Integral Design of Work Channels and Basins for the Execution of Dredging Projects

MSc. Thesis

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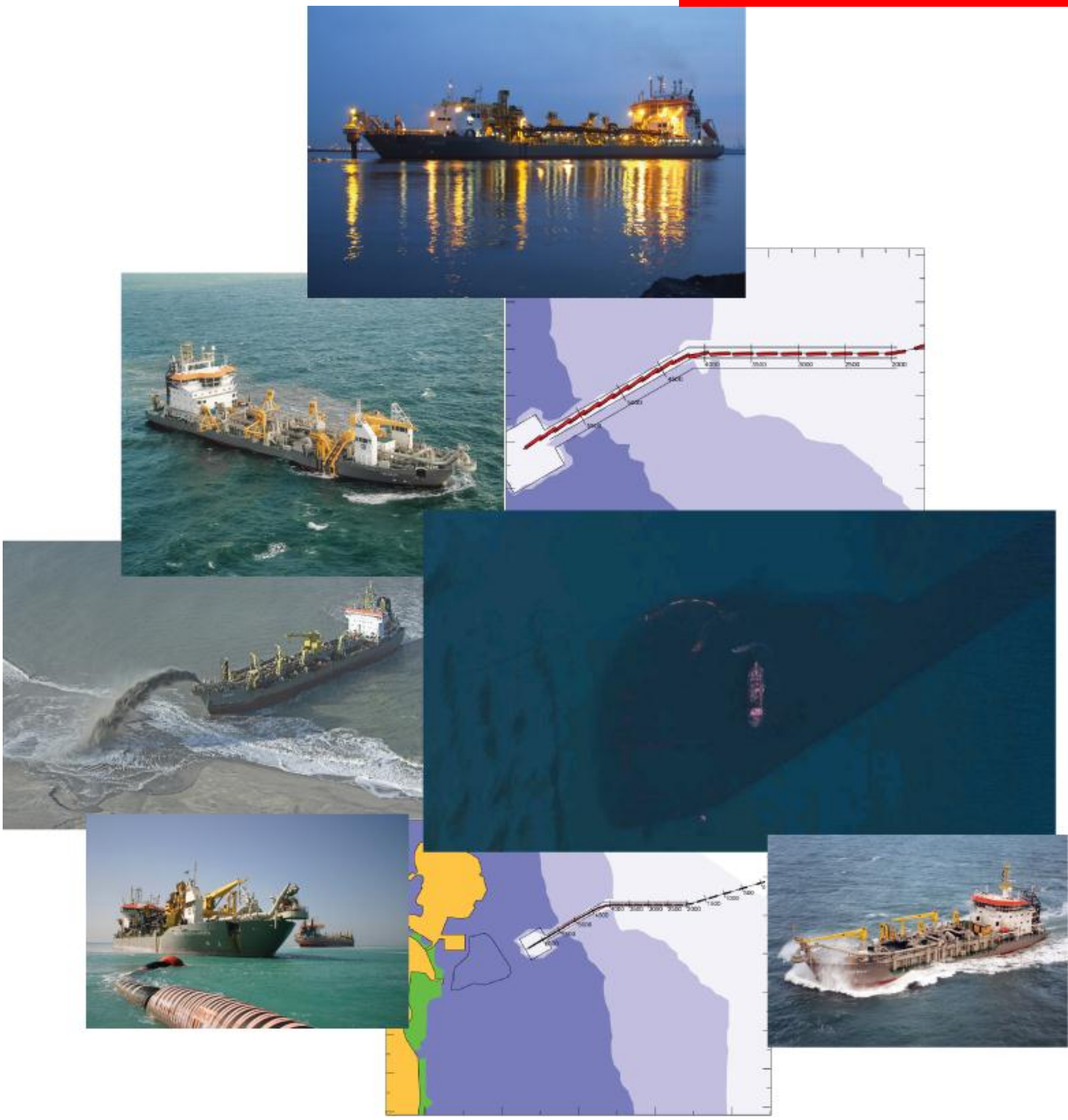

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Preface

A temporary work channel and basin are used by a trailing suction hopper dredger during the execution of a dredging project. The design of such a channel is often based on the experiences of the past, rules of thumb and guidelines for approach channels. But does the currently used design method lead to the most optimal design? This report describes the theoretical background of the design of a work channel and proposes a new design method to reach an optimization in channel dimensions and layout.

This thesis is written for the completion of the masters-program Hydraulic Engineering at the faculty of Civil Engineering and Geosciences of the Delft University of Technology. The graduation project is carried out at the engineering department of Boskalis, Hydronamic BV. A small part of the project is done at research institute Deltares.

