Optimization of the operational use of entrance channels based on channel depth requirements

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Additional MSc thesis Report

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Summary

Large capital and maintenance dredging operations are required to ensure the accessibility of many ports. The expenses associated with the dredging operations can have a significant impact on the finances of these ports. Therefore, considerable attention to the design of the width and depth aspects of access channels is justifiable.

This study considered this topic within the framework of an Additional Master Thesis (3-month internship). The objectives of the study are: i) to verify the influence of different processes and sources of uncertainties in the evaluation of minimum depth requirements; and ii) to investigate the advantages and drawbacks of different methods of depth requirement evaluation. The Port of Tubarão (Southeast Brazil) is used as a case study to verify processes and methods.

Four different approaches were considered to evaluate depth requirements for the access channel of the Port. These methods are based on either deterministic and/or probabilistic methods, and on approaches without or including wave influences.

The results for the case study indicate that ship motions due to waves have a minor influence on the required channel depth at that location during most of the time. However, in certain wave conditions (not only in terms of wave height, but also wave period and wave direction relative to the manoeuvring ship) vertical ship motions become the dominant issue regarding depth requirements; consequently waves should be included in a practical evaluation over time.

In probabilistic approaches more knowledge can be incorporated in the analysis, however, this requires detailed information. The deterministic approach, on the other hand, is simpler to use and gives good insight about the main driving variables. Although, the main drawback of deterministic methods is that the reliability of the evaluation cannot be accessed, or that conservative assumptions need to be made. This may be uneconomical.

The use of a probabilistic method for the case study led to a more optimized use of the channel in terms of accessibility in comparison to the results obtained with the deterministic method. Nevertheless, those results depend largely on the safety factors assumed in the deterministic computations relative to the probability distributions considered in the deterministic approach. Alternatively, the safety margins can be computed or calibrated for specific cases based on probabilistic calculations. In that case the results of deterministic and probabilistic methods can be similar, ensuring the required reliability of the practical deterministic approach, but not being excessively restrictive.
Acknowledgements

First of all I would like to acknowledge Martijn de Jong and Jacco Groeneweg from Deltares (HYE), and Prof. Tiedo Vellinga (TU Delft) for the opportunity of doing this Additional Graduation project. Your guidance and support was essential for the achievements of this work and is surely appreciated.

Special thanks are given to: Arne van der Hout (Deltares, HYE) for the daily assistance during the project; Jos van Doorn, Hans Cozijn and Johan Dekker from MARIN for providing the RAO data for this study and for the valuable advices to the project; Herm Jan van Wijhe from the Port of Rotterdam for sharing his experience and for enabling the visit to the control room in the Port Authority in Rotterdam; and Lindino Benedet, Lucas Silveira and Alex Falkenberg (from CB&I Brazil) for their support provided during the studies.
Contents

1 Introduction 1
  1.1 Background 1
  1.2 Objectives of the study 4
  1.3 Study area 4
  1.4 Report outline 7

2 Environmental data, channel aspects and design ship 8
  2.1 Astronomical tides 8
  2.2 Meteorological tides 9
  2.3 Short waves 10
  2.4 Access channel 15
  2.5 Long (infragravity) waves along the access channel 17
  2.6 Ship dimensions 19

3 Probability and risk criteria 20

4 Channel depth evaluation based on nautical requirements 22
  4.1 Manoeuvring margin 22
  4.2 Squat effects 23
    4.2.1 Barrass II (1979, 1981) 24
    4.2.2 Eryuzlu et al. (1994) 24
    4.2.3 Huuska/Guliev (1976) 25
  4.3 Deterministic calculations excluding the influence of waves 29
  4.4 Probabilistic calculations excluding the influence of waves 36

5 Channel depth evaluation including the influence of waves 43
  5.1 Determination of ship response to waves 44
    5.1.1 Vertical ship motions in waves 44
    5.1.2 Response Amplitude Operator and Response Phase Operator 47
    5.1.3 Joint RAO’s in the critical points 50
    5.1.4 Combining RAO’s and wave conditions 52
    5.1.5 Probability of vertical wave-induced ship motions 55
  5.2 Semi-probabilistic approach including the influence of waves 61
  5.3 Fully-probabilistic approach including the influence of waves 70

6 Final considerations 74

7 Conclusions and recommendations 75

8 References 77
1 Introduction

This Additional MSc. thesis report is part of the master program in Civil Engineering (track Hydraulic Engineering) of Delft University of Technology. The additional MSc thesis consists of 10 European Credits (ECs), which is equivalent to approximately 250-300 hours. The project was realized during an internship at Deltares (Delft, The Netherlands), unit Hydraulic Engineering, department of Harbour, Coastal and Offshore Engineering, from November 2013 to January 2014 (3 months).

As part of the learning activities of the Master Course, the main purpose of this research is investigating the different methods available to evaluate depth requirements of navigation channels. The quantitative results presented in this report are indicative only and should be considered within the context of the internship, i.e. including important assumptions and limitations.

1.1 Background

Large capital and maintenance dredging operations are required to ensure the accessibility of many ports. The expenses associated with the dredging operations can have a dramatic impact on the finances of these ports. Therefore, considerable attention to the design of the width and depth aspects of access channels is justifiable.

Accessibility problems of existing and new ports can be associated to the scale enlargement of ships; development of ports in hostile coasts and in areas without natural provisions for deep draught vessels; and the growing need for shipping safety.

The main factors which influence the required depth of an entrance channel are:
- Draught of the vessel
- Tidal benefit
- Squat effects (sinkage and trim)
- Maneuvering margin
- Vertical ship motions in waves
- Hydrographic factors (vertical tide and actual bottom profile)
- Morphologic factors (sedimentation or siltation)
- Safety level of channel transits
- Downtime of the channel

Figure 1.1 provides a scheme of the different parameters contributing to the required depth of a channel. In this case, “net-UKC” can be seen as the resistance (R) to failure. The solicitation (S), which conducts the element to failure, is associated to the minimum KC for maneuverability (nautical requirement), and to the required buffer for vertical ship motions in waves. The state just before failure, in which resistance and solicitation are in balance, is called the limit state. Probabilities of failure are generally denoted in terms of limit state functions:

\[ Z = R - S \]
Figure 1.1: Schematic representation of allowances in required channel depth.

The limit state is defined when \( Z = 0 \). The probability of failure, which is a central issue with regard to the reliability of the element, is then defined as:

\[
P_f = P(Z \leq 0) = P(S \geq R)
\]

The probability of failure of an element depends on the margin between the resistance to failure (KC) and the solicitation (minimum margin for maneuver or buffer required for vertical ship motions in waves). The way this margin is calculated can differ per case. Following the description presented in CUR-publication 190 (1997), the calculation methods can be classified in three levels:

- **Level III methods**: probability of failure is calculated by considering the probability density functions of all resistance and solicitation variables.
- **Level II methods**: probability of failure is calculated by linearizing the limit state function in a carefully selected point. These methods approximate the probability distribution of each variable by a standard normal distribution.
- **Level I method**: at this level no failure probabilities are calculated. The design method is according to the standards, which consider an element to fail if the representative value of resistance (R) is “sufficiently” smaller than the representative value of solicitation (S). The wording “sufficiently” indicates a margin, which is created by taking so-called partial safety factors into account in the design.
In the present study, Level I methods, which ensure the reliability by the use of partial safety factors, are regarded as deterministic methods. On the other hand, methods that explicitly take into account the probability distribution of the variables in the determination of resistance and solicitation to access the probability of failure of the element are called probabilistic methods (Levels II and III). The stochastic behavior of the variables can be due to uncertainties (inaccuracies) in the available parameter values (e.g., squat, bottom level, draught) or to physical behavior (ship motions in waves).

In the deterministic approach the required channel depth is obtained by adding conservative estimates of the effects of all relevant factors, in order to minimize the risk of having bottom contact or more severe incidents. It gives a clear insight in the factors determining channel depth, which is of special interest in the initial design phase. However, with the deterministic approach the probability of bottom contact during channel transits cannot be assessed since this requires a statistical quantification of the factors influencing channel operations. Therefore, the trade-off between channel depth on the one hand, and acceptable risks in channel transits and accessibility to the port, on the other hand, cannot be made.

The probabilistic approach can integrate the factors for all circumstances during the lifetime of the channel in a weighted form. The core of the approach is the determination of the probability of the ship’s keel contacting the channel bed during one channel transit (i.e. bottom touch). Therefore, using this approach in channel design and operation, uncertainties with respect to safety of channel transits and port accessibility can be quantified. The main drawback of this method, however, is the amount of statistical data required on all relevant aspects.

Till 1985 a deterministic admittance policy has been used for the Euro-Maas Channel (The Netherlands). The admittance of vessels was based on a fixed keel clearance percentage. The relation between the minimal keel clearance and the maximum draught was calculated by adding the maximum anticipated effects due to the relevant factors to determine keel clearance. The ratio between the gross keel clearance and the draught, called the keel clearance percentage, was then used to determine the accessibility of the channel (Savenije, 1995). This publication describes the probabilistic designed admittance police that replaced the previous deterministic policy.

According to Van Doorn (1985), when a probabilistic approach is applied in channel design studies, very often it results in a smaller required channel depth and thus contributes to reduced costs for the channel management authority (both capital cost and maintenance cost). The results of a probabilistic computation can be influenced by the following factors:

1. entrance procedure: when the channel is closed during extreme conditions, the average number of bottom touches will decrease;
2. channel depth;
3. accepted safety level during the use of the channel.

The first factor introduces ship waiting time, the second causes extra dredging and the third extra risk. An optimum can be found by making a cost/benefit analysis.

In practice, due to a limited amount of data it is not always possible to perform a fully probabilistic approach. Therefore several mixtures of probabilistic and deterministic approaches have been presented in literature (Strating et al., 1982; Van Doorn, 1985).
Once the channel is operative, it is generally acceptable that it is closed for navigation for some periods. In practice, this results in the possibility of deeper draught ships to access the port with shallower channels and lower costs for capital and maintenance dredging. The periods the channel is closed correspond to the downtime percentage of the access channel. The channel depths can be economically optimized, balancing the benefits of downtime reduction against costs of dredging.

Assuming the wave climate and the water level to be independent, the total downtime percentage is given by (Strating et al., 1982):

\[ DT = DT_{\text{waves}} + DT_{\text{tide}} - DT_{\text{waves}} \times DT_{\text{tide}} \]

in which \( DT_{\text{waves}} \) and \( DT_{\text{tide}} \) denote the downtime percentages due to extreme wave conditions or tidal conditions, respectively. In this report different methods are described and applied in order to evaluate the contribution of waves and tides to the downtime of an access channel.

### 1.2 Objectives of the study

The main objectives to be achieved are listed in the following:

1. Verify the influence of different processes and sources of uncertainties in the evaluation of minimum depth requirements;
2. Investigate the advantages and drawbacks of different methods of depth requirement evaluation.

As a case study, the depth requirements for access channel of the Port of Tubarão (Southeast Brazil) are evaluated. This is further elaborated in the next section.

### 1.3 Study area

The access channel to the Port of Tubarão, located in the southeast of Brazil (20°17′35″ S, 40°14′51″ W), is used as a case study for depth requirement evaluation (Figure 1.2).
Figure 1.2: Study area located in Vitoria, Espírito Santo State, Brazil. Numbers indicate the location of the berthing Piers in the Port of Tubarão.
Port of Tubarão, which is administrated by the mining company Vale, comprises 5 quays. Pier 1-north, Pier 1-south and Pier 2 (with design depth of 25.3m) are designated for (iron) ore cargo. In addition, there is a berth for grain cargo and general cargo (Pier 3 and Pier 4), and one berth for liquid bulk cargo (Pier 5). The iron ore carriers are determinant for the channel depth evaluation because of their deep-draught.

The official length of the access channel is 4,422m, with a width of 285m and a design depth of 25.3m. This ensures the access of ships with a maximum deadweight of 405,000 ton, maximum length of 365m and maximum breadth of 66.0m. The channel can be operated under maximum transversal current speed of 0.5kn.

A document published by the Port's Administration and revised in April 2013 (Administration of the Port of Tubarão and Port of Praia Mole, 2013) presents the criteria for determination of the maximum operational draught of the ships as a function of tide and wave conditions. The maximum draught allowed at a given time follows from the list presented below, having an upper limit of 23.0m, with the tide level being the instantaneous water level relative to the chart datum:

- 22,30m + tide level (with Hs < 1,00 m)
- 22,20m + tide level (with Hs < 1,10 m)
- 22,10m + tide level (with Hs < 1,20 m)
- 22,00m + tide level (with Hs < 1,30 m)
- 21,90m + tide level (with Hs < 1,40 m)
- 21,80m + tide level (with Hs < 1,50 m)

As an example, if the wave height is less than 1 meter and the water level is 0.80m (relative to the chart datum, it follows from the list that the maximum draught should be 23.10m. However, the upper limit for accessing the port is 23.0m, therefore under the exemplified conditions the maximum allowable draught is 23.0m.
The port authority of Port of Tubarão and Port of Praia Mole are responsible to monitor the meteorological parameters (wind, waves and currents). The conditions are analysed to verify the limiting conditions for the availability of the channel, in order to allow or not a ship to approach/departure the ports.

According to the Brazilian Agency for Waterway Transport (ANTAQ), 169 ships transporting dry bulk cargo called the Port of Tubarão in 2003. Only a fraction of this traffic corresponds to the deep-draught iron ore carriers that berth in Pier 2. The remaining part is composed by smaller dry bulk carriers. As an estimate for this study, it is assumed that 50 deep-draught vessels similar to the design ship use the channel yearly.

1.4 Report outline

In the next Chapter of the report an overall description of the relevant environmental processes and boundary conditions associated to the case study – Port of Tubarão – is presented. That Chapter is followed by a review of the probability and risk criteria, where acceptable probabilities of bottom contact are defined and supported.

In Chapter 4 the depth requirements of the access channel of Port of Tubarão are evaluated aside from the influence of waves. The evaluation is based on both deterministic and probabilistic methods.

Chapter 5 describes how the effects of waves and resulting ship motions are added to the methods presented in Chapter 4. This results in the semi-probabilistic approach – which uses deterministic methods in terms of nautical requirements but treats the motions of the ship as a stochastic parameter – and the fully-probabilistic method where the whole procedure involves stochastic variables.

