Probabilistic Admittance Policy Deep Draught Vessels

ir. R.Ph.A.C. Savenije
Ministry of Transport, Public Works and Water Management,
Transport Research Center (AVV).

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Abstract

The admittance policy of deep draught vessels at the harbours of Rotterdam and along the Westerschelde use a probabilistic calculation method to take advantage of the tide. Astronomical and meteorological effects, waves and different vessel types are taken into account Using this new technique, instead of the previously implemented deterministic method, the accessibility of the harbours and the safety during the channel transit has been increased, without additional dredging costs.

Keywords

Harbour, Probabilistic Admittance Policy, Waves, Vessel Movements.

Sommaire

La prudance probabilistique des vaisseau de beaucoup tirant d'eau aux les ports de Rotterdam et le long des Westerschelde fait usage d'un calcul probabilistique pour tirer profit de la marée Effet astronomique et meteorologique, des ondes et des types de vaisseaux différentes sont tenu de compte. Avec cette technique, au lieu de méthode deterministique, la accessibilité des ports et la sécurite durant le passsage du canal est élevé, sans coûter extra pour draguer.

Mots-Clefs

Port, Prudance Probabilistique de Admettre, Ondes, Movement du Vaisseau

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Summary

The probabilistic calculation method uses information about the astronomical and meteorological water effects, current, wave climate and vessel types. The previously mentioned information as well as the inaccuracies of this data is schematized using probability distributions.

The probabilistic calculation method uses information about the astronomical and meteorological water effects, current, low frequency wave energy and vessel types. The previously mentioned information as well as the inaccuracies of this data is schematized using prbability distributions.

At the Euro-Maas channel at Rotterdam a successful implementation of the probabilistic calculation method has proven to be very accurate and reliable for already ten years. Recently the same method has been introduced for the harbours situated along the Westerschelde. Both implementations increased the accessibility and the safety without additional dredging costs.

1 Introduction

The last few years, the nautical accessibility of the West-European harbours is again in the spotlights. During the sixties and seventies a clear separation developed between harbours who could and harbours who could not adapt to the progressive scale enlarging of the bulk carriers. For example, till the late fifties the maximum draught in Rotterdam, Antwerp as well as Hamburg was all the same: around 40 feet.

During the next decades the maximum draught with which the port of Rotterdam could be accessed, kept pace with the huge scaling up of the crude oil-tankers and bulk-carriers. At the moment, each year 350 channel-bound vessels (draught more than 17.40m) arrive at Rotterdam, with a maximum draught up to $22.55m$ (74 feet). Vessels heading for the Westerschelde are limited to a draught of $15.00m$. Each year more than 400 vessels with a draught more than $11.00m$ bound for Flushing, Gent & Terneuzen or Antwerp.

The design of the admittance policy of the Euro-Maas channel at Rotterdam and the Westerschelde is based on a probabilistic method. With this probabilistic method, a substantial improvement of the accessibility and safety of both channels has been achieved with only a minor change of infrastructure. A further scaling up of the bulk carriers and crude oil tankers is not expected. Nevertheless, from the market an urge exists for minimizing the accessibility restrictions.

The probabilistic admittance policy of Euro-Maas channel has proofed to enlarge the accessibility of the port of Rotterdam for already 10 years. For the Westerschelde this method is recently introduced. It is also intended to recalculate the IJ-channel at Amsterdam in the near future using this method.

Contents

This paper gives an explanation of the implemented techniques, with which the accessibility and safety of the port of Rotterdam and the Westerschelde has been improved. In the first section a brief introduction is given explaining some terms and expressions. After a short view on the previously used deterministic method, the

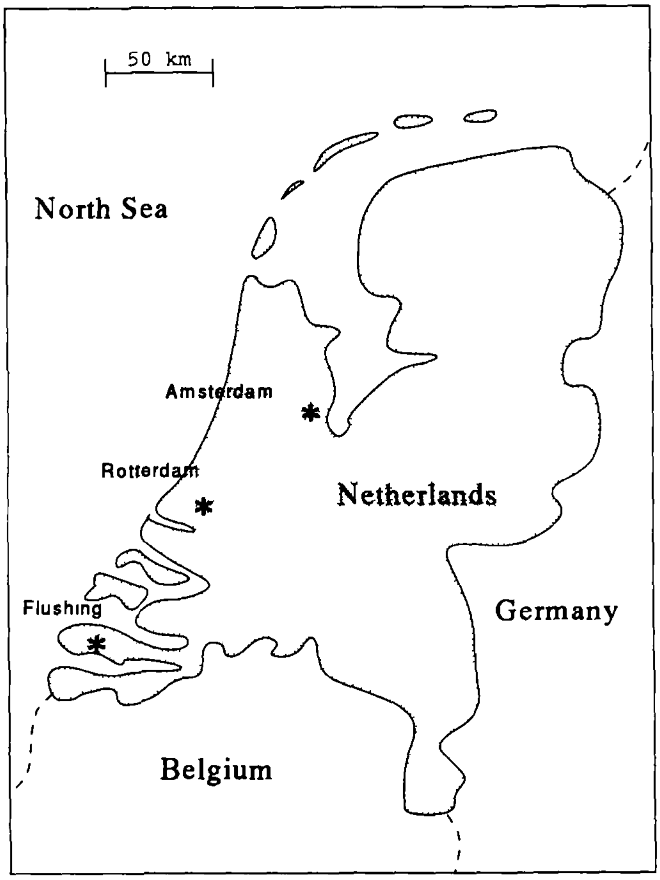

Figure 1: Major harbours in The Netherlands

design process using the probabilistic calculation method is explained in section 3. The schematization of all the information necessary for these calculations is treated in the next section (4). Familiar with this theory, two practical implementations, at Rotterdam (5) and Antwerp (6), are discussed. The paper is ended with a conclusion.

Two appendices are added, explaining the basic mathematical principles of the probabilistic calculation and showing some examples of the schematization and regimes used at Antwerp and Rotterdam. For a more thorough explanation of the probabilistic calculation method, or just out of interest or curiosity, the appended bibliography gives a list of papers and books which can be consulted.

2 Used expressions and terms

2.1 Tidal-Windows

Vessels with a draught of more than 20.00m with destination Rotterdam and vessels with a draught of more than 11.00m sailing at the Westerschelde are ***tidal-bound*** and are provided with a *tidal-window* advice. For these vessels, the available water level is not sufficient. Only using the high tide they can reach the harbour.

A tidal-window consists of two times, an opening time and a closing time (figure 2). Between those two times a vessel is allowed to enter the channel. During the channel transit tidal-windows indicate the different opening and closing times at different locations. These set of tidal-windows shows during which time period at which location the tidal-bound vessels can safely sail the channel. The tidal-window depends on vessel type, dead-weight, draught, astronomical water level, meteorological water effects and wave conditions. Also the vessel speed and current are taken into account. The more unfavorable the situation gets (e.g. more wind or waves) the narrower the tidal window becomes. In the most extreme situation no tidal window is available. In this case the vessel has to wait for the next tide and better circumstances.

