

$$(I'_{zz} - N_{\dot{r}}')\dot{r}' - (N_r' - m'x_G')r' - (N_{\dot{v}}' - m'x_G')\dot{v}' - N_v'v' - N'_{v|v|}v'|v'| - N'_{r|r|}r'|r| = N'_P + N'_R \quad (85)$$

As to cubic models, there are lateral force and yaw moment expressions of the following forms:

– For longitudinal force equations

$$(m' - X'_{\dot{u}})\dot{u} - X'_{uu}u'|u'| + (X'_{vr} - m')|v'||r'| - m'x'_G r'^2 = X'_P + X'_R \quad (86)$$

– For lateral force equations

$$(m' - Y'_{\dot{v}})\dot{v}' - Y'_v v' - Y'_{vvv}v'^3 - (Y'_{\dot{r}} - m'x'_G)\dot{r}' - (Y_r' - m'u')r' - Y'_{rrr}r'^3 - Y'_{vvr}v'^2r' - Y'_{rrv}r'^2v' = Y'_P + Y'_R \quad (87)$$

– For moment equations

$$(I'_{zz} - N'_r)\dot{r}' - (N'_r - m'x'_G)r' - (N'_v - m'x'_G)\dot{v}' - N_v v' - N'_{vvv}v'^3 - N'_{rrr}r'^3 - N_{rrv}r'^2v' - N_{vvr}v'^2r = N'_P + N'_R \quad (88)$$

This section presents some nonlinear formulations of hydrodynamic forces, the concept operation quadrants of a ship and aspects regarding modeling of forces due to the hull, to the propeller and to the rudder.

Another aspect to be highlighted is the form how effects of different agents are treated in the model. In a general way, the forces can be formulated in modular or holistic forms.

In modular models, expressions are employed for representing independently the actions of hull, propeller and rudder. Thus, the hull is modelled without propeller and rudder; the propeller and the rudder are modelled from tests in open water. However, due to the interaction hull/propeller/rudder, a way of introducing corrections to the models must be contemplated for considering the interferences.

In holistic models, the forces are modelled considering that the ship is fitted with propeller and rudder.

In the most general case, not only the actions on the hull, propeller and rudder must be modelled, but all actions previously described. It is a complex problem, but modern maneuver simulators were developed for receiving information from different origins about forces and moments acting on the ship, in graphic form and as a function of the different variables that influence each action. For example, instead of using the above expression for calculating Y_H, graphics of Y_H as a function of v, V_s and r may be provided. It is possible to elaborate the model a little further, and furnish the simulator with graphics encompassing a new variable that represents the local depth.

III.8.2. Forces induced by the propeller

In this subsection, it is initially treated an expression of forces created by a propeller that is valid about the cruising speed. Afterwards, the form of elaborating mathematical models is extended for considering the forces generated by a propeller, taking into account all possible combinations of flow speeds entering the propeller and its rotation.

Based on the form of the curves resulting from propeller tests in a circulating water tunnel (see Figure A3., page 213), it can be verified that the propeller thrust coefficient $K_T \rho n^2 D^4$ can be described, with a good approximation, by a second degree polynomial as a function of the advance coefficient $J = V_A/(nD)$, as it was done before, coming to

$$X_P = a_1 n^2 + a_2 n V_s + a_3 V_s^2 \quad (89)$$

The term containing the coefficient a3 indicates the dragging offered by the propeller with n = 0. The term containing the coefficient a1 defines the propeller thrust force in the bollard pull condition, when the ship speed is null.

When the propeller acts on the ship's wake, it becomes subject to a non-uniform speed field that is different from those verified in test conditions. Its presence implies in alterations to the flow on the aft part of the hull. Thus, it is necessary to introduce corrections to the propeller coefficients for including those effects

In most of the conventional shape propellers, the rotation produces not only a thrust in the ship longitudinal direction, but also a lateral force due to the difference of pressure between the face and the back of the propeller blades, since, with the proximity of the surface and the presence of the hull, the symmetric behavior that occurs when the propeller is deeply immerse and away from the hull no longer exists. Further to that, there is an increase on the pressure field on the hull, consequence of the alteration of the speed field along the hull at the aft part of the ship, as it can be seen in Figure A27.