The main findings of the study and recommendations for future research and applications are summarized in the last Chapter of the report.
2 Environmental data, channel aspects and design ship

2.1 Astronomical tides

The astronomical tides in the adjacencies of the Port of Tubarão were characterized based on 24 harmonic constituents published in the Catalogue of Brazilian Tidal Gauges by FEMAR (Fundação de Estudos do Mar – free translation: Sea Studies Foundation). The constituents were obtained from a water level time series measured in the Port of Tubarão between 07/06/1975 and 08/07/1975.

<table>
<thead>
<tr>
<th>Component</th>
<th>Period (hours)</th>
<th>Amplitude (m)</th>
<th>Phase (˚)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>12.42</td>
<td>0.442</td>
<td>88</td>
</tr>
<tr>
<td>S2</td>
<td>12.00</td>
<td>0.219</td>
<td>92</td>
</tr>
<tr>
<td>MSF</td>
<td>354.37</td>
<td>0.113</td>
<td>69</td>
</tr>
<tr>
<td>N2</td>
<td>12.66</td>
<td>0.098</td>
<td>69</td>
</tr>
<tr>
<td>O1</td>
<td>25.82</td>
<td>0.091</td>
<td>93</td>
</tr>
<tr>
<td>MM</td>
<td>661.31</td>
<td>0.078</td>
<td>275</td>
</tr>
<tr>
<td>K2</td>
<td>11.97</td>
<td>0.059</td>
<td>92</td>
</tr>
<tr>
<td>L2</td>
<td>12.19</td>
<td>0.056</td>
<td>135</td>
</tr>
<tr>
<td>K1</td>
<td>23.93</td>
<td>0.055</td>
<td>159</td>
</tr>
<tr>
<td>MU2</td>
<td>12.87</td>
<td>0.033</td>
<td>347</td>
</tr>
<tr>
<td>Q1</td>
<td>26.87</td>
<td>0.031</td>
<td>56</td>
</tr>
<tr>
<td>NU2</td>
<td>12.63</td>
<td>0.019</td>
<td>69</td>
</tr>
<tr>
<td>P1</td>
<td>24.07</td>
<td>0.018</td>
<td>159</td>
</tr>
<tr>
<td>O1</td>
<td>22.31</td>
<td>0.015</td>
<td>313</td>
</tr>
<tr>
<td>2N2</td>
<td>12.91</td>
<td>0.013</td>
<td>50</td>
</tr>
<tr>
<td>T2</td>
<td>12.02</td>
<td>0.013</td>
<td>92</td>
</tr>
<tr>
<td>SN4</td>
<td>6.16</td>
<td>0.013</td>
<td>108</td>
</tr>
<tr>
<td>J1</td>
<td>23.10</td>
<td>0.011</td>
<td>52</td>
</tr>
<tr>
<td>MN4</td>
<td>6.27</td>
<td>0.007</td>
<td>25</td>
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<tr>
<td>M4</td>
<td>6.21</td>
<td>0.007</td>
<td>87</td>
</tr>
<tr>
<td>M3</td>
<td>8.28</td>
<td>0.005</td>
<td>174</td>
</tr>
<tr>
<td>MK3</td>
<td>8.18</td>
<td>0.005</td>
<td>72</td>
</tr>
<tr>
<td>MS4</td>
<td>6.10</td>
<td>0.004</td>
<td>274</td>
</tr>
<tr>
<td>MO3</td>
<td>8.39</td>
<td>0.002</td>
<td>278</td>
</tr>
</tbody>
</table>

The tide is semidiurnal, with mean range of 1.32m during spring tide and 0.44m during neap tide. Figure 2.1 provides an example of a water level time series created based on the harmonic components for the period between 16/11/2013 and 30/11/2013.
2.2 Meteorological tides

The level of the sea water surface at a certain time is influenced by oceanic, meteorological and astronomical processes, which affect the water level variations through currents, density of water mass and meteorological phenomena.

Meteorological tides are natural phenomena induced by the interaction between the ocean and the atmosphere, being associated mainly to the influence of the atmospheric pressure over the water masses and the effects of wind shear stresses at the sea surface.

According to Nunes (2007) the meteorological tides in the region of the Port of Tubarão have a seasonal behaviour and can introduce low frequency oscillations in the water levels within MSL-0.6m and MSL+0.6m. The phenomenon is mainly explained by the occurrence of Ekman Transport, which is supported by the high correlation between winds parallel to the coast and occurrence of non-astronomical tidal components.

Water level time series measured in the adjacencies of the study area were not available for this study. Hence, the influence of the meteorological tides was computed based on water level time series measured and provided by IBGE (Brazilian Institute of Geography and Statistics) for the RMPG station in Macaé, located approximately 280km to the south of the study area (Figure 2.2). In absence of data from a more nearby location, this information is deemed suitable for the present indicative evaluation of channel depth evaluation methods. In this way this important process is included in the study.

Figure 2.1: Water level time series calculated based on the harmonic constituents for the Port of Tubarão.
In order to obtain a water level time series associated to the non-astronomical tides only, the astronomical tides were filtered out of the time series using a running average procedure. Spectra of water level variations for the lower frequencies associated to meteorological processes were computed based on filtered water level time series. Using 40 individual components (with periods ranging from 3 to 30 days) to represent the spectrum of non-astronomical tides, a synthetic longer range time series was derived from the spectra. It is pointed that using this procedure the chronology of the events is lost. However, it provides a longer term homogeneous time series (i.e. without gaps and inconsistencies), while preserving the general characteristics of the process.

The non-astronomical tide time series derived from this analysis was applied in the following parts of the study, in combination with the astronomical tides predicted using the harmonic components (section 2.1).

2.3 Short waves

The wave climate in the study area was characterized using a NOAA/NCEP-CFSR (30min Global model) hindcast timeseries of $H_s$, $T_p$ and Mean wave direction, covering the period between 01/01/1979 and 31/12/2009 with resolution of 3 hours. This time series is associated to the position 37.5°W 21.5°S, located in a region with water depths larger than 3000m. In such large water depths gravity waves do not feel the bottom, i.e. deep water conditions (Saha et al., 2010).

In Figure 2.3, Figure 2.4 and Figure 2.5 the joint distribution of the deep water wave parameters are presented.
### Figure 2.3: Joint distribution of wave direction and significant wave height. Deep-water condition.

<table>
<thead>
<tr>
<th>Wave direction (deg)</th>
<th>Significant Wave Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 0.5</td>
<td>0.00 100</td>
</tr>
<tr>
<td>0.5 - 1.0</td>
<td>0.05 100</td>
</tr>
<tr>
<td>1.0 - 1.5</td>
<td>0.93 99.60</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>2.25 84.35</td>
</tr>
<tr>
<td>2.0 - 2.5</td>
<td>1.89 47.09</td>
</tr>
<tr>
<td>2.5 - 3.0</td>
<td>0.63 20.86</td>
</tr>
<tr>
<td>3.0 - 3.5</td>
<td>0.22 18.20</td>
</tr>
<tr>
<td>3.5 - 4.0</td>
<td>0.04 12.21</td>
</tr>
<tr>
<td>4.0 - 4.5</td>
<td>0.01 8.11</td>
</tr>
<tr>
<td>4.5 - 5.0</td>
<td>0.002 4.20</td>
</tr>
<tr>
<td>5.0 - 5.5</td>
<td>0.01 2.17</td>
</tr>
<tr>
<td>5.5 - 6.0</td>
<td>0.01 1.17</td>
</tr>
<tr>
<td>6.0 - 6.5</td>
<td>0.001 0.17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wave direction (deg)</th>
<th>Peak Wave Period (s)</th>
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<tr>
<td>0.00 100</td>
<td>0.00 100</td>
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### Figure 2.4: Joint distribution of wave direction and peak wave period. Deep-water condition.

<table>
<thead>
<tr>
<th>Wave direction (deg)</th>
<th>Peak Wave Period (s)</th>
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<tbody>
<tr>
<td>0.00 100</td>
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<td>0.00 100</td>
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### Figure 2.5: Joint distribution of peak wave period and significant wave height. Deep-water condition.

<table>
<thead>
<tr>
<th>Wave direction (deg)</th>
<th>Peak Wave Period (s)</th>
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<tbody>
<tr>
<td>0.00 100</td>
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</table>

Optimization of the operational use of entrance channels based on channel depth requirements
A set of 255 representative wave conditions were propagated from deep to shallow waters with the model Delft3D-WAVE (Figure 2.6 and Figure 2.7). This set of conditions encompasses 91.37% of the wave cases in the offshore time series. The remaining 8.63% corresponds to short waves with offshore periods lower than 4s (0.003%), and waves approaching the coast on high obliquity, with offshore wave directions smaller than 35° (6.78%), and offshore wave directions larger than 215° (1.84%). It is assumed that the discarded conditions reach the study area with small wave heights and thus have no practical relevance for the present study.

The wave information transferred from deep to shallow waters was interpolated to the 91.37% of the offshore time series, building nearshore wave data time series at different locations with the same time span of the offshore dataset (01/01/1979 to 31/12/2009, wave data every 3 hours).

Figure 2.6: Wave conditions propagated (red dots) to convert deep water wave cases (black dots) to nearshore wave conditions at different locations.

Figure 2.7 provides an example of wave propagation from deep waters (regional domain), through the intermediate domain, to the adjacencies of the Port of Tubarão. Wave parameters and 2D wave spectra were saved in 6 locations along the access channel (Figure 2.8).

The results of the 255 representative wave conditions were interpolated to the offshore time series based on their offshore parameters. A characterization of the 30-year nearshore time series associated to the point in the seaward end of the access channel (Point 1, see Figure 2.8) is provided in Figure 2.9 to Figure 2.11. In these diagrams, the sum of the frequency of occurrence of all classes is not 100%, but 91.37%. The missing conditions are not encompassed by the interpolation matrix; consequently at these times (8.63% of time) nearshore results cannot be determined with the interpolation technique.

It is stressed that the detailed influence of the navigation channel in waves was not properly simulated in this study, since the spatial resolution of the numerical domain (with respect to
the spatial variation in wave height) and the model applied have limitations with respect to the rapidly varying depths through the slopes of the access channel of the Port of Tubarão. Nevertheless, the results are suitable to make an indicative evaluation of different channel depth evaluation approaches.

![Figure 2.7: Schematic representation of the wave propagations from deep to shallow waters using the model Delft3D-WAVE.](image)

![Figure 2.8: Wave observation points along the access channel.](image)
Optimization of the operational use of entrance channels based on channel depth requirements

Figure 2.9: Joint distribution of wave direction and significant wave height. Nearshore condition in Point 1.

Figure 2.10: Joint distribution of wave direction and peak wave period. Nearshore condition in Point 1.

Figure 2.11: Joint distribution of Peak wave period and significant wave height. Nearshore condition in Point 1.
2.4 Access channel

According to an informative document published by the Port Authority in 2013 (Administration of the Port of Tubarão and Port of Praia Mole, 2013), the access channel is 4,422m long, 285m wide, and the design depth is 25.30m. In order to properly represent the wave forcing along the channel and the ship sailing speeds, it was divided into four sections (Figure 2.12). The average and maximum sailing speed in each section are linked to the manoeuvre time and maximum squat magnitude, respectively.

Figure 2.12: Definition of channel sections. Colored lines indicate the interpolated depth contours.

The relations between the wave height time series at different points along the access channel are summarized in Figure 2.13. The nearshore time series originated from the interpolation procedure of the Delft3D-WAVE computations (section 2.3). It is highlighted that the model results were not calibrated neither validated against measured wave data. Additionally the effects of the access channel in the wave propagation were not evaluated in detail, which should include finer spatial resolution of the grid and a better discretization of the spectral domain considered by the numerical model.

Wave heights are similar in points 1, 2 and 3 (sea side locations). Wave transformation and shadowing effects start becoming pronounced in the region of point 4, being very evident in the time series of point 5 and 6.
The exit maneuver is critical in terms of channel depth requirement, since the Port of Tubarão is a loading port for the design iron ore carriers: ships arrive in the port ballasted but unloaded and the outgoing vessels have the largest draught. The sections are named according to the sequence in the exit maneuver: Section 1 is closer to the quay, followed by Sections 2 and 3 in the midway of the exit maneuver, and Section 4 is in the sea end of the dredged part of the channel. Velocities associated to each section were estimated based on expert judgement (personal communication with Herm Jan van Wijhe – Port of Rotterdam; Jos van Doorn, Hans Cozijn and Johan Dekker - MARIN). The length, wave data point, average and maximum sailing speeds for each section are presented in Table 2.2. The required time for crossing each section is calculated based on the length and average sailing speed along the section. The required time for the whole exiting maneuver according to the assumed velocity scenario is approximately 58min.

Table 2.2: Definition of the channel sections.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>740m</td>
<td>1290m</td>
<td>1315m</td>
<td>1340m</td>
</tr>
<tr>
<td>Wave point</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Average speed</td>
<td>1kn 0.5m/s</td>
<td>3kn 1.5m/s</td>
<td>4kn 2.1m/s</td>
<td>5kn 2.6m/s</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>2kn 1m/s</td>
<td>4kn 2.1m/s</td>
<td>5kn 2.6m/s</td>
<td>6kn 3.1m/s</td>
</tr>
<tr>
<td>Sailing time</td>
<td>25min</td>
<td>14min</td>
<td>10min</td>
<td>9min</td>
</tr>
</tbody>
</table>
2.5 Long (infragravity) waves along the access channel

Lower-frequency motions in the so-called infragravity band (nominally 0.003 to 0.03Hz) are generally week in the deep ocean but can be very energetic in shallow water ($m_0 > 0.01$ and 0.1m in 10m depth and at the shoreline, respectively). The generation of infragravity motions is associated to nonlinear interactions of two surface waves, which excited a forced secondary wave with the difference frequency $\Delta f$.

Instead of running a number of wave conditions in a model able to compute infragravity motions (e.g. XBeach model), the forced infragravity wave energy was computed based on local water depth and primary 2D wave spectra. This procedure was done using a Matlab program that applies the second-order nonlinear theory of Hasselmann (1962). The program was written by A. van Dongeren/Deltares in 2001.