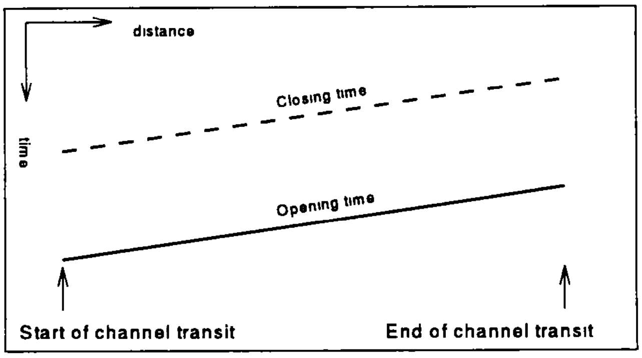

Figure 2: Tidal-Window

2.2 Downtime and Inaccessibility-Percentage

The accessibility of a harbour can be determined using the *downtime* and the *inaccessibility-percentage*. The downtime equals the percentage of the *time* during which a vessel can not access the harbour because there is no tidal-window available. The inaccessibility percentage equals the percentage of the *tides* during which no tidal-window can be provided, due to unfavorable water level or extreme waves.

These two values are quite different. For a vessel it is most important that there is an opportunity each tidal cycle during which it can reach the harbour. It is less important how long this opportunity exist during the tidal cycle. For example, if during four tidal cycles a tidal window exist which is a continuous period of 1 hour each tide, the downtime equals 84%, but the inaccessibility percentage equals 0%!

3 Design of Tidal-Windows

3.1 Deterministic Method

Till 1985 a deterministic admittance policy has been used for the Euro-Maas channel. The Westerschelde used this method till November 1995. 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 up the squat[1] vertical movements, sounding inaccuracies and sanding to the draught of the vessel, as explained in figure 3.

1 draught increase caused by the speed of the vessel (section 4.6.2)

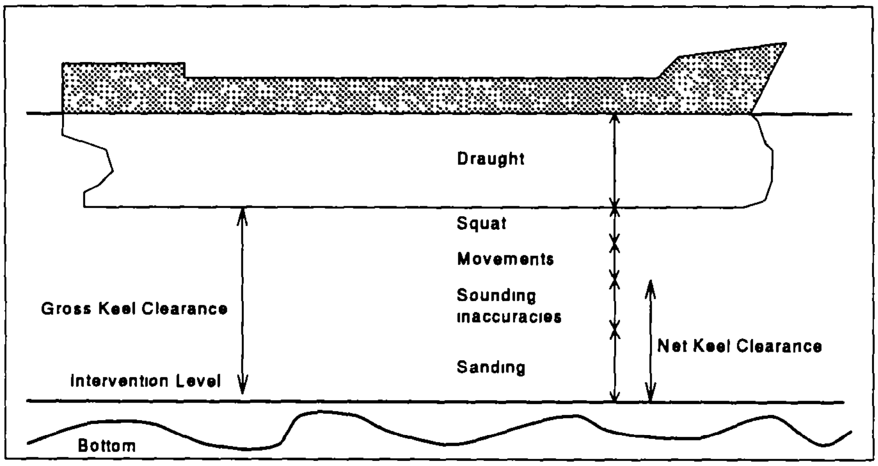

Figure 3: Keel-clearance and additions

These additions are equal to the maximum anticipated effects due to the factors mentioned before. The sum of all these additions determine the minimal gross keel clearance. The ratio between the gross keel clearance and the draught is called the keel clearance percentage. At table 1 the percentages of the major Dutch harbours are mentioned.

Channel	Keel-Clearance Outer area	Keel-Clearance Inner area
Euro-Maas channel	20%	10%
Westerschelde	15%	15%
IJ channel	17.5%	15%

Table 1: Minimal gross keel-clearance

Using these keel clearance percentages the accessibility of the channel can be determined. At the Westerschelde, the maximum draught was determined for the predicted water level at the most critical location along the channel. At the Euro-Maas channel and the IJ-channel tidal-windows were calculated at different locations along the channel, taking account of the changing water level during the channel transit.

3.2 Probabilistic Method

At this moment, the Euro-Maas channel and the Westerschelde have a probabilistic designed admittance policy, instead of a deterministic policy as described in section 3.1. All possible wave and water level conditions as well as ship characteristics are considered and used for determining an optimal accessibility. But instead of using discrete additions, each factor is translated into a probability distribution with a mean value and a variance. All the probabilistic distributions are combined and determine together the probability of touching the channel bottom.

The result of the probabilistic calculation are tidal-windows, inaccessibility percentages and downtimes. These tidal-windows and the according probability of touching the channel bottom conform to predefined safety criteria as described at section 3.5.

Now it is possible, using these safety criteria, to weigh the dredging costs against accessibility of the port.

The reliability of the tidal windows depends on the input data. The predictions and measurements of the water and wave conditions which occur in the channel have a certain inaccuracy (section 4.7). The probabilistic design method takes full account of prediction reliability as well as spreading of measurements. The exact design process is described in section 3.3.

3.3 Probabilistic Design Process

The theory of the probabilistic design is explained in appendix A. This theory has been used to develop a program called HARAP (HARbour APproach). HARAP calculates the probability of touching the channel bottom during a channel transit. It simulates a transit of a vessel. The process of determining the tidal-windows is explained in figure 4.

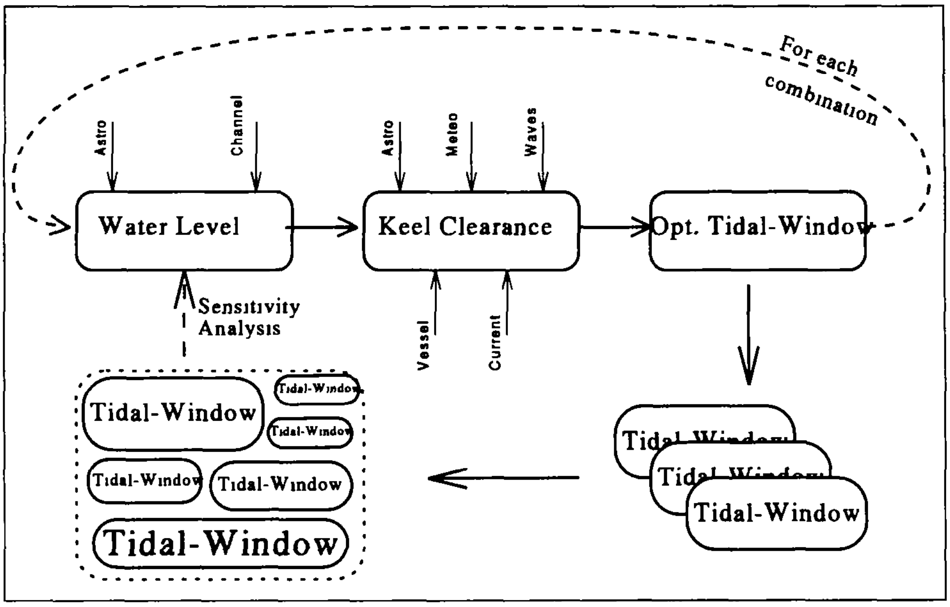

Figure 4: Process of calculating tidal-windows

During such a transit first the water level is determined. Information about astronomical and meteorological water levels, current, vessel speed and wave climate is used. This results in the calculation of the keel clearance across the channel. Next the vertical movements of the different types of vessels are added which depend on the wave climate. The final result at this stage is one optimal tidal-gate.