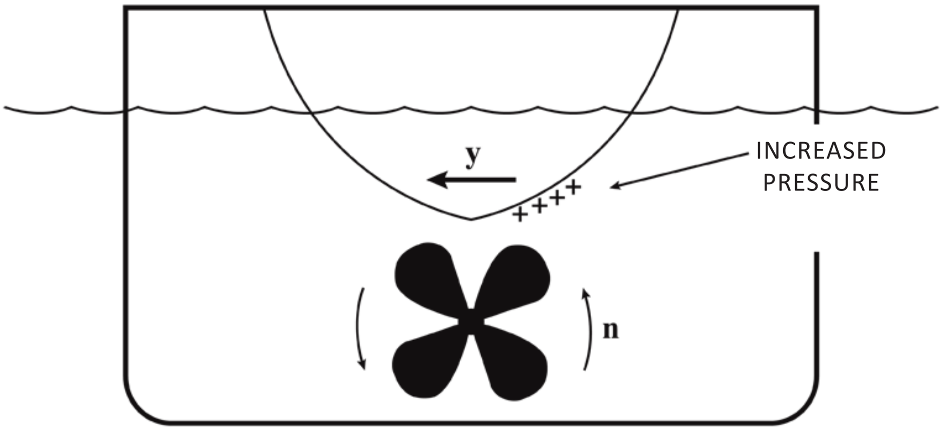

Figure A27. The figure shows schematically the paddle wheel effect, which creates a lateral force on the ship due to interaction propeller/hull

Such lateral effect, also known as paddle wheel, is strongly influenced by the ship's wake, which is a function of the advance speed.

It is possible to formulate the lateral force and the yaw moment similarly to the axial force

$$Y_P = b_1 n^2 + b_2 n V_s + b_3 V_s^2 \tag{90}$$

$$N_P = c_1 n^2 + c_2 n V_s + c_3 V_s^2$$

Coefficients b_i refers to lateral forces, whereas coefficients c_i refers to the yaw moment induced by the lateral pressure of the propeller, which is equal to the product of the coefficients in sway and the distance from the propeller to the origin of the solidary system. From the considerations presented, one can say that coefficients b_i and c_i are also affected by the presence of the hull. Thus, when seeking a mathematical model for describing forces created by the propeller, that influence from the hull must be modelled.

This form of treating the problem is restrict to the case in which the ship advances and the propeller turns in its regular positive sense, and both advance and rotation speeds create positive K_T with positive J. Actually, the possible combinations of rotation and flow speed striking the propeller can be organized by defining four operational quadrants (Figure A28.).

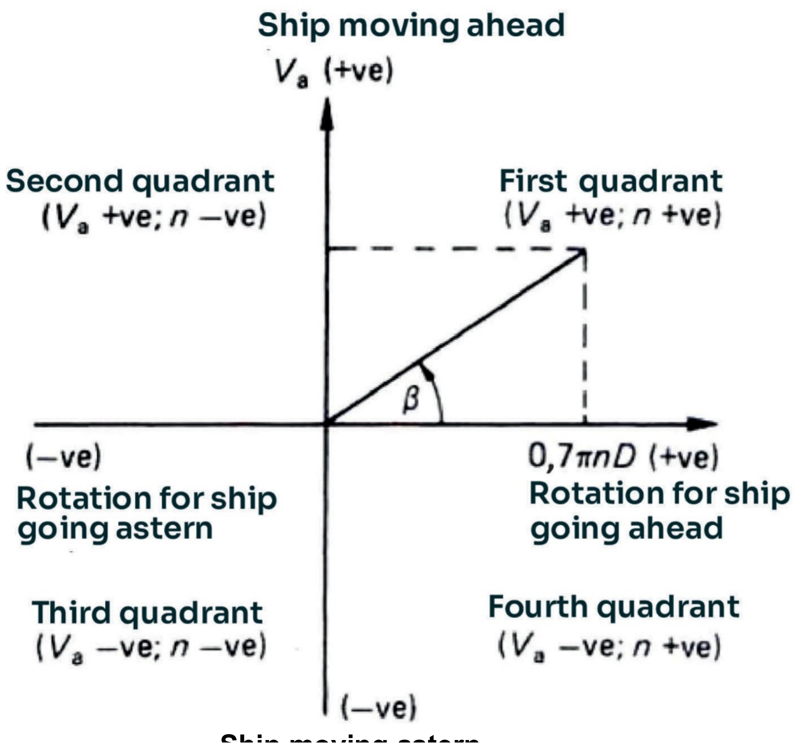

Figure A28. The four-quadrant operation of the propeller (Carlton, 2007)

Figure A29. shows the speed and force diagram in a propeller employing the profile theory to 0.7 of the radius. In that figure it can be seen that, if the incident speed is high, the resulting attack angle may generate negative forces and, consequently, $K_T < 0$, which is not contained in conventional K_T, K_Q, J diagrams.