The primary 2D wave spectra along the access channel were obtained from the 255 short wave propagations using Delft3D-WAVE. The representative water depth definition, used as input to compute the forced infragravity energy, is presented in Table 2.3. These water depths are not associated to single points in the channel, but to more regional values corresponding to the spatial scales of the long waves (which can be considered larger than the channel width, for instance). A bathymetric map of the study area is provided in Figure 1.2.

Table 2.3: Representative water depth in each channel section for computation of forced infragravity wave energy.

<table>
<thead>
<tr>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>12m</td>
<td>14m</td>
<td>16m</td>
<td>20m</td>
</tr>
</tbody>
</table>

Although the observed forced wave energy is well predicted by the second-order nonlinear theory, an analysis of data measured at 13m depth described in Herbers et al. (1992) indicates that forced waves can account for only a small part (0.007% to 30%) of the total observed infragravity energy, being this contribution largest when the infragravity energy is maximum. Therefore, in the situation described by Herbers et al. (1992) motions other than locally forced secondary waves are clearly important at infragravity frequencies. Their observations suggest that the infragravity energy that is not locally forced is mainly contributed by free waves that are generated by wave breaking process close to the shore and are trapped on the shelf (Herbers et al., 1992). It is highlighted, however, that the experiment described in this paper was conducted in a long, straight, plain sloping beach, which is a rather different situation comparing to the region adjacent to the Port of Tubarão.

The applied tool assumes a flat bottom equilibrium situation, i.e. the energy levels of forced bound long waves depend only on the local water depth and the swell-sea frequency directional spectrum. It does not take free wave energy into account, which may also be a function of the surrounding shelf and beach topography. Thus, when free waves dominate the infragravity spectrum, the estimates of the total local long wave energy level based only on forced wave energy by the second-order nonlinear theory are expected to be too low.

The outcomes of the calculations using the Matlab routine associated to a few conditions were compared to results of XBeach simulations presented in Dobrochinski (2013) for the same location. In general, the results of total long wave energy computed by XBeach show less dependency on local water depths and short wave height, which might be related to the complex transference of energy from bound to free long waves during propagation and the occurrence of free long waves released in the adjacent beach after short wave breaking. Even though the conditions around the study area go far beyond the simplified assumptions
of the second-order nonlinear theory, to some extent the results of the two methods are in agreement, supporting the application of the second-order nonlinear theory in this research project.

Results for the different channel sections obtained with the application of the second-order nonlinear theory and interpolated for the wave data time series (from 1979 to 2009) are presented in Figure 2.14.

![Figure 2.14](image1.png)

*Figure 2.14: Long wave height as a function of short wave height at the different sections of the channel. Time points from the wave data time series (01/01/1979 to 31/12/2009, time resolution 3 hours)*

In Figure 2.14 it is noted that the relation between short and long wave heights becomes steeper as the water depth is reduced (from section 4 to section 1). The higher long waves are in the order of 25cm, being associated to Section 2, where the shadowing effects of the breakwater is not so pronounced and the water depths are reduced in comparison to sections 3 and 4. Nevertheless, it is highlighted that these results are preliminary since the important contribution of free long waves to the total long wave energy is not being considered. For a more reliable estimation of the long wave climate in the area a more complex numerical model should be used (e.g. XBeach) being supported by *in situ* measured datasets.
2.6 Ship dimensions

The ship considered in the study is similar to the deep-draught very large ore carriers Valemax (Figure 2.15). These vessels carry iron ore from Brazil to European and Asian ports, with a capacity ranging from 380,000 to 400,000 tons deadweight.

![Example of Valemax vessel](http://www.vale.com)

Figure 2.15: Example of Valemax vessel (Source: http://www.vale.com).

Table 2.4 presents the definitions of the design ship considered in this study.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>360m</td>
</tr>
<tr>
<td>Breadth</td>
<td>65m</td>
</tr>
<tr>
<td>Draught</td>
<td>22.5m</td>
</tr>
<tr>
<td>Block coefficient</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Table 2.4: Design ship dimensions.
3 Probability and risk criteria

The depth and width design of harbor entrance and navigation channels, as well as operational optimization of channel dimensions, are nowadays based on computations of the probability of bottom touching during passing events. This probabilistic method leads to significant savings compared to the deterministic approach. The aspects are based on acceptable levels of risk, herein defined as the probability of bottom contact times the quantified consequences of it, which gives the expected losses associated to such undesired events. Therefore, the risk of bottom contact is related to the channel bed composition (e.g. mud, sand, rock), type of cargo (e.g. iron ore, oil, LNG, containers), and value of local environment. The acceptable risks and safety levels for the channel usage should be defined by the port or terminal authorities for each particular case (Moes, 2008). In 1985 Van Doorn stated that for most channel depth studies such a risk analysis was not made and the safety level was used to be chosen in a conservative way. However, since then the standard practice had been changed towards the inclusion of risk evaluations in the studies.

Van de Kaa (1984) compiled one of the earliest summaries of safety criteria for deep-draught vessels in port entrance channels considering the consequences of incidents and the acting environmental conditions. Four of his probability criteria for bed contact are:

1. Accident per passage under average environmental conditions: \(5 \cdot 10^{-4}\)
2. Accident with heavy damage per passage under average conditions: \(2.5 \cdot 10^{-7}\)
3. Accident per passage under extreme environmental conditions: \(1 \cdot 10^{-9}\)
4. Accident with heavy damage per passage under extreme conditions: \(5 \cdot 10^{-4}\)

Higher probabilities are acceptable during extreme environmental conditions because less vessels will use of the channel under those specific conditions. Therefore, this less strict criterion does not necessarily result in an increased number of accidents during longer periods of time.

The results of an analysis of groundings in Northern European Ports by Dand and Lyon showed in 1993 that grounding occurs with a probability of 0.03 incidents per 1000 ship movements (a probability of \(3 \cdot 10^{-5}\), or one bottom contact per 33000 ship movements) (PIANC, 1997). These ship movements probably relate to all movements of larger-size ships under general environmental conditions.

Savenije (1995) summarized the practice adopted at the Port of Rotterdam, who quotes three different norms according to the Dutch channels safety-criterion:

1) During 25 year the probability of touching the channel bottom, with maximum minor damage, must not be more than 10%.
2) The probability that a vessel during its transit touches the channel bottom must always be less than 1% for all weather condition.
3) Besides the above mentioned safety criteria, a maneuvering criterion make sure that the keel clearance never is less than 1 m.

Considering a Poisson distribution, a chance of 10% of having one bottom contact in 25 years equals a probability of 0.0042 touches per year, which corresponds to an average return period of 237 years. This criterion is based on a shipping intensity of 250 deep-draught
vessels calling the Port of Rotterdam per year (6250 vessels in 25 years), so it can be stipulated the probability of $1.68 \cdot 10^5$ bottom contacts per passage leading to significant damage. Considering the fact that only one out of ten occurrences results in more than minor damage (the other nine bottom touches lead to zero or at most minor damage) it results in the probability of $1.68 \cdot 10^4$ bottom touches per passage, now including also the events without significant damage. In this case, the resulting return period of a bottom contact is approximately 24 years (Savenije, 1995 and Moes, 2008).

The table below adapted from Moes (2008) provides an illustration of possible probability values that could be used for the depth design and operational optimization of channels according to certain risk levels. The values presented are number of years where a single bottom touch by one of the vessels would be acceptable.

Table 3.1: Acceptable return periods (years) of bottom touch. $E1 = industrialized$ marine environment, $E2 = medium$ sensitive marine environment, $E3 = very sensitive$ marine environment (Moes, 2008).

<table>
<thead>
<tr>
<th>Cargo type</th>
<th>Channel bed condition</th>
<th>Hard</th>
<th>Medium</th>
<th>Soft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dangerous</td>
<td></td>
<td>E1→50</td>
<td>E1→25</td>
<td>E1→10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E2→100</td>
<td>E2→50</td>
<td>E2→25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E3→200</td>
<td>E3→100</td>
<td>E3→50</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td>E1→25</td>
<td>E1→10</td>
<td>E1→5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E2→50</td>
<td>E2→25</td>
<td>E2→10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E3→100</td>
<td>E3→50</td>
<td>E3→25</td>
</tr>
<tr>
<td>Safe</td>
<td></td>
<td>E1→10</td>
<td>E1→5</td>
<td>E1→1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E2→25</td>
<td>E2→10</td>
<td>E2→5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E3→50</td>
<td>E3→25</td>
<td>E3→10</td>
</tr>
</tbody>
</table>

Assuming an average present risk condition, in which the dangerous associated to the cargo type is classified as medium; the consolidation of the bed is medium, as well as the sensitivity of the marine environment. This gives an acceptable return period for one bottom touch of 25 years (with 50 passages per year a probability of approximately $8 \cdot 10^4$ per passage). This value is in agreement with most of references presented above, being though more than one order of magnitude less conservative then the values indicated in PIANC guides. This can be justified by the fact that PIANC provides only one acceptable probability in contrast to the table for different risk conditions presented by Moes (2008). In this case it is expected that PIANC recommends a conservative value.

Accordingly the acceptable mean probability of bottom contact considered in the next chapters of this study is $8 \cdot 10^4$ bottom touches per passage, with a maximum probability 1% (0.01) per passage during extreme conditions. In addition, a criterion for the maneuvering margin makes sure that the keel clearance never is less than 1m.
4 Channel depth evaluation based on nautical requirements

Aside from the influence of waves (which is considered separately in Chapter 5), the required depth of the access channel is mainly determined by (see Figure 1.1):

1. Water depth;
2. Static draught of the vessel (including a static trim);
3. Squat;
4. Minimum manoeuvring margin.

In this case, for the access channel to be available the nautical criterion has to be attended:

\[ KC > \text{Minimum Manoeuvring margin} \]

With

\[ KC = \text{Water depth} - [\text{Static draught} + \text{Squat}] \]

The water depth is defined as the bottom level plus the tide benefit. Uncertainties in the definition of the bottom level have to be included in the calculation to ensure a safe use of the channel. The tide benefit is the summation of the astronomical and the meteorological tides. The last one acts as a vertical shift in the mean water level, resulting in higher high water levels when the meteorological tide is positive; and lower low water levels when the meteorological tide is negative. Nevertheless, it is highlighted that transversal currents are not being considered in the definition of access channel operational windows.

The nautical criteria for determination of the availability of the channel can also be expressed as a limit state function:

\[ Z = [(\text{Bottom level} + \text{Tide benefit}) - \text{Draught} - \text{Squat}] - \text{Minimum manoeuvring margin} \]

A section of the channel is available if \( Z > 0 \). When \( Z \) assumes negative values the water depth is not enough for a safe navigation through the section. The availability of the channel to start the manoeuvre at a given time is computed by checking the limit state function along the sections, considering the travelling time between sections. The result of such an analysis, for either deterministic or probabilistic methods, is information of the downtime of the access channel related to channel depth restrictions.

The next sections of this Chapter provide a description of the minimum manoeuvring margin definition, squat effects, and the deterministic and probabilistic computations of the operational windows of the access channel.

4.1 Manoeuvring margin

The ability of a vessel to maneuver at its design speed will decrease when the clearance between the channel bottom and the ship’s keel is reduced. This clearance and may become insufficient if it is less than a certain critical value that maintains sufficient flow under and around the ship. For instance, a vessel with a very small manoeuvring margin becomes very sluggish in manoeuvring and therefore has increased risks of collisions or path width
excursions. Therefore, a minimum manoeuvring margin is required to provide adequate maneuverability for a moving vessel.

To cover this aspect, the maneuverability margin is the time-averaged minimum clearance under the ship (KC) required to ensure good maneuverability of the ship. The available KC is determined by factors such as water depth, draught, and squat. The effect of wave-induced ship oscillations in heave, pitch and roll are not generally considered to have a significant effect on maneuverability (PIANC, 2014).

The limiting value for the maneuvering margin, i.e. the KC expressed as percentage of the draught, depends on ship type, channel dimensions and alignment, and ship traffic. A minimum value of 5% of draught or 0.6 m, whichever is greater, has been found to provide adequate margin for most cases (PIANC, 2014). The current practice of the Port of Rotterdam is applying a minimum maneuvering margin of 1m for deep draught vessels, including the Valemax vessels loaded in Brazil. This minimum requirement is adopted in the evaluation of depth requirements presented in the next sections of this report.

4.2 Squat effects

When a ship is sailing, its displacement causes a return current from the bow to the stern. A pressure drop occurs causing a water level depression zone extending sideways of the ship, which is called primary ship wave. This depression zone causes a vertical translation (i.e., sinkage) and an angular rotation about the transverse axis of the sailing ship (i.e., trim). This combination of sinkage and change in trim is called ship squat, which can have different values at the bow and stern.

The magnitude of squat is dependent on the ship type, dimensions and sailing speed. Further, vertical and lateral confined waters influence the magnitude of squat effects. The maximum squat is found either at the bow or at the stern of the ship.

Briggs (2010) states that especially for full-form ships such as tankers the maximum squat occurs at the bow. For more slender fine-form ships such as container ships and passenger liners, sometimes the maximum squat occurs at the stern. The value of Cb determines whether the maximum squat is at the bow or stern. Barrass notes that full-form ships with Cb >0.7 tend to squat by the bow and fine-form ships with Cb <0.7 tend to squat by the stern. Römisch proposes that a ship will squat by the bow if Cb>0.1Lpp/B. The block coefficient (C_b) of the design ship is 0.84, so according to Barrass approximation the maximum squat is expected to occur in the bow. The approximation of Römisch using L_{pp}=360m and B=65m also indicate that the maximum squat occur in the bow of the ship.

The guide for design of access channels published by PIANC-WG30 (1997) has 11 empirical formulas for predicting ship squat in entrance channels. In 2005, PIANC WG49 was formed to update the WG30 report on Horizontal and Vertical Dimensions of Fairways. All the methods presented in the guidelines are valid for straight channels with flat bottoms and subcritical ship speeds. The type of waterway and the block coefficient of the ship determine the appropriate formula.

Some of the most widely used formulas to compute squat are Barrass II, Eryuzlu et al., and Huuska/Guliev. These three formulas are valid for unrestricted and restricted shallow
channels when the block coefficient is larger than 0.8, being thus applicable to the Valemax vessels sailing through the access channel of the Port of Tubarao.

The formulas are based on limited laboratory and field measurements, being functions of a limited number of ship and channel parameters. Typical ship parameters include ship speed (relative to the water), block coefficient \( C_B \), and ship dimensions. Channel parameters include water depth, type of channel cross-section, side slope, and bottom channel width. Channel types are unrestricted or open channels, restricted or dredged with a trench, and canal with sides that extend to the surface.