This optimal tidal-gate consists out of *one* time: the optimal time to start the channel transit with minimal probability to touch the bottom of the channel given all the circumstances at that moment.

This process is repeated for all the different combinations of circumstances. As explained in appendix A, equation 15 makes it possible to divide all the circumstantial parameters into *regimes* or classes. Instead of calculating with all the different values only the mean or representative value of a regime is used. Regimes are used to characterize the different water level effects, vessel types and wave climates. The number of required calculations is significantly reduced by using this technique.

For each combination of regimes a tidal-window is calculated. All the probabilities for touching the bottom of the channel of all the transits are added up. This sum is compared to a safety criterion (section 3.5). Finally the different tidal-windows are enlarged, reduced or removed, changing the total probability of touching the bottom of the channel, till the required criterion has been reached.

Finally, a sensitivity analysis can be done to optimize the chosen regimes, as showed by the dashed arrow in figure 4. The result is a optimized set of tidal-windows for all the different combinations of regimes. For each vessel type a inaccessibility percentage and downtime is calculated to determine the resulting accessibility of the channel and port.

3.4 Advantages and Disadvantages Probabilistic Method

The deterministic method is based on additions which determine the keel clearance. Mostly these additions are at the outside calculation, making sure that the safety is guaranteed. This results in a keel clearance which is at most times much to large. An advantage is the simplicity of this calculation method. It is possible to calculate the keel clearance by hand.

The probabilistic method, however, can not be calculated by hand. But the determined keel clearance is much more precise. With the same channel depth a much better accessibility can be achieved. Another advantage is the predetermined safety level. Now it is possible to weigh the accessibility, the required channel depth and the desired safety level.

3.5 Safety Criteria

As explained in section 3.3, the calculation and optimization of tidal windows is done by determining the total probability of touching the channel bottom. This probability must be less or equal to a predetermined safety criterion. For the Dutch channels this safety-criterion is determined as:

- **During 25 years the chance of touching the channel bottom which maximum minor damage must not be more than 10%.**

Using a Poisson distribution, a chance of 10% equals a probability of 0.105 touches each 25 years [4]. This chance is equal to one touch of the bottom of the channel each 237 years (25/0.105 = 237). Taking into account the number of tidal bound vessels in the channel during 25 years, and the fact that only one out of ten occurrences results in more than minor damage, results in the criterion used by HARAP[2]

Besides the above mentioned safety criterion, two other criteria exist. The first criterion, the *manœuvering* criterion makes sure that:

- **The keel clearance never is less than 1 m.**

Finally the *single transit* criterion defines that:

2 For the Euro-Maas channel 6250 vessels use the channel and are tidal bound each year This results in $0.105 \times 10/6250 = 1.68 \times 10^{-4}$ as the safety criterion used by HARAP

- **The chance that a vessel during its transit touches the channel bottom must always be less than 1% at all (weather) conditions.**

Despite the fact that the last two criteria almost never limit the size of the tidal window, these criteria are necessary to guarantee a safe transit under all conditions, because the general criterion only limits the total probability of touching the bottom of the channel of all vessels together.

4 Schematization

Using some kind of schematization the amount of data can be reduced, making it possible to calculate the keel clearance and the tidal-windows with a computer program.

As described in section 3.3 and appendix A the meteorological and astronomical water levels can be divided in different regimes. Also the low frequency distribution of the wave energy is schematized into one or two values and divided into regimes. The different types of vessels can be characterized by a few parameters, and finally the channel has been divided into separate parts to simplify the input data.

The Transport Research Center, the North Sea Directorate and the Directorate General of Shipping and Maritime affairs of the Ministry of Transport, Public Works and Water Management have developed the computer program HARAP. This program uses the probabilistic theory and processes all the data. The following sections explain all the information necessary to calculate the tidal-windows. Examples of the different schematizations are showed in appendix B.

4.1 The Channel

Because within the channel there are a lot of significant variance of the water level and channel depth, the channel has to be divided into smaller segments. The length of each segment must be chosen in such a way that the channel depth does not vary to much and that the water level variances during a segment transit are not more than the inaccuracy of other influences like depth inaccuracy.

4.2 Astronomical Water Level

The astronomical water level is represented as astronomical curves, with each a determined frequency of occurrence. These astronomical curves are divided into regimes based on *tide-difference*. The tide-difference is the difference between the high water level and the previous low water level. The water levels are specified relative to the *stroke-middle*. The stroke-middle is the difference low water level and high water level (figure 5). The stroke middle is fixed with respect to a predetermined reference level. The advantage of this method is the significant smaller spreading within each regime, compared to the normally used method where the water level is determined directly relative to a predefined reference level.

The regimes of the astronomical water level are based on the frequency distribution of the tide-difference. The limits of each regime are chosen in such a way that the spreading is minimal within this regime. The values which the HARAP program use, are the mean values of the different regimes. With this limited set of values

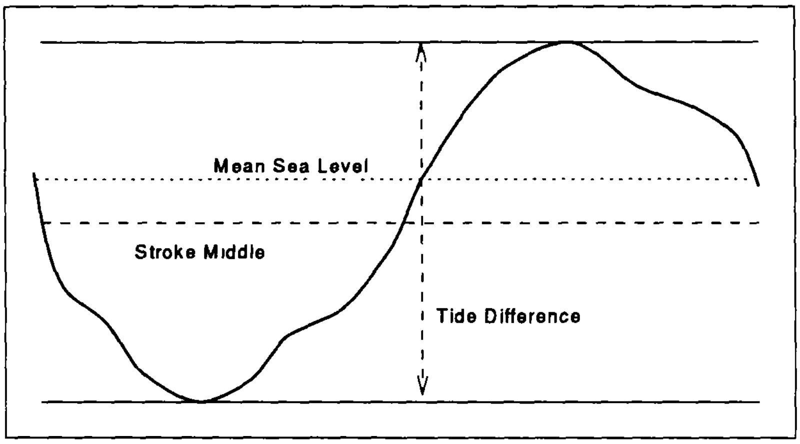

Figure 5: Astronomical water level

the astronomical water level can be used for the calculations. An example of the astronomical water level effect divided into three regimes is figure 6. Also table 4 at appendix B gives an example of the schematization.