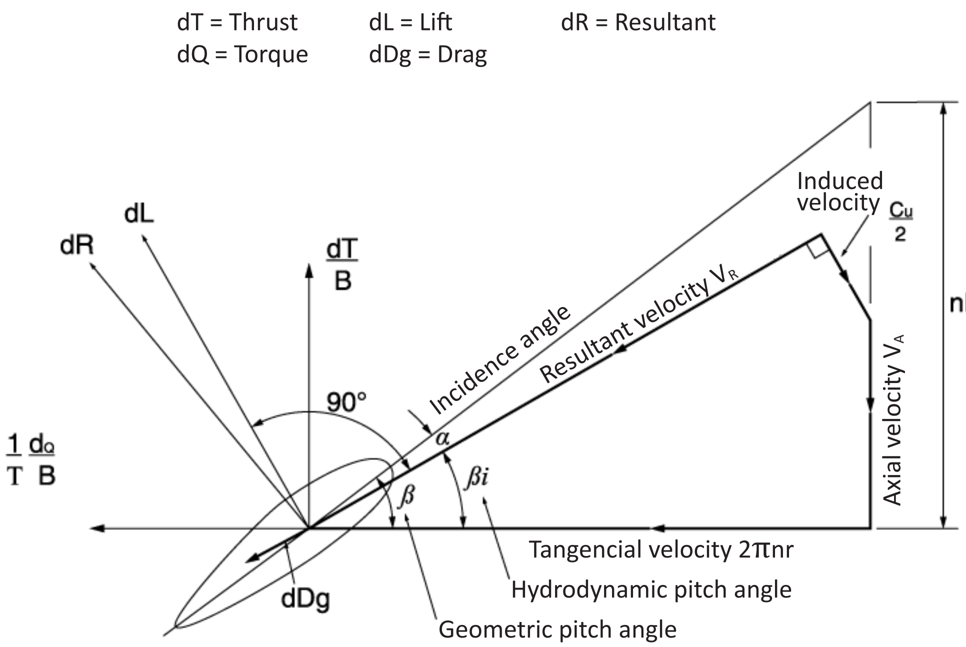

Figure A29. Speeds and forces diagram in an expanded section of a propeller blade (O'Brien, 1969)

Observing the diagram of speeds and forces and the curves K_T, K_Q, J one can verify that the operating area of a propeller described by such curves is restricted to values of J between zero and values a little larger than that of the pitch/diameter ratio P/D which, in the four-quadrant diagram is equivalent to angles between zero and approximately 35 degrees. Such graphics were obtained from an open water test. It is necessary to consider alterations to these results due to influence of the hull and, for a full description of all possibilities, diagrams of propeller forces must be employed, based on the speed incidence angle resulting from the combination of incoming flow speed and propeller rotation speed.

Figure A30., built from *Marine Propellers and Propulsion* by Carlton, initially published by van Lammeren, van Manen and Oosterveld in the SNAME 1969 Transaction, shows a diagram of coefficients C_T and C_Q for B-70 propellers with different P/D ratios for all four quadrants.