The accuracy of each formula depends on the type of vessel channel. Additionally, when performing a design analysis for ship squat, many ship and channel parameters are not known with certainty. Briggs (2010) performed a sensitivity analysis for five PIANC squat formulas on the effect of ship speed, draught, block coefficient, and water depth for an unrestricted or open channel cross-section.

According to PIANC (1997), when using the squat formulas it should be borne in mind that all of them must generalize the problem and most were developed for particular conditions and limits. For more accurate predictions of squat can be made for a given ship by the use of computer models and model tests. Additionally, squat estimations made during design can be validated by means of full-scale observations, which may lead to modifications of the allowable draught or to corrections of the maintenance dredging program.

In the following paragraphs different formulas are described according to PIANC (1997).

4.2.1 Barrass II (1979, 1981)

This formula is based on the analysis of squat results from different ships and model tests with block coefficients ranging from 0.5 to 0.9 both in open water and in restricted channel conditions for \( h/T \)-ratios ranging from 1.1 to 1.5 and \( F_{nh} < 0.7 \).

\[
S_{\text{max}} = \frac{C_B}{30} \left( \frac{S_2^2}{S_2^2 + V_k^2} \right)^{0.8} \frac{V_k^2}{30}
\]

Where:
- \( S_2 = \text{blockage ratio: } A_s/A_w \)
- \( A_s = \text{midship section area } (\sim 0.98 \text{ BT } = 1433 \text{m}^2) \)
- \( A_w = \text{wetted cross section area of the waterway } (\text{m}^2): A_w = A_{ch} - A_s \)
- \( A_{ch} = \text{equivalent wetted cross section area of channel with slope extrapolated to the water surface } (\text{m}^2) \). It is assumed the channel is 270m wide in the bottom and the side slope of the dredging cut is 1:8. The instantaneous water depth of the channel is used to compute \( A_{ch} \).
- \( C_B = \text{block coefficient } (0.84) \)
- \( V_k = \text{ship's speed relative to the water (knots)} \)

4.2.2 Eryuzlu et al. (1994)

The formula was undertook thorough model tests with general cargo ships and bulk carriers having bulbous bows (\( C_B \geq 0.8, L/B = 6.7 - 6.8, B/T = 2.4 - 2.9 \)) in laterally unrestricted water with restricted depth \( (1.1 \leq h/T \leq 2.5) \). The effect of channel width on squat was investigated in supplementary model tests carried out in a channel (height of underwater
The empirical expression obtained is presented below:

\[ S_b = 0.298 \left( \frac{h^2}{T} \right)^{\frac{2.289}{h}} \left( \frac{h}{T} \right)^{-2.972} K_b \]

Where:
- \( h \) = water depth (m). This parameter varies in time with the water level changes due to tides and surge.
- \( T \) = draught (22.5m)
- \( V \) = speed through water (m/s)
- \( g \) = acceleration due to gravity (9.81 m/s²)
- \( \sqrt{\frac{w}{B}} \) = channel width at bottom (270m)
- \( B \) = ship’s beam (65m)

4.2.3 Huuska/Guliev (1976)

This formula was developed based on model tests for lateral unrestricted waterways carried out by several laboratories. The equation accounts for a blockage factor \( K_S \) to include restricted channels and canals, using the investigations of Guliev (1971, 1973).

\[ S_b = 2.4 \frac{V}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} K_S \]

With:
- \( V \) = ship’s volume displacement (\( C_B L_{pp} B^2 T = 442260 \text{m}^3 \))
- \( L_{pp} \) = ship’s length between perpendiculars (360m)
- \( F_{nh} \) = Froude depth number (\( F_{nh} = V (gh)^{0.5} \))
- \( K_S = 7.45 s_1 + 0.76 \) for \( s_1 > 0.03 \)
- \( K_S = 1 \) for \( s_1 \leq 0.03 \)
- \( s_1 = (A_s/A_{ch})/K_1 \)
- \( K_1 \) = correction factor from graph (Figure 4.1)
- \( A_s \) = midship section area of ship (~0.98 BT = 1433m²)
- \( A_{ch} \) = equivalent wetted cross section area of channel with slope extrapolated to the water surface (m²). It is assumed the channel is 270m wide in the bottom and the side slope of the dredging cut is 1:8. The instantaneous water depth of the channel is used to compute \( A_{ch} \).
Figure 4.1: Correction factor $K_1$ based on the relative height of underwater dredged trench.

For full form ships with high $C_B$ some authors recommend other values for the coefficient 2.4. They propose coefficient values varying between 1.75 and 2.4.

For comparison proposes, squat effects as function of the sailing speed were calculated for the different sections of the channel using the three formulas described above considering a water depth of 25m (Figure 4.2 to Figure 4.5). The formula of Huuska/Guliev uses as input the height of underwater dredged trench, which is assumed to be 15m for Section 1, 13m for Section 2, 10m for Section 3, and 5m for Section 4.
Figure 4.2: Squat calculations for Channel Section 1. The dashed line indicates the assumed maximum sailing speed in this section.

Figure 4.3: Squat calculations for Channel Section 2. The dashed line indicates the assumed maximum sailing speed in this section.
Optimization of the operational use of entrance channels based on channel depth requirements

Figure 4.4: Squat calculations for Channel Section 3. The dashed line indicates the assumed maximum sailing speed in this section.

Figure 4.5: Squat calculations for Channel Section 4. The dashed line indicates the assumed maximum sailing speed in this section.

Table 4.1 presents the ship speeds along the access channel and the squat effects estimated with the different formulations. The formula of Huuska/Guliev (1976) and Eryuzlu et al. (1994)
Optimization of the operational use of entrance channels based on channel depth requirements

Calculates bow squat; Barrass II (1979, 1981) gives the maximum squat, which is likely to occur at the bow for ships with large block coefficient. It is assumed that squat effects are composed 50% by trim (towards the bow) and 50% by sinkage. Therefore the computed squat values are in the extreme bow of the ship. In the stern sinkage is compensated by trim effects, so the squat effects are zero.

Table 4.1: Ship speeds and typical squat effects along the channel, assuming a water depth of 25m.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum speed</td>
<td>1m/s</td>
<td>2.1m/s</td>
<td>2.6m/s</td>
<td>3.1m/s</td>
</tr>
<tr>
<td>Squat (E)</td>
<td>0.02m</td>
<td>0.10m</td>
<td>0.17m</td>
<td>0.25m</td>
</tr>
<tr>
<td>Squat (H)</td>
<td>0.04m</td>
<td>0.17m</td>
<td>0.24m</td>
<td>0.33m</td>
</tr>
<tr>
<td>Squat (B)</td>
<td>0.03m</td>
<td>0.14m</td>
<td>0.22m</td>
<td>0.31m</td>
</tr>
</tbody>
</table>

4.3 Deterministic calculations excluding the influence of waves

The essence of the deterministic approach (Level I method) is that a certain representative value of the resistance is divided by a factor and that the representative value of the solicitation is divided by a factor, for which the following must apply:

\[ \frac{R_{rep}}{\gamma_r} > \gamma_s S_{rep} \]

Where:
\( \gamma_r \) and \( \gamma_s \) are partial safety factors.

In the current application uncertain variables are associated to the definition of the resistance (KC). Therefore a safety margin is added to these parameters in order to cope with uncertainties. The representative values are assumed to be the mean value of the variables.

The static draught and trim of the ship: can be accurately determined; nevertheless an uncertainty around this parameter may occur. A margin of 1.5% is added to the ship’s static draught to be on the safe side regarding imprecision in the determination of the draught.

Squat effects: are calculated using the formulas of Eryuzlu et al., Huuska and Barrass II, based on the ship and channel dimensions, maximum sailing speed in the channel section and instantaneous water depth. The safety margin in the squat value compensates the uncertainties in the input parameters and formulation.

Bottom level: the definition accounts for uncertainties in the hydrographic survey and siltation. According to IHO (2008), the maximum allowable total vertical uncertainty for a “special” hydrographic survey is in the order of 0.30m. The values considered in the deterministic computations are listed in Table 4.2.
Table 4.2: Parameters and safety margins considered in the deterministic calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base value</th>
<th>Safety margin</th>
<th>Final value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship’s draught</td>
<td>22.5m</td>
<td>+1.5%</td>
<td>22.84m</td>
</tr>
<tr>
<td>Squat at bow</td>
<td>Mean of the three formulas</td>
<td>+25%</td>
<td>Mean*1.25</td>
</tr>
<tr>
<td>Maneuverability margin</td>
<td>1m</td>
<td>-</td>
<td>1m</td>
</tr>
<tr>
<td>Bottom level</td>
<td>25.30m (chart datum)</td>
<td>-0.30m (accuracy) -0.50m (siltation)</td>
<td>24.50m</td>
</tr>
</tbody>
</table>

This results in the following expression for Z:

\[
Z = (\text{Bottom level} - 0.3 - 0.5) + [\text{Tide benefit}] - [\text{draught} \times 1.015] - [\text{Squat} \times 1.25] - 1
\]

A section of the channel is available when Z>0.

Neglecting the influence of waves, the required nautical bottom level is obtained by adding the ship’s draught, squat effects and maneuverability margin. Reversely, by subtracting the nautical bottom level from this summation, the minimum required tidal benefit relative to the chart datum is obtained. Assuming a water depth of 25m for the squat calculation the values presented in Table 4.3 are obtained for the minimum required tidal benefit.

Table 4.3: Minimum tide benefit relative to the chart datum to allow maneuver in each section considering a water depth of 25m for the squat computation. Mean Sea Level is 0.82m above the zero level of the chart datum.

<table>
<thead>
<tr>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.62m</td>
<td>-0.48m</td>
<td>-0.40m</td>
<td>-0.28m</td>
</tr>
</tbody>
</table>

Up to the limits given in Table 4.3 the channel is available during unusual periods of negative tidal ‘benefits’. The outer sections are more restrictive due to the fact that the ship gains speed along the channel, resulting in more pronounced squat effects as the maneuver evolves.

Assuming a deterministic and spatially homogeneous water level time series associated to both astronomical and meteorological tides, the operational windows of the access channel are evaluated. In this case, the entire departure maneuver must be considered, accounting for the time required to cross each channel section. The availability of the channel to start a maneuver does not depend only on the water level at the starting time of the maneuver, but on the minimum water levels when crossing each channel section. Figure 4.6 schematizes the procedure used to evaluate the availability of the channel to start a maneuver.
In the top drawing of Figure 4.6 the water level is higher than the required limits for each section; therefore the maneuver can be started (last possibility). In a following time the tidal level will restrict the start of the maneuver, first by impeding the navigation through the outer end of the channel, where the limiting level is higher due to higher sailing speeds and more pronounced squat effects at this section. In the second drawing the tide level is restricting the maneuver in sections 2, 3 and 4, consequently the channel is not available at this time. During the conditions schematized there was no water level restriction for sailing in the first section of the channel; however, the channel became unavailable because there was not enough tidal benefit to allow the whole departure maneuver. The third scheme illustrates a situation with the water level rising during the maneuver and the channel becoming available after a closed window.

A Matlab routine was built to simulate the same procedure described above for a longer time span and considering depth-dependent squat effects. The main result of this simulation is the fraction of time the channel is available. Information about the availability of each individual channel section and the length of the tidal windows can also be derived. For instance, a small number of rather long periods of unavailability of the channel may probably be more adverse to the port operations than a greater number of shorter periods of unavailability. From the availability of each individual section, critical locations can be identified that have a major contribution to the downtime of the channel.

The channel was evaluated for the period between 01/04/2008 and 01/09/2008 (5 months). It is highlighted that only the astronomical tides correspond to the conditions that took place in
reality during this time. Non-astronomical tides were added via a synthetic time series built from the spectrum of non-astronomical (i.e. meteorological) tides. Even though the overall influence of these processes is reasonably well included in the analysis, the chronology of the events is not reproduced.

The results for the computation considering a draught of 22.50m are presented in Figure 4.7 in the form of a water level time series with indication of the periods the channel is available (green line) and non-available (red). For this definition of the channel, ship and tides, deep-draft vessels with draught lower than 22.5m can use the channel in 100% of the time, since low tidal levels are not low enough to restrict the navigation through the sections.

For sake of comparison between the different methods, a similar simulation was run considering the ship’s draught equal to 23.60m. The resulted time series of water levels with indications of the periods the channel (non-) available is presented in Figure 4.8. During 46.6% of the time period considered in the analysis (5 months) the channel is available, in the other times low water levels restrict the navigation through the channel, hence not allowing the start of the maneuver. The majority of closed windows in this fictitious time series are shorter than 10 hours. The average the length of these non-operational periods is 6.4 hours and the maximum length is 23 hours. Note that these correspond to this example time series and may not describe general downtime/unavailability values.

Figure 4.9 indicates the fraction of time each section is available in comparison to the availability of the channel as a whole, considering draught equal to 23.6m. Channel section 4 the main contributor for operability of the channel. This is due to the higher sailing speeds at this section, resulting in more pronounced squat effects. For instance, the operability of the channel could be improved by deepening this outer section. On the other hand, a reduction of the depths along section 1 would not result in a substantial increase in the channel downtime, since it is very likely that the other sections of the channel are unavailable when the water levels are restricting navigation through section 1.

For a better understanding of the influence of the parameters and associated safety margin in the definition of the availability of the channel, different simulations were performed considering draught of 23.6m and increasing gradually the number of safety margins adopted. The resulting availability percentages are presented in Table 4.4.
As expected, the inclusion of different safety margins in the analysis has a great influence on final results of availability of the channel. It is highlighted, however, that the absolute influence of each safety margin cannot be derived from this analysis, since the sequence the different margins are added influence the final results.
Figure 4.7: Time series of water level with indication of the periods the channel is (non-) available. Deterministic simulation considering ship’s draught of 22.5m. Note that in this situation the channel is available 100% of the time.
Figure 4.8: Time series of water level with indication of the periods the channel is (non-) available. Deterministic simulation considering ship's draught of 23.6m.
4.4 Probabilistic calculations excluding the influence of waves

In a probabilistic approach, the parameters in the limit state function are assumed to be stochastic, with the uncertainties included in the probabilistic distribution of the values for the variables. At each time along the water level time series the probability of having negative \(Z\) (failure) in the sections of the channel is computed, including traveling times between sections. The joint probability of failure consists of the sum of the individual contribution from the different channel sections, and should be acceptable for the channel to be available.