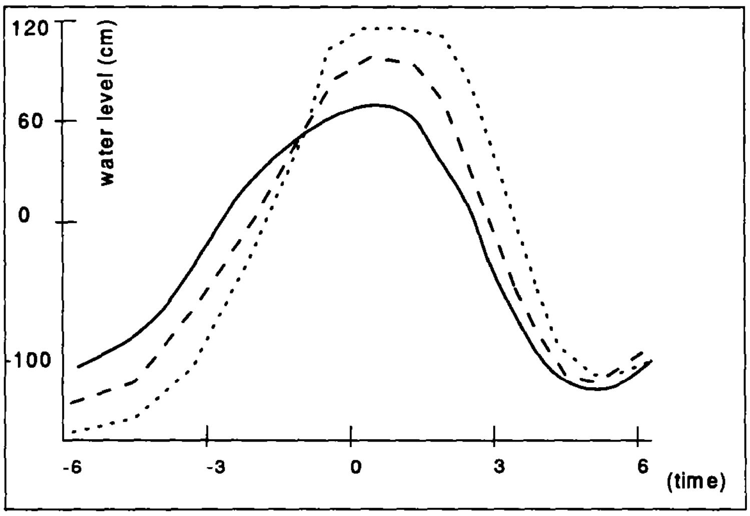

Figure 6: Three astronomical regimes

4.3 Meteorological Water Level

The meteorological water level is defined as the difference between the astronomical water level and the real water level measured during low and high water. These meteo effects are deviations of the astronomical water level as caused by wind and air pressure effects. Also the meteo effect is divided into regimes, based on the frequency of occurrence. Again the spreading is kept as low as possible by choosing the most optimal limits of the regimes.

Because the stroke-middle as described in section 4.2 is by definition constant during one tidal cycle, it is also incorporated in the meteorological regimes.

4.4 Current

For the HARAP calculations, the current can be defined using current speed and current direction. The current is important for determining a safe transit through the channel because:

- The cross-channel current limits the manoevrability near the harbour entrance, and
- The current is used for determining the squat of a vessel.

The cross-channel current must be determined with measurements and calculation models. The current in the channel mostly is extracted from tidal stream atlasses cause almost no current measurement time series are available. With this information the sailing speed of the vessel can be determined and the squat can be calculated.

4.5 Wave Climate

The wave climate is important for determining the vertical movements of the vessels, and therefore should be studied carefully. The wave climate can be divided into different wave directions and frequencies. For the Euro-Maas channel and the Westerschelde the wave frequencies are projected to one wave direction which is the most critical one. The frequencies can be displayed using a wave energy density spectrum. For the Euro-Maas channel the wave frequency density spectrum has been schematized using the *lfe* parameter (figure 7).

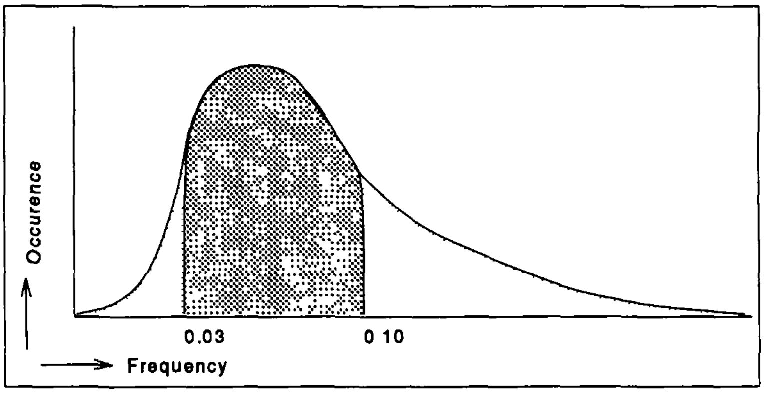

Figure 7: Wave frequency distribution, He_{10}.

This rather simple one-parameter schematization of the wave climate is necessary because of the fact that a more detailed description cannot yet be predicted accurately enough. The *lfe* parameter gives the amount of low frequency energy in the range between 0.03 and 0.1. This parameter is translated to a significant low frequency wave height, the He_{10}.

$$He_{10} = 4\sqrt{m_0}, \quad m_0 = \sum_{a}^{b}(S(f)\Delta f) \tag{1}$$

In this equation $a = 0.03$ and $b = 0.10$. The frequency is f and the spectral density equals $S(f)$. An example of the regimes based on the predicted low frequency wave energy is showed in table 6 at appendix B.

For the Westerschelde however a second parameter is used, the H_{res} value. The H_{res} parameter equals the amount of energy in the range between 0.1 and 0.5 as showed in figure 8.

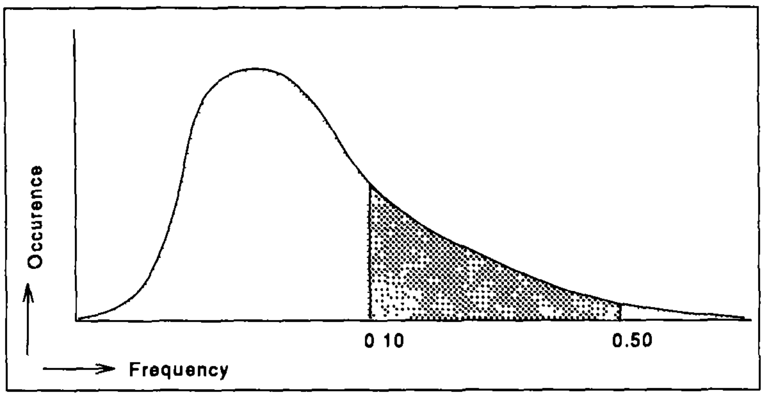

Figure 8: Wave frequency distribution, H_{res}.

Because tidal windows have to be assessed in advance of the actual channel passage, use has to be made of predictions of the *lfe* parameter. A frequency distribution of the actually occurring low frequency wave energy given a predicted energy is used in order to incorporate the influence of the prediction inaccuracy into the admittance policy in a fully probabilistic way. An example of a prediction matrix is showed in table 7 at appendix B. This frequency distribution has been determined by an analysis of a record of predicted and occurred wave energies.

4.6 Vessels

Besides information about the waves, water level and current, also the specifications of vessels have to be determined. For the port of Rotterdam, two types of vessel are considered. The bulk carrier and the crude oil tanker. At the Westerschelde container vessels and bulk carriers are considered. All the different types of vessels react differently on waves and swell. Also the squat depends on the type of vessel.

4.6.1 Vertical Movements

To determine the keel clearance of a vessel, one has to know the vertical movements of the vessels due to waves and swell. The relations which are necessary to know have been determined based on a lot of tests. Models have been made of different types of vessel and put into a water basin, simulating all the different (wave) conditions according to reality.

The vertical movements of a ship as induced by the low frequency wave energy are a combination of heave, roll and pitch motions. Besides the wave energy spectrum, the vertical movements depends on:

- type, size, deadweight, cargo, center of gravity, etc.
- speed,
- wave angle,
- ratio between water depth and draught.