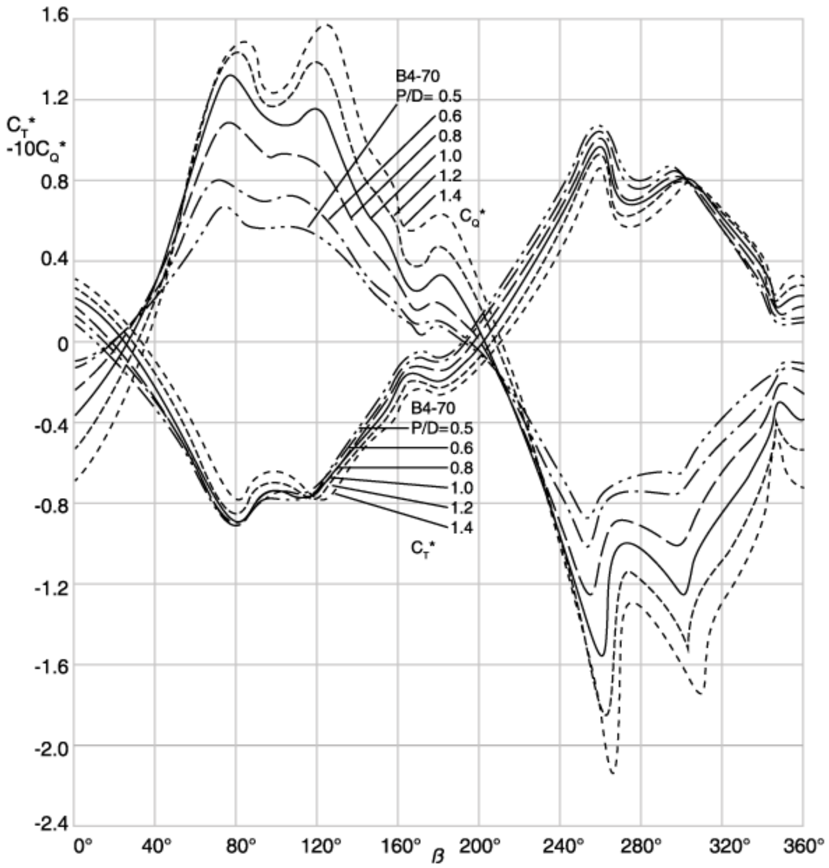

Figure A30. Diagram of coefficients C_T and C_Q for B-70 propellers with different P/D ratios, for all four quadrants (Carlton, 2007, Figure 6.10.)

where

$$C_T = T/(1/2\rho V_R^2 A_0) \tag{91}$$

$$C_Q = Q/(1/2\rho V_R^2 A_0 D)$$

where V_R is the relative propeller/fluid velocity at 0,7 radius profile; A_0 the propeller disc area; T the propeller thrust and Q its torque.

Obviously it is not possible, by approximation with a second-degree parabola, to formulate the propeller force coefficient for all quadrants. Other algorithms must available, and the use of tables with refined discretization can be a more adequate technique when mounting a model for simulation. Effects of the presence of the vessel ahead of the propeller must be incorporated in the model.

III.8.3. Rudder-induced forces

The rudder is treated as a standard device that produces lateral and longitudinal forces and induces turning moment. In mathematical modeling, it is essential that the interactions imposed by the hull and the propeller be related to lift and drag forces. It can be assumed, as it was done previously, that the rudder normal force is proportional to the attack angle δ and a function of the aspect ratio λ (see Figure A25.)

$$L = 1/2\ (\rho A_R U_R{}^2 f(\lambda)\delta \qquad (92)$$

where A_R is the rudder area, U_R the incident speed, λ the aspect ratio and δ the attack angle. The function $f(\lambda)$ can be empirically estimated, employing, for instance, the expression presented in the PNA,

$$f(\lambda) = \frac{6.13\lambda}{\lambda + 2.25} \qquad (93)$$

The lifting coefficient test is performed at an incident constant speed on the whole rudder area. The use of test results for rudders fitted astern of the ship demands the introduction of certain corrections. For an idealized situation of uniform flow U overlapped to a rotation effect n, it can be said that the incident speed on the rudder at a distance R from the rotation center is given by

$$U_R{}^2 = U^2 + 4n\pi RU + 4\pi^2 n^2 R^2 \qquad (94)$$

As behind the ship there is no entry of uniform flow on the rudder, U_R depends on the ship's speed u0 and on the propeller's rotation n, which is conceptually different from the way how rudder tests are conducted. Besides that, behind the ship there is no entry of uniform flow due to the presence of the ship and the propeller. Keeping the conception of the model, an equivalent speed is employed, that depends on the ship's speed and on the propeller rotation, and with force coefficients that correct such effects. Thus, the coefficients depend not only on the characteristics of the rudder, but also on the characteristics of the propeller and hull. A similar approach is employed as to drag. Further to that, for large attack angles the lift is no longer proportional only to the rudder angle, as it can be seen, for instance, in Figure A25. It is, then, introduced a cubic formulation for lateral force and moment

$$Y\{R\} = (b_1 n^2 + b_2 u_0 n + b_3 u_0{}^2)\delta + (b_4 n^2 + b_5 u_0 n + b_6 u_0{}^2)\delta^3 \qquad (95)$$

$$N\{R\} = (a_1 n^2 + a u_0 n + a_3 u_0{}^2)\delta + (a_4 n^2 + a_5 u_0 n + a_6 u_0{}^2)\delta^3$$