Excluding the influence of waves, the limit state function compares the available KC and the minimum required margin for maneuver. In this case, the stochastic behaviour of the variables considered in the probabilistic calculations is only related to uncertainties in their definition. The limit state function is given below, with the stochastic variables bolded:

\[
Z_{\text{section}} = \left[ \text{Bottom level} + \text{Tide benefit} - \text{Draught} - \text{Squat} \right] - \text{Minimum manoeuvring margin}
\]

In most of the cases failure (negative values of \(Z\)) will not directly mean bottom contact, since the maneuverability margin has to be reduced to zero (and \(Z\) to -1) before the ship actually touches the ground (in this Chapter the influence of waves is neglected). However, it is assumed that the maneuverability of the ship is significantly reduced if this margin is lowered, leading, for example, to an accident due to the lack of rudder response. Therefore it is considered unacceptable when the available KC becomes smaller than the maneuverability margin (1 m).
This risk criteria presented in Chapter 3 originated from references that provide acceptable probabilities of bottom touch considering (within others variables) the effects of vertical ship motions in waves. The applicability of the same risk criteria as when waves are included in the analysis is not explicitly reported in literature. Since to a certain extend the reduction of the maneuverability margin does not lead to bottom contact, the use of the same criteria would lead to too conservative results.

It is clear that there is room for discussion in the definition of the acceptable probability of bottom contact excluding the influence of waves. Nevertheless the risk criteria described in Chapter 3 is applied to the limit state function presented in this section. This criteria states that the acceptable probability of bottom contact for all environmental conditions is $8 \times 10^{-4}$ per passage, which can be regarded as the upper limit for the average chance of bottom contact during the times the channel can be used. The maximum allowable probability of bottom contact per passage is 1%. This value is expected to occur fewer times, ensuring that the mean probability per passage is sufficiently low. The same probability limits are applied in the probabilistic calculation for the chance of having the maneuverability margin reduced. Therefore, the availability of the channel is given by:

$$\sum_{section=1}^{4} \Pr(Z_{section} < 0) < 0.01$$

Once the distributions of the variables are properly defined, the main advantage of the probabilistic method in comparison to the deterministic method is that the reliability of the system can be accessed, with reliability defined as the probability that the limit state is not exceeded.

The deterministic method, however, relies only on safety factors applied to the relevant parameters. In this case there is no strict control on the final probability of failure of the system, which can be either excessively safe leading to unnecessary capital and operational costs; or unsafe resulting in hazards to navigation, environment and port operations.

The parameters of the distributions considered in the probabilistic computations are presented in Table 4.5. The upper limit of the distribution of ship’s draught, squat effects, survey accuracy and siltation corresponds to the values adopted in the deterministic simulation (see Table 4.2). However, since the variables are assumed to be independent, the joint probability of having extreme values for all variables is rather low. Therefore, the results of the probabilistic computations are expected to lead to a more optimized operation of the channel in comparison to the results of the deterministic computations presented in the previous section.

For each time point of the water level time series the probability of failure was calculated using both FORM method (First Order Reliability Methods) and Monte Carlo method. The form methods use a linear approximation of limit state together with the assumption that random variables are normal, and then the limit state is also a normal variable. The Monte Carlo methods comprise a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. Simulations are run many times over in order to obtain the distribution of an unknown probabilistic entity (Z in this case).
Table 4.5: Parameters considered in the probabilistic computations. (CV=coefficient of variation=σ/μ; σ=standard deviation; μ=mean)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Assumed uncertainty</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship’s draught</td>
<td>22.5m</td>
<td>CV=0.005</td>
<td>Normal</td>
</tr>
<tr>
<td>Squat at bow</td>
<td>Mean of the three formulas</td>
<td>CV=0.1</td>
<td>Normal</td>
</tr>
<tr>
<td>Maneuverability margin</td>
<td>1m</td>
<td>n/a</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Bottom level</td>
<td>25.30m</td>
<td>+/- 0.30m (survey accuracy)</td>
<td>Triangular</td>
</tr>
<tr>
<td></td>
<td></td>
<td>μ=0.07m (siltation)</td>
<td>Exponential</td>
</tr>
</tbody>
</table>

The calculations were done using Matlab programs from the OpenEarth Tools. The results of the two methods converged up to probabilities much lower than the threshold value for the use of the channel (0.01). The individual contribution of each section is the maximum probability of bottom contact during the passage (i.e. in case of falling tide probably the maximum probability occurs in the final part of the section when the water level is slightly lower). The joint probability was computed by summing up the contribution of each section. Finally, the channel is defined as available at the times when the probability of failure does not exceed 1%.

The results of the probabilistic simulation considering ship’s draught of 22.50m is presented in Figure 4.10. In agreement with the results of the deterministic computations for the same draught, in this case the channel is available in 100% of the time period analysed.

To better compare the performance of the methods, the probabilistic approach was also run considering a draught of 23.60m. Results are presented in Figure 4.11. In this case it is noticed that in certain occasions, when the water level is lower, the chance of not having enough water depth for the maneuver become unacceptable, leading to period of unavailability of the channel. During the 5 month simulated with the probabilistic approach the channel remained available during 96.6% of the time, which is considerable higher than the fraction of time the channel is available in the deterministic results (46.6%). Consequently, the number of downtime events is considerable lower, as well as the maximum length of unavailability periods. For this probabilistic simulation the average probability of failure during the time the channel is available is $3.7 \times 10^{-4}$ per passage. According to the premises adopted in this study, this means that the safety level for this example case is acceptable.

The large difference between the results obtained with the deterministic and probabilistic method is directly associated to the definition of the safety margins (deterministic approach) and probability distributions (probabilistic approach). The safety margins were defined before comparing the results of the deterministic and probabilistic approaches, being chosen in a conservative way. Though, this may result in rather low the joint probability of occurrence of all these pessimistic values. The probabilistic approach, in the other hand, relies in the definition of the probability distributions, which are necessarily available in every case. This method incorporates more knowledge in the analysis, allowing to certain extent compensation between favourable and unfavourable effects of uncertainties. Nevertheless, partial safety factors can be computed or calibrated for specific cases based on probabilistic calculations.
The resulting safety margins can make the results of deterministic and probabilistic to be similar, ensuring the required reliability, but not being excessively restrictive.

A comparison between the results obtained using deterministic and probabilistic methods can also be based on the minimum required gross keel clearance during a specific condition, with the gross keel clearance being the difference between the bottom level and the level of the ship’s keel, encompassing all applicable allowances. For a situation with draught of 22.3m and excluding the influence of waves, the minimum required gross keel clearance computed by the deterministic approach (as used in this study) is 2.51m, which includes the siltation buffer (0.5m); allowances related to survey accuracy (0.3m) and definition of draught (0.33m), squat effects (0.37m); and the minimum maneuverability margin (1m). Using the probabilistic approach with the probability distributions presented in Table 4.5, the gross keel clearance must be at least 1.81m for having the channel available (probability of failure inferior to 1%). Nonetheless, by following the definitions currently applied by the port presented in Chapter 1, the required gross keel clearance under mild wave conditions is 3.0m.

Despite the number of limitations and assumptions incorporated to the quantitative evaluations, there is an indication that the use of the channel of the Port of Tubarão could be optimized, reducing channel downtime, dredging costs and/or allowing deeper-draft vessels to use the channel (increased cargo loads).
Figure 4.10: Time series of water level with indication of the periods the channel is (non-) available. Probabilistic simulation considering ship's draught of 22.50m. Note that in this situation the channel is available 100% of the time.
Figure 4.11: Time series of water level with indication of the periods the channel is (non-) available. Probabilistic simulation considering ship’s draught of 23.60m.
In Figure 4.12 the availability of each individual section is presented versus the availability of the channel as a whole. In agreement with the deterministic results, the critical section of the channel is section 4 due to more pronounced squat effects in this section. Additionally it can be noticed that the availability of the overall channel is slightly lower than the availability of section 4. The reasoning behind this is that the availability as a whole is computed based on the joint probability of failure considering the individual contribution of each section. Therefore, in some occasions it is possible that none of the individual sections is closed, but the navigation through the overall channel is not considered safe enough, leading to downtime.

Figure 4.12: Fraction of time that each section of the channel is available (blue bars) and availability of the channel as a whole (red dashed line). Probabilistic simulation considering ship’s draught of 23.60m.
5 Channel depth evaluation including the influence of waves

When the influence of waves is included for the evaluation of channel depth requirements, the availability of the channel is determined according to two criteria, both based on the available net under keel clearance (KC):

\[ KC = [\text{Bottom level} + \text{Tide benefit}] - [\text{Static draught} + \text{Squat}] \]

\[ KC > \text{Minimum Manoeuvering margin} \quad (1^{\text{st}} \text{ criteria: nautical requirement}) \]

\[ \Pr(\text{Bottom contact} | KC) < 0.01 \quad (2^{\text{nd}} \text{ criteria: buffer for motions}) \]

The first criterion is a requisite for navigation, therefore is applicable to every combination of environmental conditions. When the first criterion is not met then the maneuver is not feasible. Once the first criterion is met, the second criterion is verified. In that case the full KC is available as buffer for motions due to waves. Only when both criteria are met the maneuver will be considered feasible.

The probability of bottom contact due to wave-induced motions equals the probability that the vertical downward displacement of the most critical point of on the ship’s keel exceeds the net keel clearance during the transit. Thus, the probability of bottom contact depends on the wave condition and associated ship motions response. When the ship shows increased vertical motions due to wave effects, a larger KC is required to ensure acceptable probabilities of bottom contact.

Following a similar approach as presented in the previous Chapter, the availability of the channel can be accessed via limit state functions. In this case:

\[
\begin{align*}
Z_1 &= KC - \text{Minimum manoeuvering margin} \\
Z_2 &= KC - \text{Negative hull excursion}
\end{align*}
\]

With:
Negative hull excursion = stochastic variable Rayleigh distributed and dependent on the ship response intensity

A section of the channel is available when both \( Z_1 \) and \( Z_2 \) are positive. The first criteria can be checked using either deterministic or probabilistic methods, as described in the previous Chapter. The second criterion is probabilistic, since it involves a stochastic variable, i.e. vertical ship motions due to waves. The combination of approaches applied for the two limit state functions either result in a semi-probabilistic approach (first criteria deterministic and second criteria probabilistic) or in a fully-probabilistic approach, with both criteria treated using probabilistic concepts.

In the next sections of this Chapter a detailed description of the applied method to determine ship response to waves is provided. This is followed by the definition and results of the semi-probabilistic method. In the last section the fully-probabilistic approach is presented.
5.1 Determination of ship response to waves

5.1.1 Vertical ship motions in waves

The dynamics of rigid bodies and fluid motions are governed by the combined actions of different external forces and moments as well as by the inertia of the bodies themselves.

The motions of a ship, just as for any other rigid body, can be split into three mutually perpendicular translations of the center of gravity, \( G \), and three rotations around \( G \) (Journée and Massie, 2001). Figure 5.1 presents the definitions of the basic ship motions and the body-bound coordinate system \( G(x_b; y_b; z_b) \). The origin is the center of gravity of the body. The positive \( x \) direction is towards the bow, the positive \( y \) direction is towards portside, and the positive \( z \) direction is upward. The signs of the rotations are right handed.

![Figure 5.1: Body-bound coordinate system \( G(x_b; y_b; z_b) \) (source: https://wiki.marin.nl).](image)

To define where a body is in the earth fixed (EF) system, both its position and its orientation needs to be known. This is done using a 6 component vector. The first three components determine the position of the center of gravity of the body:

- Component 1 (surge) is positive from stern to bow
- Component 2 (sway) is positive from starboard to portside
- Component 3 (heave) is positive from keel towards deck

To specify the orientation of the body, three rotation angles are used. The order in which the rotations are applied is:

- Component 4 (roll) is a rotation around the surge axis. Starboard down is positive.
- Component 5 (pitch) is a rotation around the sway axis. Bow down is positive.
- Component 6 (yaw) is a rotation around the heave axis. Bow to portside is positive.

A sinusoidal progressive wave with frequency \( f_w \) and amplitude \( \zeta_a \) causes water level fluctuations \( \zeta \). At a fixed location these fluctuations have the following nature:
\[ \zeta(t) = \zeta_a \cos(2\pi f_w t) \]

with:
- \( \zeta(t) \): instantaneous water level elevation at a fixed location (m)
- \( \zeta_a \): wave amplitude (m)
- \( f_w \): wave frequency (Hz)
- \( t \): time (s)

The ship responds with \( R(t) \),
\[ R(t) = R_{a,j} \cos(2\pi f_e t + \varepsilon_{R_{\zeta,j}}) \mid j = 1, \ldots, 6 \]
in which:
- \( R_a \): response amplitude of each of the six components of motion
- \( f_e \): encounter frequency, the frequency at which a ship senses a wave
- \( \varepsilon_{R_{\zeta}} \): phase angle of each of the six components of motion related to the harmonic wave elevation at the average position of the ship’s center of gravity
- \( j = 1 \): surge motion (x)
- \( j = 2 \): sway motion (y)
- \( j = 3 \): heave motion (z)
- \( j = 4 \): roll motion (\( \Phi \))
- \( j = 5 \): pitch motion (\( \theta \))
- \( j = 6 \): yaw motion (\( \Psi \))

If the ship response is supposed to be linear, i.e. independent of wave height, then:
\[ \frac{R_a}{\zeta_a} = \text{constant} = \text{RAO} \]
\[ \varepsilon_{R_{\zeta}} = \text{constant} = \text{RPO} \]

with:
- RAO: response amplitude operator
- RPO: response phase operator

The absolute motions of the ship are related to the steadily translating coordinate system \( O(x; y; z) \). This coordinate system is moving forward with a constant ship speed \( V \) and the \((x; y)\)-plane lies in the still water surface. If the ship is stationary, the directions of the \( O(x; y; z) \) axes are the same as those of the body-bound coordinate system (Journée and Massie, 2001).