Low frequency waves (swell) are the most important factor for the vertical movements. For each wave spectrum a large data set of measured wave spectra is necessary. For each type of vessel a ship movement spectrum is determined, using the response characteristic of that vessel. This movement spectrum is then reduced to a single parameter, the H_mO_{sch}. With linear regression methods this value can be related to a characteristic value of the low frequency wave energy He_{10}:

$$Z_s = a \times He_{10} + b \tag{2}$$

Z_s denotes the vessel movement and a and b are regression parameters. The regression parameters depend on the speed, wave direction and the ratio of depth and draught.

4.6.2 Squat

The squat is the draught increase of a vessel due to the sailing speed. The squat depends on shape, water depth and speed. For the port of Rotterdam the simplified *Tuck-Taylor* equation is used:

$$Squat = C \times \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} \times \frac{\Delta}{L_{pp}^2} \tag{3}$$

C denotes the squat constant, Δ the water displacement and L_{pp} the length of the ship. For the Euro-Maas channel a C value 1.75 has been used for the bulk carriers and 1.91 has been used for the oil tankers. The Froude number F_{nh} equals:

$$F_{nh} = \frac{v}{\sqrt{gh}} \tag{4}$$

In which v denotes the speed, h the water depth and g gravity acceleration. The speed is measured related to the ground, so current is taken into account.

4.6.3 Speed and Vessel Regimes

At each segment of the channel a speed must be defined for each different type of vessel. All the information about the speed at the different segments together is called a speed regime. Totally three different speed regimes are defined for the Euro-Maas channel, a slow, medium and fast regime. With the information about the different speeds the position of the ship can be defined. For the Westerschelde no different speed regimes are used.

The keel clearance is not calculated for each different vessel. They are grouped together based on their draught, size and type. For each type of vessel, different groups are defined. Within each group, a characteristic vessel has been chosen. The size and draught of this vessel is used for calculating the vertical movements and keel clearance. An example is showed in table 5 at appendix B.

4.7 Inaccuracies

To guarantee a correct probabilistic design the inaccuracies must be taken into account in a probabilistic way. If this is not possible, for example if no distribution is known of the concerned inaccuracy, an addition must be used. However, this deterministic method (section 3.1) can cause a very conservative result on the calculations, resulting in a over-dimensioned design.

4.7.1 Probabilistic Inaccuracies

The HARAP calculations use the following probabilistic inaccuracies:

1. Prediction inaccuracy of the He_{10}. This inaccuracy is implemented with the prediction frequency distribution as described in section 4.5.
2. Spreading of the relation between the vertical movement of the vessel and the low frequency wave energy (section 4.6.1), implemented by a fixed deviation.
3. The draught inaccuracy as described in section 4.7.3 is implemented with a fixed deviation and a spreading.
4. A deviation is used for the inaccuracy of the water level. This is a combination of inaccuracies caused by water level predictions, meteo schematization and astro schematization.

4.7.2 Deterministic Inaccuracies

The following inaccuracies are not implemented in a probabilistic way, but by using additions for the calculations.

1. A addition of one knot ($0.5m/s$) to the sailing speed with which the squat is calculated. This compensates the speed fluctuations during the channel transit and the shape differences between the different types of vessels.
2. A addition for the sand-waves which cause a depth decrease of the channel.

4.7.3 Draught Inaccuracies

A special kind of inaccuracy is the draught inaccuracy. Tidal-bound vessels access the harbour with use of a tidal-window based on a previously announced draught. The actual draught mostly varies around this value. The difference between the announced draught and the actual draught is about $+7cm$, with a variance of $15cm$. Assumed is that this difference is mainly caused by the change of the density of the water between the moment of the announcement and the moment that the vessel enters the channel.

5 The Implementation at Rotterdam

In this section the specific problems, techniques and schematization of the port of Rotterdam and the Euro-Maas channel is discussed. Rotterdam was the first harbour which used the probabilistic method. It resulted in a safe and highly accessible harbour.

5.1 The Euro-Maas Channel

From the North-Sea, through the *Selected Route* and the *Approach Area*, the harbour can be accessed through the *Euro-Maas channel.* The total length of the Euro-Maas channel, calculated from the entry-point till the head of the harbour is about $57km$ ($\approx$ 31 miles), see figure 9.

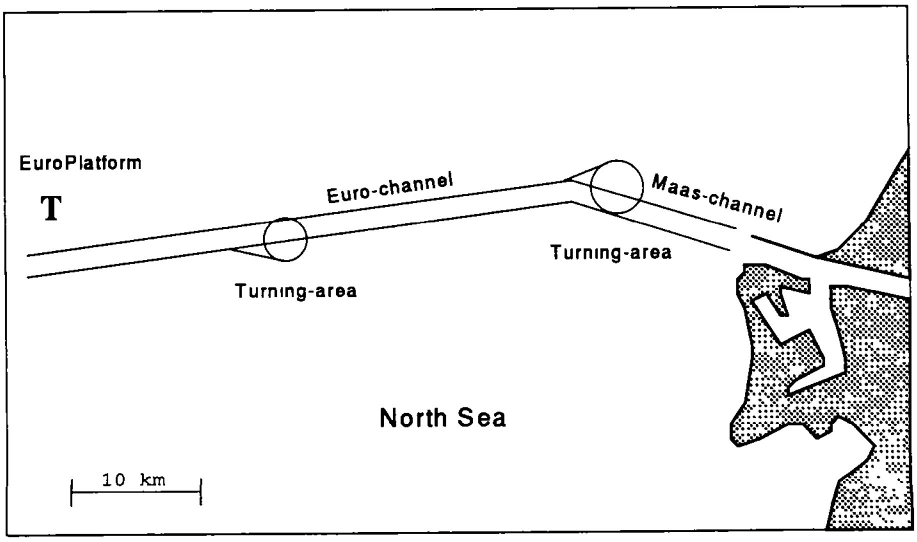

Figure 9: General view of the Euro-Maas channel

The first part, the Euro channel, is $45.65km$ ($\approx$ 25 nautical miles) and $600m$ wide. The depth of this part is about $25m$. Halfway down the Euro channel a turning-area is situated with a diameter of $2700m$. This turning-area can be used in emergency situations when the harbour can not be accessed on time due to the tide or weather conditions. At the end of this channel another turning-area is situated with a diameter of $1600m$. The second part, the Maas channel, is $11.35km$ ($\approx$ nautical miles). The depth of this part of the channel is $24.3m$. The bottom of the channel is almost level. The width is $600m$ at the beginning and $500m$ at the end [1]. The inner (harbour) area consists of the *Maasmond*, the *Caland channel* and the *Beer channel* with the attached harbours and moorings. The depth of the inner area is about $23.75m$.

Vessels with a draught of more than $17.40m$ (57 feet) are channel-bound, they can sail the channel on every tide except during very extreme weather conditions. Vessels with a draught of $20.00m$ (65.5 feet) and more are tidal-bound and are provided with a *tidal window* advice.

5.2 Cross-Channel Current

Vessels with draughts of over $21.95m$ do have a cross-channel current restriction near the harbour entrance. Because only tidal stream atlas data was available, only covering the average current pattern, no distinction could be made between spring and neap tide. For this reason and because the wind effects are also not yet predictable the period with maximum current velocities is excluded for all conditions, in order to guarantee the safety. In practice this means that vessels with a draught over 21.95m may not enter the harbour between 0 hours and 2.5 hours after high water.