There is a similar expression for drag force, however, as it is an effect of viscous origin based on experimental results for profiles, wings and rudders, it is prescribed a quadratic dependence relatively to the attack angle

$$X_R = (c_1 n^2 + c_2 u_0 n + c_3 u_0{}^2)\delta^2 \qquad (96)$$

Having in mind that the rudder is fitted at the ship's wake, after the propeller, and that it will be subject to the same conditions to which the propeller is subject, that is, it will be subject to the four quadrant conditions to which the propeller is subject. There are other aspects to consider

– in a same quadrant, different J mean different incidence angles of flow on the propeller, creating different flows on the rudder. Thus, for each quadrant, different curves of lift coefficients and dragging coefficients must be formulated. There are different a_i, b_i and c_i coefficients as a function of the quadrants and of values of J;

– as the rudder is located at the ship's wake, behind the propeller, ai, bi and ci coefficients must be corrected due to the interaction with the hull and the propeller;

– the generation of force on the propeller is associated to an increase of axial speeds of fluid particles that pass through the propeller and in its surroundings. Such increase of linear speed demands that a torque be applied to the propeller, which will cause an increase of speeds in the propeller area, originating a rotation movement on the fluid particles around the propeller axis. Such speed alterations will act on a certain area of the rudder. Figures A.31. and A.32. show, based on the propeller disc theory, schematics on how the rudder is affected by such effects. The lateral view indicates that, due to the action of the propeller, there will be an alteration to the incident speeds in an area along the rudder height. The top view shows that when the rudder is deflected, there will be an area along its chord that will be inside the flow altered by the propeller, and there might be another area outside such flow.

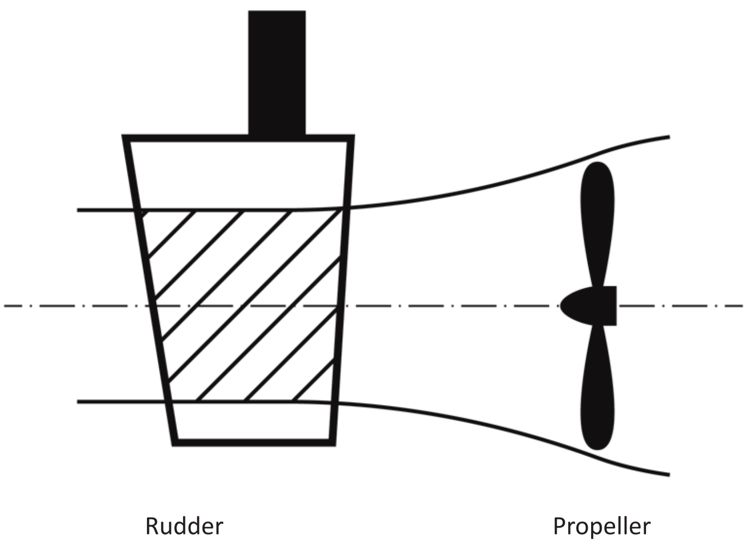

Figure A31. Lateral view of the propeller/rudder set

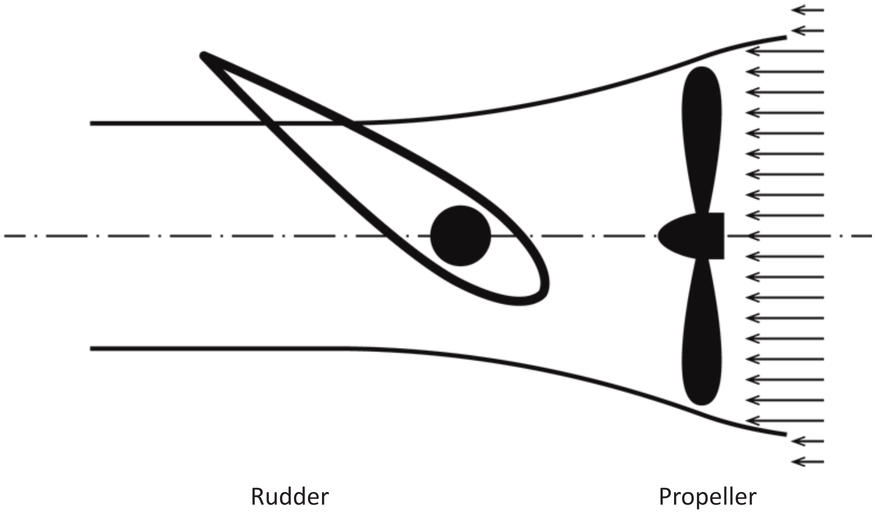

Figure A32. Top view of the propeller/rudder set

Figures A33. and 334., schematically built from *Marine Rudders and Control Surface* by Molland and Turnock, present results for lift and drag coefficients of a rudder acting behind a B series propeller for different quadrants. The tests were performed in a wind tunnel, and the results for some combinations of flow and rotation speeds are presented. The rudder section is of a NACA 0020 profile, the propeller diameter is 80 cm and the pitch/diameter ratio is 0.95.