Vertical motions at different locations on the ship’s keel (i.e. critical points), determinant for channel depths, are made up heave, roll and pitch contributions. The vertical displacement of a certain point in the ship’s hull \( P(x_b; y_b; z_b) \) can be determined by a linear superposition of three harmonic motions, which results in a harmonic motion as well:
\[ h(\omega_e, t) = z - x_b \theta + y_b \Phi = h_a \cos(\omega_e t + \varepsilon_{h_{\zeta}}) \]

where:
- \( h_a \): motion amplitude
- \( \varepsilon_{h_{\zeta}} \): phase lag of the motion with respect to the wave elevation at G.
The contribution of heave (z) does not depend on the position of point analysed. Though, pitch and roll (θ, Φ) are angles, so the further the point is from the centre of rotation, larger vertical displacements are observed. Therefore, critical points in terms of vertical motions tend to be located at the forward or aft extreme end of the ship, or at one of the shoulders.

The description provided so far applies for single harmonic progressive waves. However, in practical cases this assumption is not realistic. Sea conditions can be described as a summation of an infinite number of regular sinusoidal waves, being described by:

$$\zeta(t) = \sum_{n=1}^{\infty} \zeta_n \cos(2\pi f_w t + \xi_n)$$

The phases between the components, ξn, are supposed to be random.

A sea state can also be represented by the two-dimensional variance density spectrum, showing how the variance of the surface elevation η(x,y,t) is distributed over frequencies and directions:

$$E(f, \theta) = \lim_{\Delta f \to 0} \lim_{\Delta \theta \to 0} \frac{1}{\Delta f \Delta \theta} E\left\{ \frac{\eta^2}{2\xi_n^2} \right\}$$

The dimension and S.I. unit of E(f,θ) are [m²/Hz/radian] or [m²/Hz/degree]. The volume of E(f,θ) is equal to the total variance $\eta^2$ of the sea-surface elevation.

The time dependent ship response in a sea condition becomes:

$$R(t) = \sum_{n=1}^{\infty} R_n \cos(2\pi f_n t + \xi_n + \varepsilon_{R\xi_n})$$

or in the frequency domain:

$$S_{RR}(f_e, \theta) = RAO(f_e, \theta)^2 \cdot E(f, \theta)$$

with:

- $S_{RR}(f_e, \theta)$ = Spectral density of the ship response;
- $RAO(f_e, \theta)$ = frequency- and direction-dependent ship’s Response Amplitude Operator.

The spectral moments, which provide the characteristics of the spectrum, are defined as:

$$m_i = \int_{0}^{\infty} S_{RR}(f_e, \theta) \cdot f_e^i \, df_e$$

The zeroth moment of the ship response spectra represents the total variance of the vertical motions of the vessel, which can be seen as a parameter that indicates the intensity of the motions. Combined with the second moment, they can be used to describe the average zero-crossing period of the motions: $T_{m02} = (m_d/m_2)^{1/2}$.
5.1.2 Response Amplitude Operator and Response Phase Operator

The basic vertical ship responses are governed by a differential equation which is, in general, similar to the well-known mass spring system. They also have a natural frequency at which the RAO is maximum. In the RAO's of the critical points several peaks may occur due to the contributions of the three basic motions, roll, pitch and heave.

Knowing the ship's Response Amplitude Operator curves, the ship motions in various wave conditions can be computed. To determine the RAO's there are two possibilities (Van Doorn, 1985):

- Physical model investigations;
- Computations.

The first method has the advantage of being accurate. The second one, which generally involves the application of a 3D panel code for shallow water based on potential flow, is relatively cheap. Which method is preferred will depend on the size of the project and the required accuracy.

The method to calculate ship motions described above is based on the assumption of linearity of the ship response to waves. This means the assumption of a linear relation between wave height and ship response (i.e., the RAO is constant for all wave heights per wave frequency and direction). Additionally, it is assumed the validity of the so-called superposition principle, which states that the response in irregular waves with given variance density spectrum is equal to the sum of responses to the regular sinusoidal waves that together would have the same variance density spectrum, but in a discretized form.

According to Van Doorn (1985) linearity was found to be sufficient both for deep and shallow water, even under relatively extreme conditions. Differences found between RAO-values in regular waves of the same period and of different height were insignificant. Differences found between RAO-curves from tests in irregular waves and the RAO-values from tests in regular waves were either insignificant or attributable to model effects.

Model tests described by De Jong et al. (2010) confirmed that, for their application, the errors introduced by linearization and by ignoring additional damping due to the proximity of the bottom were very small.

For the present study typical RAO/RPO data associated to large bulk carriers were provided by MARIN. This data is referent to a ship similar to the Valemax vessels, with length between perpendiculars of 360m, draught of 22.5m, and breadth of 65m. Four sets of RAO/RPO data were provided: for water depths of 1.1 and 2 times the ship’s draught and for sailing speed of 0 and 3m/s (0 and 6kn).

RAO and RPO data for heave, pitch and roll associated to a water depth of 1.1 times the ship’s draught and sailing speed 3m/s are presented in Figure 5.2, Figure 5.3 and Figure 5.4.
Figure 5.2: RAO and RPO for heave motions. Ship is aligned to the 0-180° axis, pointing 180°.

Figure 5.3: RAO and RPO for pitch motions. Ship is aligned to the 0-180° axis, pointing 180°.
The figures indicate that heave motions are mainly related to lower frequency waves. As wave lengths become shorter than the ship length the transfer functions tend to zero. In beam waves, it is not the wave length to ship length ratio but the wave length to ship breadth ratio that is of importance. Similar observations can be drawn for pitch and roll movements, however pitch movements are more pronounced on wave directions aligned to the ship axis (0° reaching the stern and 180° reaching the bow), while roll movements are mostly associated to beam waves.

For very low wave frequencies (periods longer than 100s), the response operator for heave motions tend to one, since the ship simply follows the water surface. In such conditions the wave steepness becomes very small, making pitch and roll RAO’s tend to zero.

Phase information associated to heave motions is approximately symmetrical along the x- and y-axis (differences occur in the longitudinal axis because the ship hull is not symmetrical along its x-axis). For pitch movements RPO data is mirrored through the x-axis (0-180°). Even though the influence of the hull asymmetry along its x-axis, it can be noticed that for some frequencies the effects of waves approaching from the bow (180°) and stern (0°) are 180° out of phase. For roll movements RPO data is also mirrored through the x-axis (0-180°), however in this case the effects of waves reaching the ship’s port side (90°) and starboard side (270°) are 180° out of phase.

The phase differences relative to the water surface elevations are determinant when coupling the three vertical motions. Under certain conditions movements may be in phase, enhancing each other, while in other cases movements can be out of phase, reducing the resultant motion. For every location along the ship’s hull, the joint (heave + pitch + roll) RAO can be computed, taking into account the phase relations between movements.
Uncertainties associated to the RAO data are related to the draft of the ship since RAO information depends on draught, weight distribution along the ship, viscous damping of roll motions (uncertainties in the order of 10%), uncertainty in heave and pitch (~5%) (personal communication with Jos van Doorn, Hans Cozijn and Johan Dekker). The available data have also been used for larger and smaller depths. Since primarily the approach is evaluated here this is not critical and indicative results suffice. In shallower waters the vertical motions of the ship are generally damped, so using RAO information associated to smaller draught/depth ratios can be seen as a conservative approach.

5.1.3 Joint RAO’s in the critical points

Generally, the critical points where ship motions are largest are located at the forward or aft extreme end of the ship, or at one of the shoulders. The most critical point depends on the wave condition (angle of wave incidence and wave frequency), ship's speed and ship type. Figure 5.5 shows the locations of the critical points considered in this study, where the RAO’s are expected to be larger, resulting in larger ship motions for the same excitation wave spectrum. In Table 5.1 the position of the critical points in the ships coordinate system are presented.

![Figure 5.5: Location of critical points along the hypothetical ship's hull.](image)

**Table 5.1: x,y-coordinate of the 7 critical points.**

<table>
<thead>
<tr>
<th>Critical point</th>
<th>x, y coordinate (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(+180, 0)</td>
</tr>
<tr>
<td>2</td>
<td>(+128, +32.5)</td>
</tr>
<tr>
<td>3</td>
<td>(-132, +32.5)</td>
</tr>
<tr>
<td>4</td>
<td>(-180, +18)</td>
</tr>
<tr>
<td>5</td>
<td>(-180, -18)</td>
</tr>
<tr>
<td>6</td>
<td>(-132, -32.5)</td>
</tr>
<tr>
<td>7</td>
<td>(+128, -32.5)</td>
</tr>
</tbody>
</table>

The joint RAO's, calculated based on the response amplitudes and relative phases for heave, pitch and roll, are presented in Figure 5.6. The response is expected to be symmetrical across the ship's x-axis. Differences in the figures are related to plotting and interpolation procedure.
Figure 5.6: Joint heave, pitch and roll RAO for the different critical points. Water depth of 1.1 times the ship’s draught and ship speed of 3m/s.
5.1.4 Combining RAO’s and wave conditions

**Primary waves**

The ship’s response is not only influenced by the wave height, but also the wave direction and frequency. Further, these additional wave parameters determine the position of the critical point along the ship’s hull. In Figure 5.6 it is noted that generally the response of the ship is very limited for wave periods shorter than 10s. Point 1 has a response influenced by heave and pitch only (y-coordinate is zero thus roll is also zero). The influence of roll motions in point 4 and 5 is also limited since these points are closer to the rotation axis. The highest joint response operators are found for the points 2, 3, 6 and 7, where roll contribution is maximum.

These RAOs were combined with the simulated 2D wave spectra to determine the 2D motion spectra, considering the orientation of the vessel relative to the incoming wave direction along the sections of the channel. This was done by ‘rotating’ the RAOs to match the heading of the vessel (keeping the reference for the wave conditions earth-fixed).

To have a better visualization of the influence of the different parameters along the channel, one arbitrary wave condition and its effects in terms of ship motions were further analysed. The offshore parameters are $H_s=4.3\text{m}$, $T_p=12.3\text{s}$, and $P_{\text{dir}}=155^\circ$. After propagation along the continental shelf, in the entrance of the channel $H_s= 2.67\text{m}$, $T_p=12.1\text{s}$ and $P_{\text{dir}}=138^\circ$. Relating this illustrative condition to the overall wave climate, at the same nearshore location, waves bigger than 2.5m occur 0.88% of the time (on average 3.2 days per year). Periods longer than 12s are more common, occurring 11% of the time. However, waves bigger than 2.5m and with periods longer than 12s are quite unusual. Their frequency of occurrence is 0.24% (on average 21 hours per year).

Figure 5.7 illustrates the calculation of the ship motion spectra from the two-dimensional wave spectra and joint RAO. The multiplication of the wave spectrum and the joint RAO squared gives the ship motion spectrum. In the example presented in Figure 5.7 the wave energy is not in frequencies/directions where the ship response is high, consequently the resultant response is limited. The motion spectrum includes two peaks, one matching the location where the wave energy is higher and the second near the location where the response operator is maximum. Even though the wave energy is very limited in this region of the spectrum, the squared response amplifies it to relatively significant motion levels.

The same procedure presented in Figure 5.7 is considered for the other critical points along the ship’s hull and other sections of the channel. Table 5.2 presents the wave and motion parameters associated to the most critical point for the different sections for the considered example.
Optimization of the operational use of entrance channels based on channel depth requirements

Figure 5.7: Example of ship motions computation. Left: two-dimensional variance density spectrum of short waves [m²/Hz/degree]; Center: joint response amplitude operator (water depth of 1.1 times ship’s draught, sailing speed of 3m/s). Right: ship motions spectrum in m²/Hz/degree; [motion height = 4 \( (m_{0,motion})^{0.5} \)].

Table 5.2: Short wave condition and associated ship response along the access channel in the considered example.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hs (m)</td>
<td>2.10</td>
<td>2.65</td>
<td>2.65</td>
<td>2.67</td>
</tr>
<tr>
<td>Tp (s)</td>
<td>12.1</td>
<td>12.1</td>
<td>12.1</td>
<td>12.1</td>
</tr>
<tr>
<td>Wave dir (deg.)</td>
<td>157.5</td>
<td>147.5</td>
<td>142.5</td>
<td>137.5</td>
</tr>
<tr>
<td>( m_{0,motion} )</td>
<td>4.01E-02</td>
<td>1.75E-02</td>
<td>2.41E-02</td>
<td>2.31E-02</td>
</tr>
<tr>
<td>( m_{2,motion} )</td>
<td>1.94E-04</td>
<td>8.73E-05</td>
<td>1.34E-04</td>
<td>1.20E-04</td>
</tr>
<tr>
<td>( 4(m_{0,motion})^{0.5} ) (m)</td>
<td>0.80</td>
<td>0.53</td>
<td>0.62</td>
<td>0.61</td>
</tr>
<tr>
<td>( T m_{0,2, motion} ) (s)</td>
<td>14.4</td>
<td>14.2</td>
<td>13.4</td>
<td>13.8</td>
</tr>
</tbody>
</table>

The significant wave height in Section 1 is smaller due to shadowing effects of the breakwaters of the port and the effects of shallow water processes such as refraction and bottom friction. However, in this section the maximum ship motion response is observed, which is related with the different channel and ship alignment in this section. In section 1 the heading of the ship is 200° (in other sections 164°), which makes the ship more exposed to beam waves (where the response amplitude is higher), resulting in a more pronounced motion response.

In sections 2, 3 and 4 the heading of this channel and ship is 164°. The significant wave height is similar in the three points, but the response in section 2 is slightly smaller. This can be related to the direction of the waves in this section, which are closer to the ship’s longitudinal axis (response amplitude is generally lower in these directions). However, the
same reasoning does not apply for sections 3 and 4, which have different wave direction but similar response. This is probably due to a different distribution of energy in the 2D wave spectrum (e.g. directional spreading) and specific characteristics of the response amplitude operator, resulting in a distinct ship motions spectrum.

Low frequency waves

A similar analysis is done for the 1D spectrum of forced infragravity motions calculated with the second-order nonlinear theory of Hasselmann (1962) based on the short wave spectrum and the local water depth. The computation of the ship vertical motion spectrum from the 1D forced long wave spectrum and response amplitude operator is presented in Figure 5.8.

For the computed infragravity wave spectrum it is considered a cutting frequency of 0.033Hz, which means that (long) wave components with periods shorter than 30s are excluded from the spectra. The RAO information was interpolated from the directional dependent information, assuming that the direction of the bound infragravity waves corresponds to the peak wave direction of the short wave spectrum. Additionally, bound long waves have different celerity and wave length as compared to free waves with same frequency. Still, the same RAO information is applied for these waves.