5.3 Vessel Types

The tidal-bound vessels accessing the port of Rotterdam can be divided into two types: bulk carriers and crude oil tankers. Vessels up to a maximum draught of 22.55m (74 feet) can access the channel. For each type of vessel twenty groups are defined, selected on their draught and deadweight. As described in section 4.6. Totally three different speed regimes are defined for the Euro-Maas channel, a slow, medium and fast regime. This technique is used for optimizing the tidal-windows as explained in the next section.

5.4 Converging and Diverging Tidal-Windows

Formally a tidal window was calculated in a way that within certain speed limits slow as well as fast vessels could always use that tidal window. This resulted in diverging tidal-window (figure 10); the tidal window at the end of the channel must be larger than the tidal window at the beginning of the channel to make sure both the fast and slow vessel, departed at the same time, can enter the harbour within the last tidal-window.

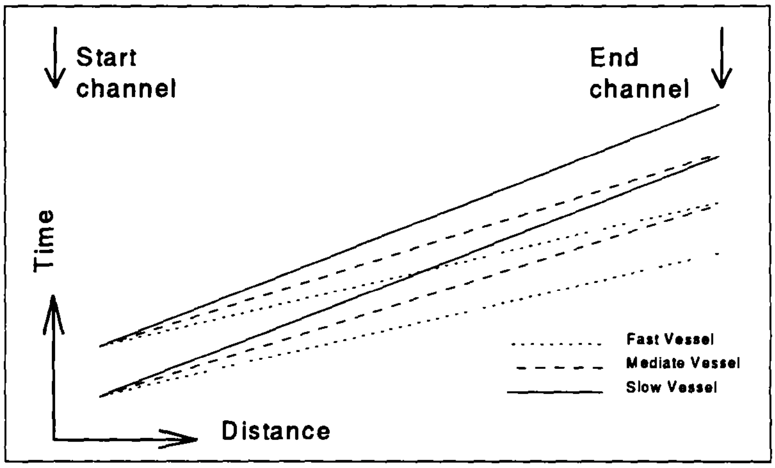

Figure 10: Diverging tidal-windows

As previously stated in 5.2, vessels with draughts of over 21.95m do have a current restriction. They may not enter the harbour between 0 to 2.5 hours after high water. This current restriction gives a problem together with a diverging tidal window that can be used by fast as well as slow vessels. The slow vessel causes the tidal window to close rather early, during the unfavorable ebb tide, denoted by the continuous line in figure 10. This is unfavorable for fast vessels because they have a greater squat. This problem limits the accessibility of the harbour considerably.

In the new admittance policy tidal windows are given for different speed regimes. This allows fast ships to start their channel trip later. Previously fast vessels could not start later, in spite of the already risen water level which compensates the extra squat. This proved to be a good solution for a practical problem.

This new policy results in three tidal windows, one for each speed, which together are a converging tidal window as explained in figure 11. With this improvement there are more possibilities for tidal windows, although sometimes not all the different speeds are possible.

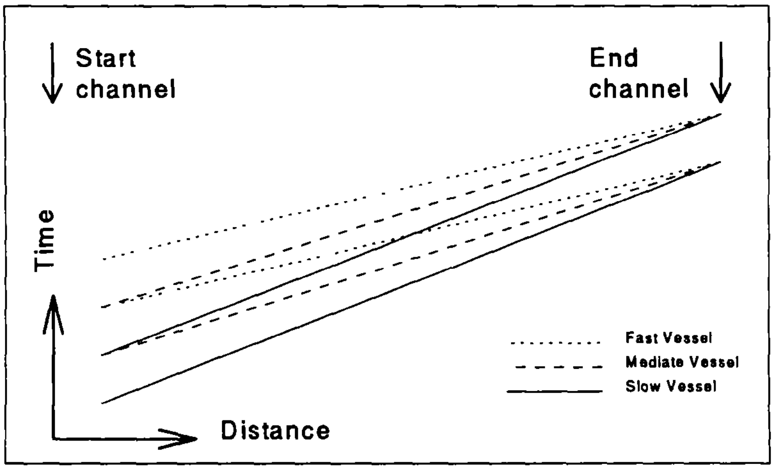

Figure 11: Converging tidal window

5.5 Water Levels and Waves

As explained in 4.2 the astronomical water level regime is determined by the tide-difference at Hoek van Holland. Previously, this regime was determined by the astronomical high-water level at Hoek van Holland and Europlatform. Because the high-water levels, just like the low-water levels, can change every day this schematization was not accurate. The stroke-middle, which denotes the daily changing high-water level is combined with the meteorological water level (section 4.3). Both the astronomical water level and the meteorological water level are divided into three regimes.

The wave energy is characterized by a single parameter, the He_{10} value. With this value the vertical movements of the different vessels is calculated. The different low frequency wave energies are divided into ten different regimes.

5.6 Accessibility

The changes mentioned in the previous sections resulted in an decreasing inaccessibility percentage. As an example of the advantages gained by the improvements, table 2 shows the inaccessibility percentages for two deep draught bulk carriers before [2] and after [1] the new implementations.

	Inaccessibility Percentage	
Draught	Before	After
21.95	3.2%	1.2%
22.55	12.2%	6.1%

Table 2: Inaccessibility percentages deep draught bulk carriers

5.7 Future Improvements

5.7.1 Neural Networks

In order to improve the rather coarse current restriction (4.4) in 1996 a permanent on-line current measurement location just next to the Maas channel will be installed. In order to obtain current predictions experiments are being carried out using *neural networks*. In the IJ-channel a neural network proved to be very well able to predict the current [5]. The Neural Networks are able to learn complex non-linear processes from examples. Their principle is based on the working of the biological brain. Numerical models are not yet able to provide operational predictions because of the large spatial variation of the current. The required fine grid models still ask too much computational time.

5.7.2 Individual Tidal Windows

At the moment, a tidal window is being calculated for a group of vessels, not for a individual vessel (section 4.6.3). Within this group, the most critical vessel is used for determining the vertical movements. In contradistinction to before, when only model tests were possible, now computer calculations can reliably determine the vertical movements.

In august this year a project has started to measure the exact movements of large vessels, in order to validate the calculations. Accelerations, speeds and displacements are measured, together with accurate information of the wave energy, in order to better tune the response functions to the individual vessel.

Large vessels like the *Berge Stahl* with a draught of 74 feet are calculated with their actual size, instead of the sizes defined by the group it belongs to. This way much more accurate calculations are possible. This means that the draught of the specific vessel must be given with great accuracy.

The goal is to determine an individual tidal window for every vessel, calculating the vertical ship movements of that vessel, given the predicted wave spectrum, besides using the predicted water level curve instead of the astronomical and meteorological water level regimes.

It is to be expected that these investigations will significantly increase the accessibility of the port of Rotterdam.