First I would like to thank the members of my graduation committee. Professor Han Ligteringen and Professor Cees van Rhee from the Delft University of Technology for their feedback on the report. Henk Verheij from the Delft University of Technology and Deltares and Vincent Hermeling from Boskalis / Hydronamic for their daily guidance and extensive feedback. I would also like to thank Boskalis and Hydronamic for giving me the opportunity to work on this very interesting project and for providing a place to work. Thanks also goes out to Deltares for providing the fast-time simulation software and a workplace to make the simulation runs.

Furthermore, I would like to thank everyone who supported me by giving the information necessary to complete this thesis. Special thanks goes out to the crew of the dredging vessels “Willem van Oranje”, “Prins der Nederlanden” and “Queen of the Netherlands” for giving their view on the project and for the hospitality on board.

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Tom IJsebaert
Delft, December 2010

Summary

During the execution of reclamation projects by Boskalis, often a temporary work channel and basin are required. This work channel is used by the dredging equipment to reach the project site as close as possible. The project site is often located in very shallow water which makes an approach channel necessary. The basin is used to transport the dredged material ashore and to make a turn. Often, these work channels are only used during the execution of the project and are only used by trailing suction hopper dredgers (TSHD's). That specific situation is considered in this thesis. Nowadays, the design of a work channel is based on the guidelines regarding approach channels for ports. This often leads to an over- or underestimation of the channel dimensions, which could result in unnecessary high costs. More insight in the backgrounds of a TSHD in a work channel must lead to an optimization of the channel and basin layout and dimensions.

The design rules on approach channels formulated in the most commonly used guidelines are all based on the interaction between ship, environment and channel. These factors all have an influence on the design of a channel. The most important characteristics of a ship are the dimension given by the length, beam and draught. The movement of the ship through the channel is mostly based on the manoeuvrability and speed of the ship. The manoeuvrablity can be expressed by characteristics like hull shape, dimensions, mass, propulsive power and rudder area. The most important environmental influences are wind, currents, waves and tides. Wind and currents give the ship a certain drift angle while sailing and therefore influences the required channel width. Waves and tides mainly cause a vertical movement of the ship resulting in a larger channel depth. The shape and dimensions of the channel cross-section are also of great importance. In a shallow, restricted channel interaction forces occur between the ship, channel bottom and channel banks. One of the most important results of sailing in shallow water is an increase of squat. Squat is the hydraulic phenomenon by which the forward movement of a ship in shallow water creates an area of lowered pressure under the hull, resulting for the ship to sink deeper into the water compared to a ship that is not moving. This is of great importance for the determination of the channel depth for a certain sailing speed. In case of two-way traffic in the channel, the interaction forces between two ships must also be taken into account in the determination of the channel width. All the above influences combined will lead to the design of the dimension of a channel. However, not all influences have to be taken into account in case of a TSHD in a work channel.

Nowadays, the most currently used guidelines are given by the nautical institutions PIANC, USACE, Japan Institute of Navigation, Spanish Port Authority and the Canadian Coast Guard (CCG). A comparison between the guidelines is made based on a case study. In general the guidelines can be divided into empirical methods (PIANC, USACE and CCG), analytical methods (Japan) and a combination of the two (Spain). Following from the case study, the largest differences between the guidelines are found in the channel width. Compared to the eventually constructed width, the guidelines by USACE and Japan show an underestimation, the guidelines by PIANC and CCG give a slight overestimation and the Spanish guideline gives a large overestimation. A large problem of the empirical methods is that they do not give a continuous result for increasing environmental conditions. Also these methods are often widely interpretable. However, the method of PIANC does give a good estimate in this case study. The under- or overestimation seen in all guidelines can be

assigned to the fact that these guidelines are developed for the design of an approach channel to a port which has to last for a long time, not for a temporary work channel.

Five projects executed in the past by Boskalis are analyzed to gain insight in the currently used design procedure of a work channel. It is clear that nowadays the PIANC guidelines are used and that the engineers at Boskalis interpret the guideline in such a way that the minimum channel dimensions are reached. This results in low estimated costs during the tender phase, but also leads to the fact that often the channel does not satisfy the requirements of the TSHD's during the construction phase. Adjustments to the channel are then inevitable.

Based on the experiences from executed projects, interviews with captains and available theories, a new design-tool is set up especially for the design of a work channel and basin for a TSHD. The design method is based on the PIANC but only the influences that are important for a TSHD in a work channel are taken into account. Also the empirical character of the PIANC method is not used in the new design-tool. This means that one set of input parameters results in one channel cross-section. The channel depth is calculated by a superposition of the TSHD's maximum draught, the maximum squat, an allowance for wave response and a safety margin depending on the bottom material of the channel. The maximum squat is calculated by the method of Ankudinov which shows the best correlation with squat measurements of a TSHD in shallow water. The channel width is a combination of the TSHD's swept path, an allowance for bank suction forces and sinusoidal movement of the TSHD and an allowance for ship-ship interaction. The swept path is calculated based on the drift angle due to currents and the beam and length of the TSHD. From interviews with TSHD captains followed that the influence of wind is not important. The dimensions of the turning basin are calculated with the ships length and is also based on the experiences of TSHD captains. For the given input values, the design tool computes the dimensions of a one-way and a two-way cross-section and the dimensions of the basin.