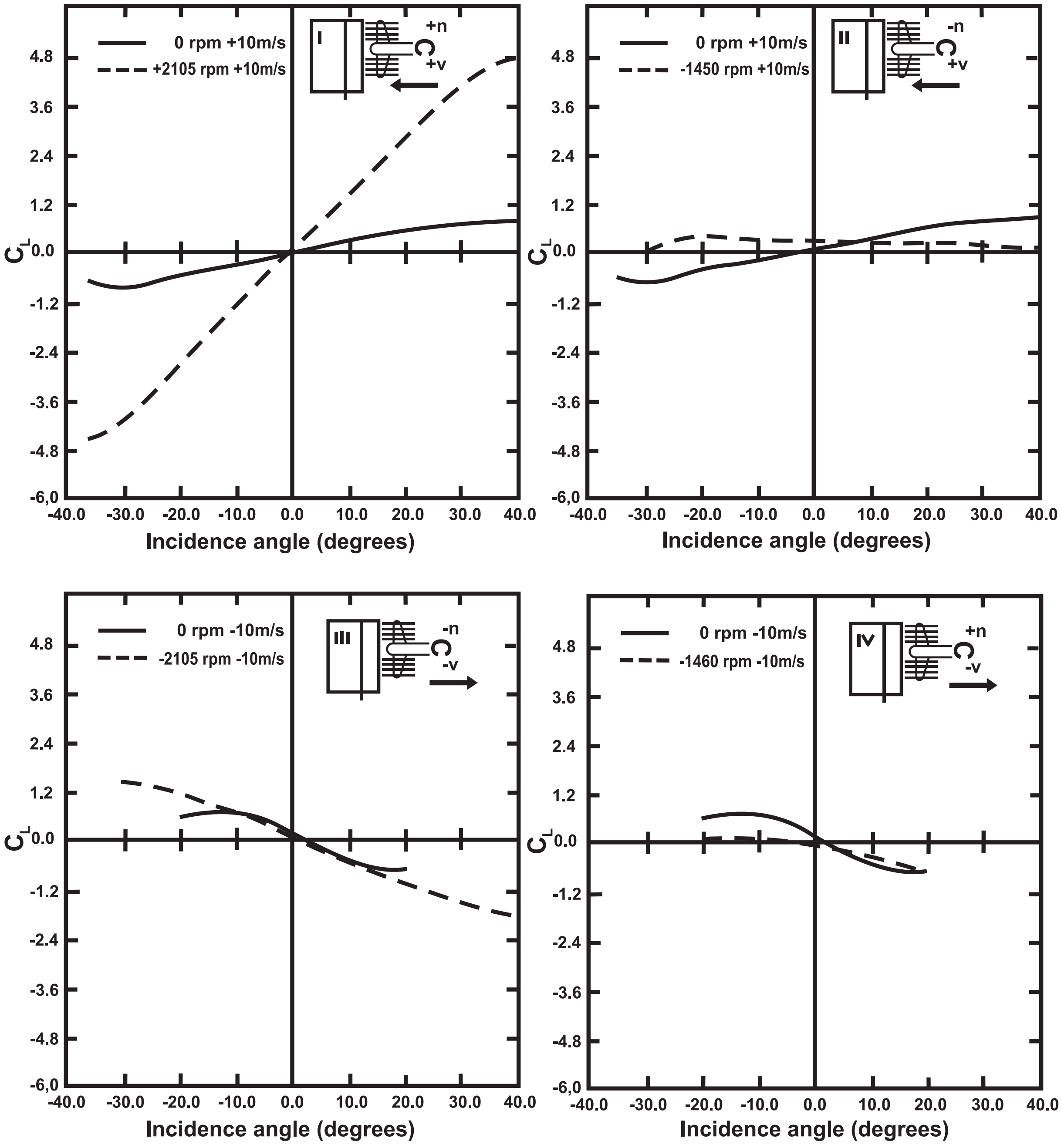

Figure A33. Sustaining coefficient on a rudder (lateral rectangular view), acting behind a B series propeller for different quadrants (based on Figure 5.87., Molland e Turnock, 2007)