6 Implementation at Westerschelde

From 1990 till 1993 the Transport Research Center and the Directorate Zeeland did research about the possibility of implementing a probabilistic admittance policy for the Westerschelde. This resulted in a trial period started November this year. As a result of implementing this probabilistic method of determining tidal-windows a safer channel transit is pursued. After this trial period of two years is decided if the probabilistic method is going to be used permanently.

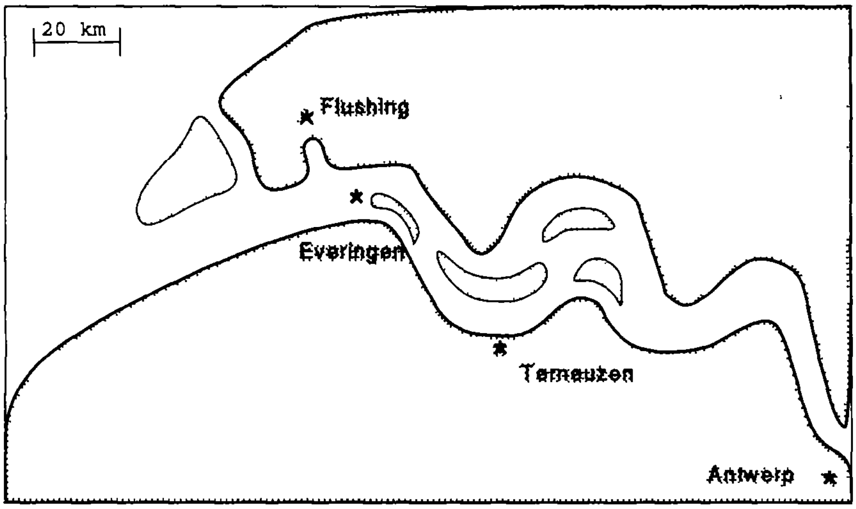

Figure 12: Westerschelde

6.1 The Channel

The Westerschelde (figure 12) is a natural waterway. The depth is enlarged by dredging. In contradiction to the Euro-Maas channel, the cross section of the Westerschelde is not constant. Along the channel are some natural shallowness or *bars*. These bars determine mostly the accessibility of the different harbours along the Westerschelde.

The vessels can have destination Vlissingen, anchorage Everingen, Terneuzen and Flushing. However, the probabilistic method is only applied to the outer area, the channel till Flushing. The other destinations have tidal-windows calculated as explained in section 6.4. The schematized channel is $65km$ and ends at Flushing. The depth of this part of the channel varies between $18.9m$ at the port of Flushing and $15.5m$ halfway the channel. Near the port of Flushing is an anchorage. Vessels with destination Antwerp can wait here if it is not possible to sail to Antwerp using one tidal cycle or if they need to unload. The distance from Flushing to Terneuzen is $20km$. The remaining part of the Westerschelde from Flushing to Antwerp is about $65km$.

6.2 Cross-Channel-Current

At the entrance of the port of Flushing a very strong cross current exists. Only during a very short period the current is not to strong to enter the harbour. This period occurs 1.5 hours after high water and lasts 1 hour. Due to this fact, the accessibility of the port of Flushing is mostly determined by the cross-channel current restriction. Even with the probabilistic calculation method the inaccessibility percentage can not be lowered very much.

6.3 Vessel Types

The supply of vessels at the Westerschelde consists mostly out of cargo vessels. A distinction can be made between *Panamax* bulk carriers and *Cape-Size* bulk carriers.

The Panamax bulk carriers have a maximum breadth of $32.31m$. The Cape-Size bulk carriers which sail on the Westerschelde are vessels which can not sail through the Panama canal and have a breadth up to $45m$. The maximum depth with which the vessels can access the Westerschelde is about $15m$. Each type of vessel is divided into 19 regimes with a depth from $11m$ up to $15.40m$.

6.4 Time Windows

The Westerschelde can be divided into two parts, the outer area and the inner area. The outer area is the part from the sea till Flushing, and the outer area is the channel from Flushing to Antwerp. At the outer area the low frequency which determines the vertical movements of the vessels is quite important. However at the inner area almost no low frequency wave energy is present. This results in a almost neglectable vertical movement of the vessel at this area.

One of the most important advantages of the use of the probabilistic program HARAP is the ability of determining very accurate the response of the vessel due to waves. Decided is, because there is almost no low frequency wave energy at the inner area, not to use the probabilistic calculation method for the Westerschelde from Flushing to Antwerp. But to provide general tidal windows for the complete Westerschelde, the accessibility of the inner area is included with the probabilistic calculations by use of *time-windows.*

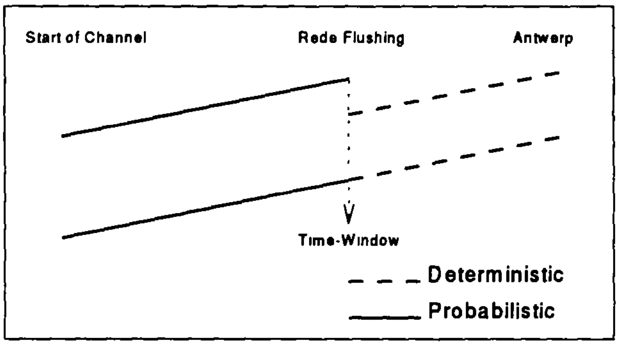

Figure 13: Time-Window

The tidal-windows for vessels with destination Terneuzen or Antwerp are calculated with the probabilistic method up to Everingen. For the destination Terneuzen and Antwerp restrictions are available indicating the latest possible time to arrive at this harbour. These restrictions are determined in a deterministic way. This time, subtracted with the time necessary to sail from Everingen to this harbour, indicates the latest possible time to depart from Everingen. The earliest and latest time possible to depart from Everingen is called a time-window (figure 13).

This time-window which depends on the destination is combined with the probabilistic tidal-window. A integrated tidal-window is available for each destination in the outer area as well as in the inner area. It is possible that there is no tidal-window available for a destination at the inner area caused by a unfavorable time-window. In this case a tidal-window is supplied with destination Everingen. The vessels can wait at this anchorage for the next tide cycle.

6.5 Water Levels and Waves

The water level along the Westerschelde is measured at four different places, because the channel very long. The astronomical water level is divided into five regimes, and the meteorological water level effects are divided into six different regimes.

The wave energy is characterized by two parameters, He_{10} and H_{res}. With this method the low frequency wave energy (He_{10}) as well as the remaining very low frequency wave energy (H_{res}) can be used to determine the vertical movements of the different types of vessels.

6.6 Accessibility

The inaccessibility percentage of the vessels heading for Flushing and Everingen are given at the following table 3. A distinction has been made between the Cape-Size bulk carriers and the Panamax bulk carriers.

Vessel	*Destination*	*Draught*	*Inaccessibility Percentage*
Cape-Size	Flushing	15.40m	68%
Cape-Size	Flushing	13.40m	7.5%
Panamax	Everingen	14.60m	46%
Panamax	Everingen	11.60m	0.5%

Table 3: Inaccessibility percentages Westerschelde.