An assessment of the design tool is made based on a case study. The design of a work channel is calculated by the design tool and several runs are made with the fast-time simulation software SHIPMA. The results concluded that the design-tool gives a slight overestimation of approximately 20%. This overestimation can be seen as a safety margin in the design, to take uncertainties in some of the assumptions into account.

The design tool computes the dimensions of a one-way channel and a two-way channel. The choice between the two channels can be made according to an analysis of costs. When choosing for a two-way channel, the benefits of using two TSHD's must weigh up to the extra production costs and the extra costs of a larger channel. This all depends on the used TSHD('s) and the nature of the project. For the analysed case, a larger reclamation volume leads to the choice for a one-way channel with a large TSHD. The smaller the reclamation volume gets, the more profitable a two-way channel with two small TSHD's gets. However, because of the large amount of parameters that influence the costs, it is very hard to give a general recommendation on when to use a one-way or a two-way channel.

The research carried out in this MSc thesis resulted in a design tool to compute the dimensions of a temporary work channel and basin. However, there are still a lot of uncertainties in the theories behind the movement of a TSHD in a shallow, restricted water. Therefore some recommendations are set up to improve the design tool in the future. The channel depth largely depends on the amount of squat. It is recommended to set up a program to investigate the squat of a TSHD in a shallow, restricted water. Test results can be used to make a validation of the method of Ankudinov for this particular situation or to set up a new prediction method. It is also recommended to keep up-to-date concerning ship-ship interaction forces and bank suction effects as these subject are still under research. The sinusoidal movement of a TSHD in a channel is also hard to predict. It is recommended to collect DGPS-data to gain more insight on this subject. During the interviews, the captains indicated a sailing speed of 6 to 8 knots in loaded conditions and 14 to 16 knots in unloaded conditions. The analysis of costs concluded that these speed do not always result in the lowest costs. Because of the fact that this analysis is based on several assumptions, it is recommended to do more research on the optimal sailing speed of a TSHD in a work channel.

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1. Introduction

1.1. Background

Royal Boskalis Westminster nv (further written as Boskalis) is involved in projects all over the world concerning the construction and maintenance of ports and waterways, the creation of land in water and the protection of shores and coastlines. The construction of these projects requires a large amount of dredging activities, executed by Boskalis' own fleet. This fleet contains a great variety of dredging equipment, like trailing suction hopper dredgers (TSHD's), cutter suction dredgers (CSD's), backhoes, stone-dumping vessels and fallpipe vessels. During the execution of the projects these vessels often have to operate in shallow waters, which can result in the demand for a temporary work channel.

One of the examples is a project where land is being reclaimed. Huge amounts of material are required, mostly obtained from the sea bottom and transported to the reclamation area. This transport can be done by equipment like TSHD's, self-propelled or towed (splithopper) barges or by (floating) pipelines. A problem for the vessels or barges occurs when the destination of the dredged material is surrounded by a shallow sea or shoal. In this case it is necessary to dredge a temporary access channel for the large vessels to come closer to the project site. At the end of such a channel, often a basin is created to handle the dredged material and to be used for the vessels or barges to turn.

The term 'work channel' is used intensively in this MSc. thesis. Here it is defined as follows: *the temporary access channel and connected turning- or handling basin, only used during the execution of a dredging project*. In this MSc. thesis only work channels used by TSHD's are considered.

The MSc. thesis is carried out at Hydronamic BV, division Ports and Waterways (further written as Hydronamic) and Delft University of Technology. Hydronamic is the in-house engineering company of Boskalis and is closely involved in the preparation and realization of Boskalis' projects. Delft University of Technology has guided the thesis from the Faculty of Civil Engineering and Geosciences, section Hydraulic Engineering, chair Ports and Waterways. Research institute Deltares is also involved by providing the opportunity to use their fast-time simulation software.

Figure 1.1 - Satellite image of a TSHD in the basin of a temporary work channel

1.2. Problem definition and research questions

Because of the temporary use of the work channel and the well-defined design ship, it is not required to satisfy the standard nautical requirements in the design. Besides that, a work channel is used as a tool in the execution of a dredging project and therefore falls under the responsibility of Boskalis. Requirements for channel design are included in guidelines for the design of fairways and (approach) channels, made by national and international institutions. Guidelines or manuals especially made for the design of a work channel are not available. Nowadays the design of a work channel is based on the available guidelines on fairways and approach channels, combined with experience in the field of the design of work channels. The experiences of helmsmen of TSHD's using the work channels are also involved in the design procedure.