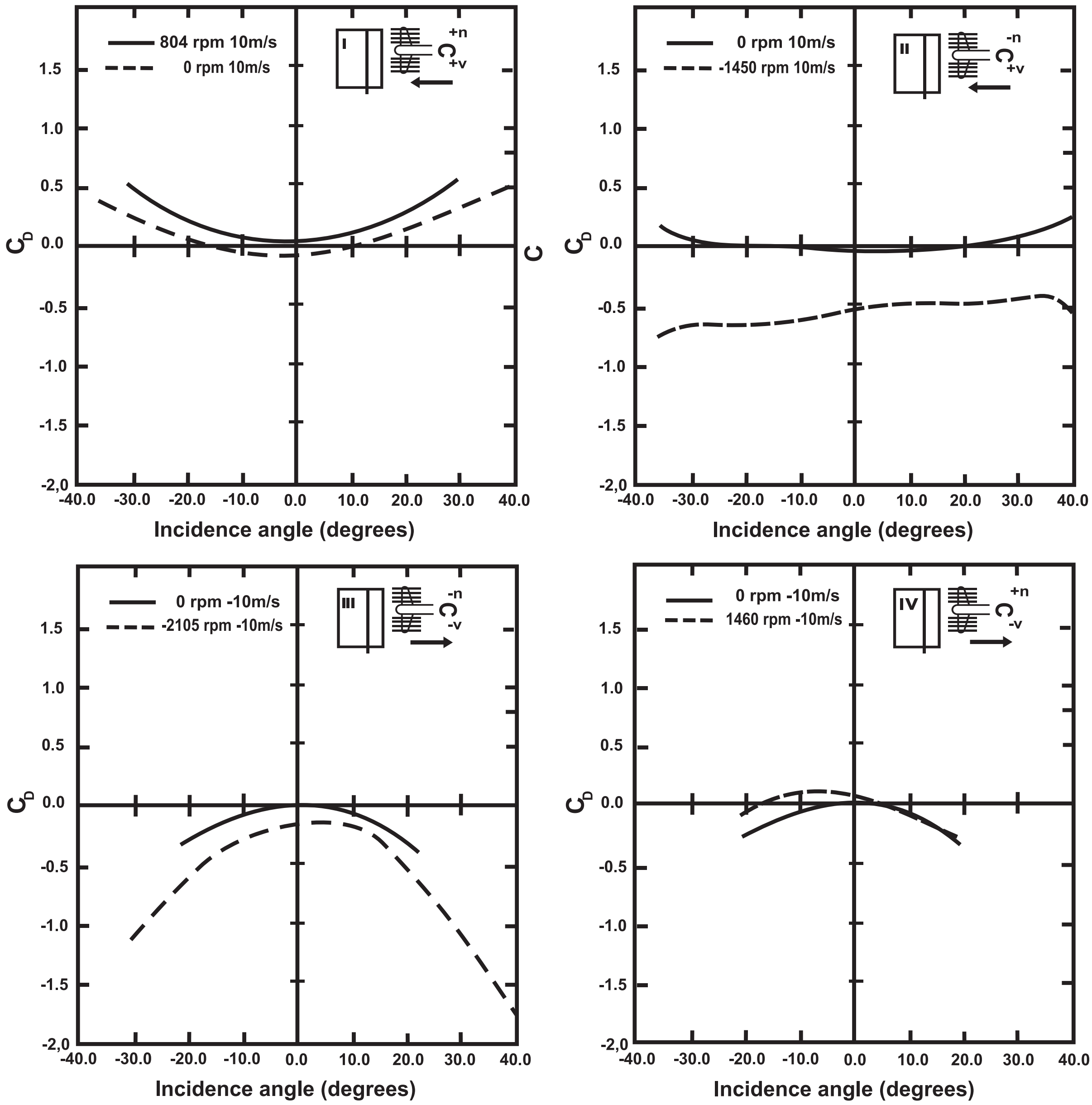

Figure A34. Drag coefficients on a rudder (lateral rectangular view) acting behind a B series propeller for different quadrants (based on Figure 5.87., Molland e Turnock, 2007)

III.9. Additional effects to be included in a maneuvering simulator

The third part of this appendix presented basic aspects of mathematical modulation of a maneuvering simulator, keeping the focus on the hydrodynamics of the hull, the rudder and the propeller. As it was presented in Part II, for application to different practical problems as verification of possibility to reduce operational restrictions in a given terminal, assessment of feasibility to operate with a new ship (for example, of larger draught), dimensioning of areas and dredging depths in channels and maneuvering basins, risk assessment, etc., additional effects must be included in the maneuvering model, as

- Wave effects (first and second orders);
- Current effects;
- Wind effects;
- Shallow water effects;
- Bank and channel effects;
- Effects of thrusters and auxiliary thrust devices;
- Effects of interaction between crafts;
- Effects of engine dynamics;
- Action of force of tugboats;
- Action of fenders, mooring ropes, mooring buoys, piers and other topics relating to berthing/ unberthing of vessels.