![Figure 5.8: Ship motions computation for forced infragravity waves for wave condition Hs=2.1m, Tp=12.1s, PDir=157.5° and local water depth of 12m (section 1). Top left: forced infragravity wave spectrum. Top right: joint response amplitude operator. Bottom: ship motion spectrum [motion height = 4 (m0,motion)^0.5].](image)

Table 5.3 presents the forced infragravity wave and ship’s motion parameters associated to the most critical point for the different sections.
Table 5.3: Forced long wave condition and associated ship response along the access channel.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H_{m0,\text{long}} (m))</td>
<td>0.17</td>
<td>0.16</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>(T_{m0m2} (s))</td>
<td>61.0</td>
<td>59.9</td>
<td>55.7</td>
<td>53.0</td>
</tr>
<tr>
<td>Wave dir (deg.)</td>
<td>157.5</td>
<td>147.5</td>
<td>142.5</td>
<td>137.5</td>
</tr>
<tr>
<td>(m_{0,\text{motion}})</td>
<td>3.15E-03</td>
<td>3.24E-03</td>
<td>1.66E-03</td>
<td>5.55E-04</td>
</tr>
<tr>
<td>(m_{2,\text{motion}})</td>
<td>1.09E-06</td>
<td>1.21E-06</td>
<td>7.15E-07</td>
<td>2.59E-07</td>
</tr>
<tr>
<td>(4(m_{0,\text{motion}})^{0.5}(m))</td>
<td>0.22</td>
<td>0.23</td>
<td>0.16</td>
<td>0.09</td>
</tr>
<tr>
<td>(T_{m0.2,\text{motion}} (s))</td>
<td>53.7</td>
<td>51.8</td>
<td>48.2</td>
<td>46.3</td>
</tr>
</tbody>
</table>

The decrease of forced infragravity wave energy from section 1 to section 4 is associated to the increase in water depth. The direction presented in the table corresponds to the peak wave direction of the short waves. Since the response operators are larger than one in this case, the ship’s motion is amplified in relation to the wave motion.

Table 5.4 provides an overview of the individual components of ship motions and the combined response assuming linear superposition of the wave energy (\(m_{0,\text{motion short}} + m_{0,\text{motion long}}\)). Since the amplitude of the motions is related to the square root of the energy, the contribution of a secondary source of motions is limited.

Table 5.4: Ship response along the access channel (m) during a wave condition with \(H_s=2.67m\), \(T_p=12.1s\) and \(P_{dir}=137.5^\circ\) in the outer end of the channel [motion height = \(4(m_{0,\text{motion}})^{0.5}\)].

<table>
<thead>
<tr>
<th>Ship motion</th>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion(_{short})</td>
<td>0.80</td>
<td>0.53</td>
<td>0.62</td>
<td>0.61</td>
</tr>
<tr>
<td>Motion(_{long})</td>
<td>0.22</td>
<td>0.23</td>
<td>0.16</td>
<td>0.09</td>
</tr>
<tr>
<td>Motion(_{total})</td>
<td>0.83</td>
<td>0.58</td>
<td>0.64</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Even though the forced infragravity waves shown a limited contribution in this case, the combined ship response is considered in the subsequent sections of this study. Nevertheless, in coastal regions it is highly recommended to consider the use of a more sophisticated tool to compute infragravity wave motions, which considers not only the forced long wave but also the reflected free long waves.

5.1.5 Probability of vertical wave-induced ship motions

Once the motions spectrum is built from the combination of the RAO information and the wave spectrum, statistics of motions can be derived. These analyses were performed in the time domain and spectral domain.

The analysis in time domain gives a good insight and visualization of the process however is more costly in terms of computations, especially when considering a large number of spectral components for a large number of sea states. Additionally, performing both analyses with the different methods is a good approach to check the applicability of the methods and consistency of the code.

In the time domain analysis a large number of harmonic motion components with random phases are superposed in order to build a time series of the vertical position of the critical
point. The components are obtained from the 2D joint spectrum of motions. Figure 5.9 shows an example of time series of ship motions for the same wave condition discussed in the previous section (Hs=2.67 m; Tp=12.1 s; PDir=137.5°).

![Wave induced ship motions - Critical point 6](image)

**Figure 5.9**: Synthetic time series of ship motions including the joint effects of heave, pitch and roll. Red dots indicate the maximum negative excursion per individual (independent) ship motion. Critical point 6, wave condition Hs=2.67 m, Tp=12.1 s, Pdir=137.5°.

The histogram of vertical displacement associated to a very long time series of ship motions matches a Gaussian distribution. The probabilities represent the chance of finding the vertical displacement at a given instant (Figure 5.10).
Optimization of the operational use of entrance channels based on channel depth requirements

Figure 5.10: Probability density function of the vertical position of Critical point 6 from a long synthetic time series of ship motions. Wave condition $H_s = 2.67\, \text{m}$, $T_p = 12.1\, \text{s}$, $P_{\text{dir}} = 137.5^\circ$.

The information from the Gaussian distribution cannot be used directly in the method to determine probabilities of bottom touch because within a certain extent of time the vertical position of the critical point is not an independent variable (there is dependency between the vertical positions occurred just before/after a given instant). However, in this case it becomes complicated to include the influence of the time the ship is exposed to a give wave condition in the computations of probability of bottom contact. For instance, if the ship spends more time in a section, it is expected an increase of the probability of bottom contact in that section.

The effect of exposure time can be easily included when the motion signal is divided into individual (independent) motions, where each individual motion have a maximum negative vertical excursion (red dots in Figure 5.9). In order to have a very good statistical representation of the process, a rather long time series of ship motions was build, giving 85,990 individual ship motions with an average period of 13.9s. As expected for wave heights in a record where conditions are not depth limited and being this process a linear Gaussian process, the probability distribution of the maximum negative vertical excursion of the critical point follows a Rayleigh distribution (Moes, 2008). Hence, the distribution of maximum local maxima is only known if the process is a narrow-band process. Provided that the spectral width parameter approaches zero, the peaks of maximum individual excursion of critical points ($z_c$) follow a Rayleigh-distribution:

$$PDF_{\text{Rayleigh}}(z_c) = \frac{1}{m_0} e^{-z_c^2/2m_0} \quad \text{(Probability density function)}$$

$$CDF_{\text{Rayleigh}}(z_c) = Pr(z_c \leq X) = 1 - e^{-z_c^2/2m_0} \quad \text{(Cumulative distribution function)}$$

As it is noticed in the equations, the probability distribution can be described with the variance of the time series of vertical displacement of the critical point ($m_0$). The variance can also be
obtained from the integration of the motion spectra along the frequencies and directions. For this specific wave condition, the $m_0$ obtained from the time series analysis and spectral analysis were 0.02312 m$^2$ and 0.02306 m$^2$, respectively, being thus both methods in agreement. Additionally, there is agreement between the mean period of individual wave in the time-series built record ($T_{\text{mean}}=13.9s$) and the mean period computed from the motion spectrum ($T_{m0.2}=13.8s$).

Figure 5.11 presents the histogram of maximum negative vertical excursions obtained from the time series data and from Rayleigh distribution (using $m_0$ of ship motion spectrum). The cumulative distribution from the time series analysis and following Rayleigh distribution is presented in Figure 5.12.

![Figure 5.11: Probability density function of the maximum negative excursions of Critical point 6 during individual (independent) ship motions. Histogram derived from a long synthetic time series of ship motions. Wave condition $H_s=2.67m$, $T_p=12.1s$, $P_{\text{dir}}=137.5^\circ$.](image-url)
Therefore, having the zeroth moment ($m_0$) of the motion spectrum, the probability of bottom contact per individual motion can be determined using Rayleigh distribution. The effect of exposure time is included by dividing the time required to cross a section with homogeneous and stationary wave conditions ($T_{pass}$) by the mean period of the motions (square root of $m_0/m_2$), which gives the expected number of individual motions. It follows that:

$$
Pr\{A > 0\} = 1 - \left[1 - \exp\left(-\frac{KC^2}{2m_0}\right)\right]^{T_{pass}/\sqrt{m_0/m_2}}
$$

with:
- $A =$ number of bottom touches during passage through the channel section;
- $T_{pass} =$ duration of channel transit (stationary conditions);
- $KC =$ net-keel clearance (waterdepth minus ship’s draught and minus the local squat);
- $m_0, m_2 =$ zeroth and second moment of the spectra of ship motions;
- $\exp\left(-\frac{KC^2}{2m_0}\right) =$ probability of bottom contact per individual (independent) motion;
- $T_{pass}/\sqrt{m_0/m_2} =$ expected number of individual motions during passage through section.

As the vertical displacement of a critical point of the ship is assumed to be a stationary Gaussian and ergodic process, the probability of touching the channel bottom can also be computed according to the theory of extremes (Strating et al. 1982; Van Doorn, 1985):
Pr\{A > 0\} = 1 - \exp\left(-T_{pass} \frac{m_2}{m_0} \exp\left(-\frac{KC^2}{2m_0}\right)\right)

= 1 - \exp(-\lambda T_{pass})

\lambda = \frac{\sqrt{m_2}}{m_0} \exp\left(-\frac{KC^2}{2m_0}\right) = \text{average frequency of one bottom touch.}

Considering the \(m_0\) associated to the wave condition described in the previous section (0.0231m^2) and assuming a KC of 1 meter, the probability of bottom contact per individual ship motion is 3.98 \cdot 10^{-10}. For instance, if the ship takes 30 minutes to cross the section and the mean period of the ship motions is 13.8s, the expected probability of bottom contact in that section is rather low: 5.19 \cdot 10^{-8} (results are exactly the same for both methods). This theory applies in case each occurrence of bottom contact can be seen as an independent event. This prerequisite is met in case \(KC/(m_0) >> 1\), which means that the number of bottom touches needs to be small. Additionally, this approach is not applicable to channel transits under changing wave conditions relative to the ship. To take these variations into account the channel is divided into sections. If the conditions can be assumed stationary along each section, the number of bottom contacts can be computed.

The probabilities presented in the previous paragraph are associated to one critical point in the ship’s hull and one section of the channel. However, the probability of bottom contact per passage must be compared to the pre-defined safety criteria. Therefore the information from other critical points and sections must be treated.

In the standard practice described in literature, the probability of bottom contact in one channel section is derived from the most critical point (higher \(m_0\) and associated \(m_2\) of motions spectrum). Especially in the outer sections of the channel, where squat effects in the bow are more pronounced, higher probabilities of bottom contact tend to be associated to the critical points located in the bow of the ship; being the influence of the other critical points generally limited in this case.

Though, a different approach is adopted here: the probability of bottom contact per section is the joint probability of bottom contact including the contribution of all critical points. The reasoning behind this approach is that, when the ship is moving in waves, for instance, the chance of the bow touch the bottom is smaller than the chance of any point in the ship’s hull heat the bottom. If this assumption is right, all relevant independent critical points should be considered in the analysis, thus:

\[P_{joint}\{A > 0\} = 1 - \prod_{CP=1}^{7} \left[ 1 - Pr(A_{CP} > 0) \right]\]

The total probability bottom contact per passage is obtained by addition of the contributions for all sections, giving the upper limit of this joint probability:

\[P_f = \sum_{section=1}^{k} P_{joint,section}\{A > 0\}\]
5.2 Semi-probabilistic approach including the influence of waves

The combined deterministic/probabilistic approach includes both the verification of nautical requirements using the deterministic procedure and the effect of ship motions due to waves, assuming the excursion of the critical points a stochastic Rayleigh distributed process. The determination of the (non-) availability of a section of the channel at a given time is given by two criteria: nautical and buffer for motions. The criteria can expressed in terms of limit state functions:

\[ KC = [\text{Bottom level} - 0.5 - 0.3] + \text{Tide benefit} - [\text{Static draught} \times 1.015] - [\text{Squat} \times 1.25] \]

\[ Z_1 = KC - \text{Minimum Maneuuvring margin} \quad (1^{\text{st}} \text{ criteria: nautical requirement}) \]

\[ Z_2 = KC - \text{Negative hull excursion} \quad (2^{\text{nd}} \text{ criteria: buffer for motions}) \]

Failure occurs when \( Z_1 < 0 \) or \( Z_2 < 0 \).

The nautical requirement is fulfilled when \( Z_1 \) is positive. The second criterion is satisfied if the probability that \( Z_2 \) assumes negative values is sufficiently low (less than 0.01). In this case the net keel clearance is enough to ensure the required safety level along the section. If \( Z_2 \) is negative the vertical excursion of the hull exceeds the net keel clearance, resulting in bottom contact (failure). The probability of failure in one section is a function of the net under keel clearance (KC) and the motion spectrum (\( m_0 \) and \( m_2 \)):

\[ \Pr(Z_2 < 0) = \Pr(A > 0) = 1 - \left[ 1 - \exp\left(\frac{-KC_2}{2m_0}\right) \right]^{\frac{m_0^2}{m_2}} \]

This calculation can also be done the other way around, using as input the spectrum parameters and the maximum allowable probability of bottom contact (0.01) to obtain the minimum required buffer for motions to ensure the predefined safety level. When the required buffer for motions is smaller than 1 meter (minimum manoeuvring margin) the first criterion prevails and the results of the combined deterministic/probabilistic method are exactly the same as the deterministic method based on nautical requirements only (section 4.3). If the required buffer of motions exceeds the maneuverability margin, the second criterion becomes critical to determine the availability of the channel section.

For the availability of the channel, however, the probability of bottom contact along the entire channel must be considered by combining the safety level of the individual sections. As a result, it is possible that at a given time all sections are available (individual probabilities of bottom contact < 1%), but the combined probability of bottom contact is larger than 1%, leading to unavailability of the channel as a whole.

Figure 5.13 presents the histogram of KC in section 4 associated to the deterministic simulation considering the ship’s draught of 22.50m. In section 4 the nautical requirements are stricter due to the higher sailing speeds and squat effects in this section, in the other sections KC values are expected to be slightly larger.

According to the first criterion, independently of the acting wave condition, the channel is closed when the under keel clearance is less than 1m. From Figure 5.13 it follows that this nautical requirement is always met in this simulation, leading to no downtime of the section.
due to this criteria. This agrees with the results of the deterministic simulation based on nautical requirements only (section 4.3).