6.7 Future Developments

The number of container vessels sailing at the Westerschelde is increasing. Decided is to implement this vessel type with the probabilistic calculation method of the tidal-windows. Therefore first an investigation has to be done to determine the draught and breadth of all the different container vessels.

Also there are a lot of outgoing vessels form Antwerp and other harbours to the sea. Suggested is to calculate tidal-windows not only for the vessels with destination Flushing, Everingen, Terneuzen and Antwerp, but also for the outgoing vessels from the different harbours along the Westerschelde.

7 Conclusion

The probabilistic calculation method is a great improvement compared to the deterministic method. Although, the process of schematizing the necessary information and optimizing the computer calculations is quite complex and time consuming.

However the resulting tidal-windows are very accurate and considers all the different weather and wave conditions the vessel can meat during the channel transit. The new probabilistic admittance policy for the Euro-Maas channel resulted in a very high accessibility of the port of Rotterdam.

The admittance policy design of the channel can be optimized using a pre-defined safety criteria, ensuring a safe channel transit. The vessels at the Westerschelde profit by the use of the recently implemented probabilistic calculation method; the risks of touching the bottom of the channel have been minimized. With new improvements, being developed right now, even better results are expected for both channels.

Without any additional costs for dredging the safety and accessibility of a harbour can be increased using the existing channel configuration.

A Theory

A probabilistic approach integrates design factors in such a way that all possible circumstances during the lifetime of the object to be designed, contribute to the design in a weighted form.

The probability that the ship touches the channel bed due to wave-induced motions, equals the probability that the vertical downward displacement, $z_c(t)$, of the most critical point in the ship's keel(i.e. the point witch the highest probability of touching) exceeds the net keel clearance, $\overline{KC}$, during the transit [3].

The theory of extrema of stochastic processes provides an expression for the probability that the absolute maximum of $z_c(t)$ will not exceed $\overline{KC}$ in one transit, provided that the second spectral moment m_2 of $z_c(t)$ is finite.

$$Pr\left[z_c(t)_{max} \le \overline{KC} \mid 0 \le t \le T_p\right] = \Phi(\overline{KC}) \cdot \exp\left[-\sqrt{2\pi m_2} T_p \frac{\phi(\overline{KC})}{\Phi(\overline{KC})}\right] \tag{5}$$

$$\phi(\overline{KC}) = \frac{1}{\sqrt{2\pi m_0}} \exp\left\{x - \frac{1}{2}\frac{\overline{KC}^2}{m_0}\right\} \tag{6}$$

$$\Phi(\overline{KC}) = \int_{\infty}^{\overline{KC}} \phi(x)\, dx \tag{7}$$

The probability of touching may be computed using a Poisson process description if, besides the previous conditions, the level of $\overline{KC}$is so high that the number of exceedances of this level within disjunct time intervals are independent. This condition is approximately fulfilled if $\overline{KC}/sqrtm_0 \gg 1$. According to [3] the probability of k bottom touches in period T_p and the intensity $\lambda(\overline{KC})$ is given by:

$$Pr\left[\underline{A}\left(\overline{KC}; T_p\right) = k\right] = \frac{\left\{\lambda(\overline{KC})T_p\right\}^k}{k!} \exp\left\{-\lambda(\overline{KC})T_p\right\} \tag{8}$$

$$\lambda(\overline{KC}) = \sqrt{2\pi m_2} \cdot \phi(\overline{KC}) = \sqrt{\frac{m_2}{m_0}} \cdot \exp\left\{-\frac{1}{2}\frac{\overline{KC}^2}{m_0}\right\} \tag{9}$$

if $\underline{A}\left(\overline{KC}; T_p\right)$ is defined as the number of bottom touches in T_p. Considering a channel with different wave conditions, the number of bottom touches $\underline{A}_j$ at wave condition j in the period of time T depends on the number of channel transits $\underline{B}_j$ at this condition. The intensity and the expected number of channel transits then equals:

$$\delta_j = \lim_{T \to \infty} \frac{N_j(T)}{T} \tag{10}$$

$$E\{\underline{B}_j\} = \delta_j f_j T \tag{11}$$

Each wave condition j can be characterized by an energy density spectrum and a mean direction of wave propagation, and has a specific frequency of occurrence f_j. This results in a Poisson distribution for $\underline{A}$ with parameter ξ.

$$Pr[\underline{A} = k] = \frac{\xi_k \cdot e^{-\xi}}{k!} \tag{12}$$

$$\xi = TT_p \sum_j \lambda_j (\overline{KC}) \delta_j f_j \tag{13}$$

Next, equation 13 will be extended by the incorporation of the variation in the average water-level from one channel transit to another. With T_n the total amount of time in period T that the n^{th} class of water-levels occurs:

$$\xi = T_p \sum_j f_j \sum_n \lambda_{jn} \left(\overline{KC}_n\right) \delta_{jn} T_n \tag{14}$$

Finally the channel can be split in different parts with each different conditions. In each section we can use different speeds and wave climates. With m the number of sections, we get the following equation.

$$\xi = \sum_j \sum_m f_{jm} T_{pm} \sum_n \lambda_{jmn} \left(\overline{KC}_{mn}\right) \delta_{jn} T_n \tag{15}$$

B Examples Different Regimes

Regime	*Frequency of Occurrence*	*Regime Limits(m)*	
		Lower	*Upper*
1	10	2.00	2.87
2	15	2.88	3.32
3	30	3.33	3.93
4	30	3.94	4.45
5	15	4.46	5.39

Table 4: Astronomical regimes westerschelde based on tidal-difference Flushing

Draught	*Draught*		*Deadweight*	
Regime	*From*	*To*	*Panamax*	*Cape-Size*
1	1100	1160	67700	101500
2	1160	1220	71500	106900
3	1220	1250	73500	109700
...	...	...	...	...
17	1510	1520	90500	135200
18	1520	1530	91100	136100
19	1530	1540	91800	137100

Table 5: Draught regimes bulk carriers Westerschelde

He_{10} *regime*	*Limits*	*Calculation Value*	*Frequency* of Occurrence
1	0–25	12.5	0.8658
2	26-40	32.5	0.0669
3	41-55	47.5	0.0291
...	...	...	...
9	131–145	137.5	0.0016
10	> 145	220	0.0066

Table 6: Predicted He_{10} climate Euro-Maas channel

Occurred	*Predicted Wave Regime*					
Wave Regime	1	2	3	...	9	10
1	0.9543	0.4906	0.2557	...	0.0007	0.0000
2	0.0386	0.3517	0.3239	...	0.0041	0.0001
3	0.0059	0.1358	0.2719	...	0.0191	0.0007
⋮	⋮	⋮	⋮	⋱	⋮	⋮
9	0.0000	0.0000	0.0000	...	0.0946	0.2352
10	0.0000	0.0000	0.0000	...	0.0451	0.3343

Table 7: Wave prediction matrix Euro-Maas channel

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