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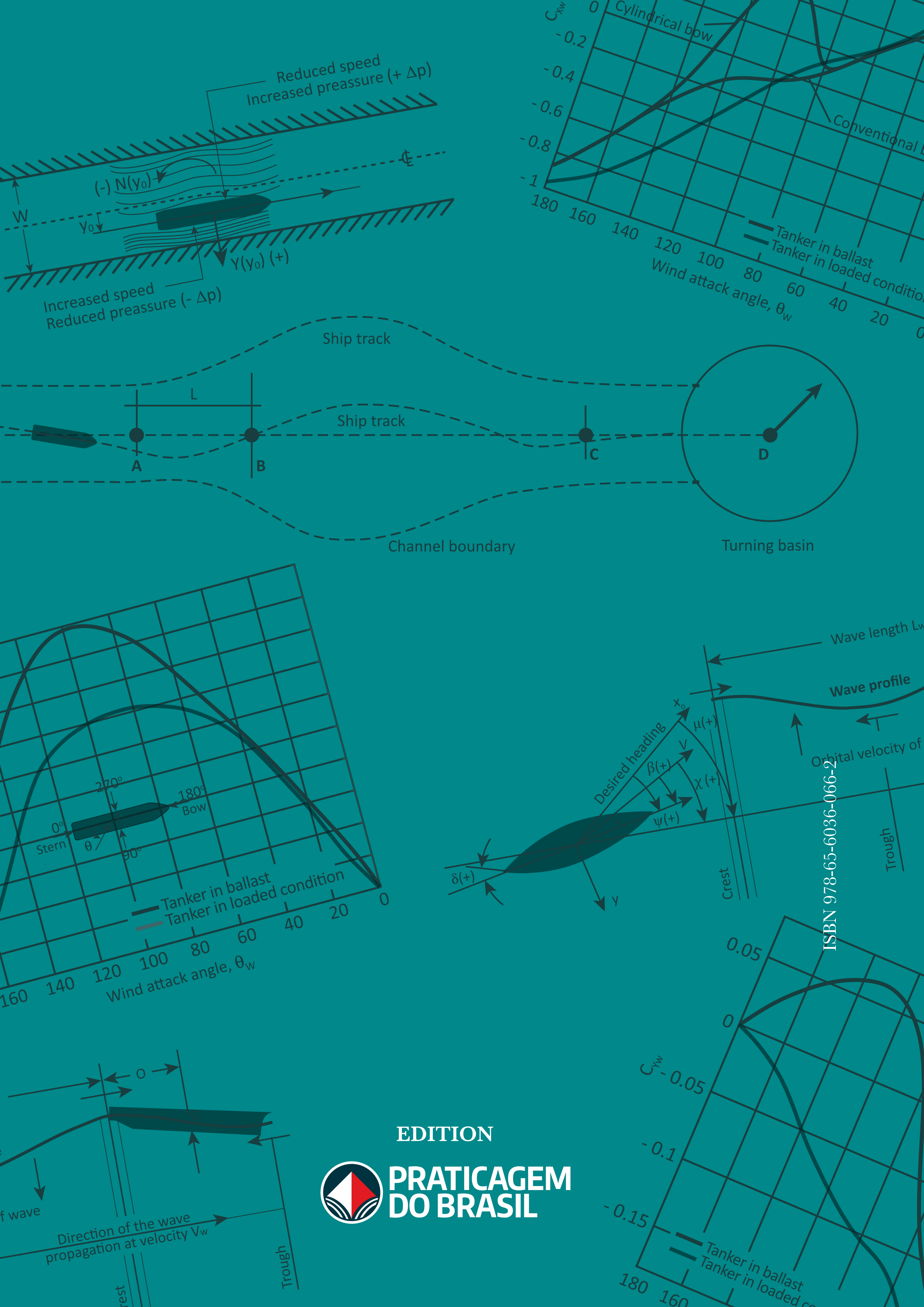

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