When ship motions associated with waves are included in the computation the analysis becomes more restrictive, since during certain wave conditions the required KC may be larger than 1m leading to a predominance of the second criterion. In this case the criterion for ship motions may overrule the maneuverability requirement. The unavailability of a channel section exclusively related to waves occurs when the KC is smaller than the required buffer for motions and larger than 1m (if KC<1m the channel will be closed to attend nautical requirements).

Figure 5.13: Histogram of net under keel clearance associated to the section 4 during the simulated period.

However, the results obtained in this study indicate that in most of the time the required buffer for motions is smaller than 1m. Figure 5.14 to Figure 5.17 present the required buffer for motions in the four sections of the channel for the simulated period between 01/04/2008 and 01/09/2008. The buffer for motions can be seen as the minimum under keel clearance required to ensure a probability of bottom contact smaller than 1%.

Despite the lower wave action, the required buffer for motions in section 1 is generally larger. This is in agreement with the results for the one specific wave condition presented in the previous sections and related to the heading of the ship in this section (200°), which leads to more beam wave energy incidence in comparison to the other sections with 164° orientation. In the other sections the response signals over time are similar, with a tendency of increase of the required buffer for motions from section 2 to section 4, as the section becomes more exposed to waves. Therefore, it is evident that not only wave heights are relevant, but also wave period and the direction relative to the ship’s heading.

Only in some occasions the buffer for motions exceeds the minimum maneuverability margin, becoming determinant for the definition of the availability of the channel. However, at those
occasions there is a great chance that the available KC is sufficiently large to ensure the required safety level (Figure 5.13) and, thus, the channel remains available. Consequently, the simulations considering the combined deterministic/probabilistic method with a ship draught of 22.50m gave the same results of the deterministic simulation based on nautical requirements only: the channel operative during 100% of the time. In other words, when a ship draught of 22.50m is considered, waves had no influence on the results for the simulated period (Figure 5.18). During this simulation, the average chance of bottom contact associated to ship motions is considerably low: $1.5 \times 10^{-8}$ per passage.

As in the previous sections, in order to further analyse the results of the method, a simulation was done increasing the ship’s draught to 23.60m. This reduces the available KC by 1.1m plus some additional squat effect due to the larger ratio between draught and water depth. The same ship motion characteristics were assumed for the ship with 23.6m draught as for the ship of 22.5m draft, which is not completely correct but is valid for comparison purposes within the context of the present study. The results of the deterministic/probabilistic simulation considering a ship draught of 23.60m are presented in Figure 5.19.

Considering the deterministic method, during approximately 53% of the time the nautical requirements are not attended (KC<1m), leading to downtime of the channel. Including waves in the analysis the downtime does not increase substantially, instead only during a short period of time the channel was not available exclusively due to wave effects (Figure 5.20). In this simulation the average probability of bottom contact due to wave motions is $4.3 \times 10^{-6}$ per passage, which is far below the required value.
Figure 5.14: Time series of the required buffer for motions to ensure acceptable chances of bottom contact in section 1.
Figure 5.15: Time series of the required buffer for motions to ensure acceptable chances of bottom contact in section 2.
Figure 5.16: Time series of the required buffer for motions to ensure acceptable chances of bottom contact in section 3.
Figure 5.17: Time series of the required buffer for motions to ensure acceptable chances of bottom contact in section 4.
Figure 5.18: Time series of water level with indication of the periods the channel is (non-) available. Semi-probabilistic simulation including the influence of waves and considering ship’s draught of 22.50m.
Figure 5.19: Time series of water level with indication of the periods the channel is (non-) available. Semi-probabilistic simulation including the influence of waves and considering ship’s draught of 23.60m.
Optimization of the operational use of entrance channels based on channel depth requirements

5.3 Fully-probabilistic approach including the influence of waves

The last method evaluated in this study is fully-probabilistic. This means that both the first and second criteria (nautical and wave motions) are checked in terms of probabilities of failure. As in the previous sections, the availability criteria are defined as limit state functions.

\[ KC = [Bottom\ level + Tide\ benefit] - [Draught + Squat] \]

\[ Z_1 = KC - Minimum\ Manoeuvring\ margin \quad (1^{st}\ criteria: \ nautical\ requirement) \]

\[ Z_2 = KC - Negative\ hull\ excursion \quad (2^{nd}\ criteria: \ buffer\ for\ motions) \]

Failure occurs when \( Z_1 < 0 \) or \( Z_2 < 0 \).

In the current method, the net keel clearance (KC) is calculated in a probabilistic way; therefore KC is not a deterministic but a stochastic variable. The distributions of the stochastic variables considered in the computation of KC are the same as applied in section 4.4 (see Table 4.5). As in the previous section, the vertical excursion of the hull of the ship is treated as a Rayleigh distributed stochastic variable.

The chance of KC to be less than 1m is checked by applying the first criteria. The probability of failure associated to the second criterion depends on the ship motions but also on the stochastic KC. Therefore, the joint probability of KC and bottom contact due to waves (given the KC value) is computed to derive the expected probability of bottom contact. This procedure is expected to result in smaller and more realistic probabilities of bottom contact.
due to ship motions in comparison to the method applied by the semi-probabilistic method, where the deterministic (rather low) KC is applied to the computation.

Probability of not attending the first criterion: \( \Pr(Z_1 < 0) \)

Probability of not attending the second criterion: \( \Pr(Z_2 < 0) = \int_0^\infty \Pr(KC) \cdot \Pr(A > 0 \mid KC) \, dK \)

Where, as described in previous sections:

\[
\Pr(A > 0 \mid KC) = 1 - \left[ 1 - \exp \left( -\frac{KC^2}{2m_0} \right) \right]^{\text{pass}} \cdot \exp \left( -\frac{m_0}{2} \right)
\]

The channel is available only if the first criterion and the second criterion are attended during the whole departure maneuver, considering the travelling times between the sections. The overall probability of failure can be determined by the probability of having negative \( Z_1 \) plus the probability of having negative \( Z_2 \). If the combined probability of failure is smaller than the threshold value (0.01) the required safety level is satisfied and thus the channel is available.

\[
P_f = \Pr(Z_1 < 0 \text{ or } Z_2 < 0) \approx \sum_{\text{section}=1}^{4} \Pr(Z_1 < 0) + \sum_{\text{section}=1}^{4} \Pr(Z_2 < 0)
\]

This procedure is done using the Monte Carlo method, where for each tidal time 100,000 simulations are realized to compute the probabilities of failure. In the current application, the expected value for the probability of failure due to the second criteria (ship motions) was derived directly from the 100,000 Monte Carlo simulations of KC. In this way the stochastic behavior of KC is properly included in the calculations.

The fully probabilistic method is assumed to be more complete. Its main advantage is to provide the safety level of the system, while the deterministic method aims that all the variables are in the ‘safe side’ by adding safety margin. However, in the last case there is no control over whether the resultant safety level is safe enough (or excessively safe, leading to unnecessary expenses). Additionally, the fully-probabilistic method includes the influence of wave motions in the simulation by computing the chance of bottom contact due to the vertical motions of the ship. Even though the results indicate that ship motions are small in the current application of the method, during certain conditions this aspect can become critical to the safety of the channel, and consequently it cannot be neglected.

Figure 5.21 presents the results obtained by applying the fully-probabilistic method to the simulated period, considering a ship draught of 22.50m. In agreement with the other methods applied, the channel can be operated during 100% of the time under these conditions. The average chance of bottom contact per passage during the simulation was considerably lower than the required level.

As for the other methods of depth requirement evaluation applied in this study and described in the previous sections, the depth requirements of the channel were evaluated considering a ship’s draught of 23.60m (Figure 5.22). The results obtained from this fully-probabilistic simulation were similar to the results obtained by the probabilistic method excluding the influence of waves (section 4.4), meaning that the wave effects were not so relevant under the simulated conditions. In this simulation the channel remained available during 96.8% of the time. The average probability of bottom contact per passage during the simulation was considerably lower than the required level.
Figure 5.21: Time series of water level with indication of the periods the channel is (non-) available. Fully-probabilistic simulation including the influence of waves and considering ship’s draught of 22.50m
Figure 5.22: Time series of water level with indication of the periods the channel is (non-) available. Fully-probabilistic simulation including the influence of waves and considering ship’s draught of 23.60 m
6 Final considerations

In the present study several assumptions have been made, setting limitations to the quantitative results obtained here. The list below summarises a number of assumptions and limitations included in this study:

- Assumptions regarding ship dimensions, shape (critical points) and manoeuver procedure;
- Ship’s heel, effects of changes in water density and channel bed forms were neglected;
- Squat effects were assumed to occur only in the bow of the ship (50% sinkage effects and 50% dynamic trim effects), which may not be fully correct;
- Limited number of RAO data applied (2 ship speeds times 2 water depths);
- Arbitrary definition of safety factors applied in deterministic calculations and probability distributions considered in probabilistic calculations;
- Effects of the uncertainties in the wave data and RAO data were not incorporated by the methods;
- No extensive investigation on the number and length of channel sections required to properly discretise the channel;
- Effects of currents transversal to the channel were neglected. These currents may lead to additional downtimes and changes in ship alignment relative to waves along the channel;
- In probabilistic methods, the maximum speed of the ship in each section was considered deterministic, while in most of the cases the maximum value is not reached. Together with the conservative characteristics of PIANC formulas, this leads to conservative estimates of squat effects;
- Simplified analysis of infragravity waves since the method applied does not account for free long waves.
- If the length and period of infragravity waves is sufficiently long, their effects can become relevant for the maneuverability. Consequently, they cannot be averaged in the calculation of KC, becoming part of the verification of the nautical requirement.

These assumptions and limitations, however, do not dramatically impact the comparison between the different approaches tested, nor do they impede the interpretation of the preliminary results obtained.
7 Conclusions and recommendations

As part of the master program in Hydraulic Engineering of Delft University of Technology, the main purpose of this study is associated to educational ends. This context, together with the important assumptions and limitations incorporated to the study, should be considered when analysing the quantitative results presented in this report. The main objectives of this study, as proposed in the introductory Chapter, are:

1. Verify the influence of different processes and sources of uncertainties in the evaluation minimum depth requirements;
2. Investigate the advantages and drawbacks of different methods of depth requirement evaluation.

The downtime of the access channel of the Port of Tubarão (southeast Brazil) due to vertical restrictions was evaluated by comparing the available net keel clearance (KC) with the minimum vertical nautical requirement (maneuverability margin) and required buffer for vertical ship motions in waves. Four different approaches were considered, based on deterministic and probabilistic methods and with or without the influence of waves in the computations.

The results of this study indicate that for this specific case study and for that particular channel and vessel combination, the downtime of the channel due to vertical restrictions is mainly associated to the time dependent water levels and its effects on the minimum nautical requirements. Wave-induced ship motions were of secondary importance. This limited contribution of waves is related to the characteristics of the ship and its response in waves (described by the RAOs) in comparison to the typical wave conditions for the area relative to the maneuvering ship (alignment and sailing speed). Nonetheless, under specific conditions and at other locations waves can significantly affect the required channel depth; therefore vertical ship motions due to waves should be incorporated in a real case application.

The alignment of the channel sections included in the case study proved to be a relevant aspect for the computation of ship motions. For instance, the ship motions were more prominent in section 1, which is relatively sheltered for short wave energy but has a different orientation, enhancing the influence of incident beam waves. Therefore, a system to be used in the design or operation of access channels should apply not only wave information in terms of wave heights, but also in terms of wave period and wave direction relative to the sailing ship. This data can be derived from local measurements or numerical models.

Most of the differences between the methods applied for the evaluation of channel depth requirements are related to the use of probabilistic and deterministic approaches to the check of the nautical requirement (i.e. minimal manoeuvring margin). The use of probabilistic methods incorporates more knowledge to the analysis (but also requires more knowledge to be applied), allowing, to a certain extent, compensation between favourable and unfavourable effects of uncertainties. This reduced considerably the amount of downtime during the period simulated and led to a more optimized use of the access channel in terms of accessibility in comparison to the results of the deterministic approach.

Such compensation does not apply for the deterministic method as it is considered in the present study, since safety margins were added to the deterministic calculations resulting in conservative values for all the variables involved. The margins compensate uncertainties in
the determination of the variables, minimizing the probability of failure. The joint probability of occurrence of all these pessimistic values at the same time may be considerably low if too conservative margins are adopted. However, if no safety factor is applied the probability of failure can be rather high at specific situations.

Differences between deterministic and probabilistic methods depend largely on the definition of the safety factors assumed in deterministic computations, relative to the probability distributions considered in the probabilistic computations. In this study, the safety margins were defined adopting a conservative estimate for each uncertain variable, irrespective of the results of the probabilistic method. Nevertheless, partial safety factors can be computed or calibrated for specific cases based on probabilistic calculations. In that case, the resulting safety margins can make the results of deterministic and probabilistic to be similar, ensuring the required reliability by using the practical deterministic approach, but not being excessively restrictive.

Ultimately, the choice of method to be used will depend on the judgement of the engineer. In any case it is likely that an exact and most optimal approach will not be reached due to uncertainties in the input parameters. Considering that, the evaluation should always consider means to compensate the uncertainties, being on the safe side. This is also applicable for probabilistic methods, for which safety factors may be applied to compensate uncertainties in the definition of distributions.

Although the quantitative results obtained in this study should be considered with care due to the number of limitations and assumptions, there is an indication that the use of the channel of the Port of Tubarão could be optimized by including additional knowledge to the analysis. This would mean a lower channel downtime, reduced dredging costs and/or the possibility of allowing deeper-draft vessels to use the channel (increased cargo loads).

Finally, the main advantages and drawbacks of the deterministic and probabilistic approaches are summarised below:

**Deterministic approach**

- **Advantages:**
  - Simpler to use and understand;
  - Less information required.

- **Drawbacks:**
  - No detailed evaluation of probability of bottom contact possible;
  - Conservative assumptions required;
  - Relies on pre-defined safety factors, which are case dependent and not always available;

**Probabilistic approach**

- **Advantages:**
  - Incorporates more knowledge in the analysis;
  - Reliability of the results can be evaluated via statistical distributions;

- **Drawbacks:**
  - Probability distributions of the variable are not always available thus assumptions have to be made (which may introduce uncertainties to the method).
8 References