It is shown that the design of a work channel is largely based on experience and intuition, rather than on a clear guideline. Due to a shortage of time such a guideline is never investigated by Hydronamic. There also seems to be a lack of scientific insight in the factors that play a role in the design and use of a work channel.

The shortage of technical research on this subject has several consequences for the design and use of a work channel. On the one hand it can lead to a design underestimating the channel dimensions, on the other hand there is the risk of overdimensioning of the channel. Both will lead to an unnecessary increase of costs, either in dredging costs of the channel or in the lower productivity or damage of the TSHD using it. More insight in the factors which have an influence on work channels must lead to an optimization of the channel- and basin dimensions.

As a result of the problem stated above, the following central research question is formulated:

What is the optimal design of a work channel for TSHD's in an arbitrary situation?

To come to the answer of this question, the following sub-questions must be answered:

- *Which factors determine the movements of a ship in a channel and are therefore of influence on the design of a channel?*
- *What are the current design guidelines, where are they based upon and what are the differences between them?*
- *Where is the design of a work channel within Boskalis currently based upon and how does the design relate to the theory and practice?*
- *Which factors determine the movements of a TSHD in a temporary work channel and how can these factors be quantified (either based on theories or based on experiences of TSHD captains)?*
- *What is the most optimal lay-out of a work channel?*

The answer to the central research question leads to the following end-product:

The formulation of a guideline with a design tool for the integral design of a work channel used by a TSHD during the execution of dredging projects

1.3. Research approach and report outline

To find an answer to the above mentioned research questions, the following approach was followed. First of all a literature review is done to gain more insight in the theory behind channel design. Also the most commonly used design guidelines are examined and the differences between them are made clear. After that the typical characteristics of a TSHD are investigated to gain insight in the differences between a TSHD and a more conventional ship where the guidelines are based upon. Also the behavior of a TSHD in a temporary work channel is researched. The knowledge of the TSHD and its behavior in a work channel is gathered through a literature review, an analysis of constructed projects of Boskalis and by interviewing some of the TSHD captains. This combination of theory and practice has led to the formation of a new design tool to calculate the dimensions of a temporary work channel and turning basin especially made for a TSHD. To assess the use of this design tool, a fast-time simulation study for a representative case is made. The design is made by the design tool and the simulation results made it able to check the design for varying environmental influences. Finally an analysis of the influence of costs on the final design choice is made.

The report is structured according to the above mentioned research approach. In chapter 2 the design considerations for a channel are given. All the important theories used to quantify the behavior of a ship in a channel are discussed. Chapter 3 gives a thorough inventory of the most commonly used design guidelines. All the important characteristics of the design methods are given and a comparison between the several guidelines is made in a qualitative and a quantitative way. Chapter 4 is the introduction into the TSHD, giving all the typical characteristics. The analysis of projects within Boskalis involving a temporary work channel and basin is given in chapter 5. Also the interviews with the captains are included. This chapter gives an overview of the strengths and weaknesses of the currently used design method within Boskalis. Chapter 6 combines the theories and experiences to form a design tool for the calculation of a work channel for a TSHD. Chapter 7 discusses the case study that is used to assess the results of the design tool. The results of the fast-time ship simulator are analyzed in this chapter 7. Chapter 8 discusses the aspect of costs in the choices that are made in the design of a temporary work channel. A balance is made between the dredging costs and the consequences for the productivity of the TSHD for a one-way or a two-way cross-section. Chapter 9 sums up all the results of the thesis and answers the research questions that are set up in chapter 1.

2. Design considerations

The design rules on approach channels formulated in the most commonly used guidelines are all based on the interaction between ship, environment and channel. These influences must be considered in the design of a channel. All of them influence the design in their own way and are discussed in this chapter.

2.1. Design ship characteristics

The design of a channel starts with the determination of a design ship. This is mainly based on the maximum dimensions of the ship, like the length, beam and draught. Not always the ship with the largest dimensions is considered the design ship, where often the largest ships get special rules and attention to encounter or leave a port like a tidal window or tug assistance. The selection of the design ship should be based on dimensions, manoeuvrability under certain conditions and the type of cargo. This often leads to more than one design ship and it is therefore common practice that a particular design ship is used for the design of a specific dimension of the channel. The ship with the largest beam can be used to determine the channel width, the ship with the largest draught can determine the channel depth. The right design ships must lead to a situation where all the expected ships can use the channel in a safe and effective way.

Ship dimensions

The combination of the length and beam of the ship will be one of the most important parameters in the design of the channel width. Under the influence of environmental factors (wind, waves, currents) the ship makes a drift angle β between the longitudinal axis of the ship and the straight path (see Figure 2.1). This results in a wider path than the width of the ship, which must be taken into account in the design of the width and alignment of the channel. At larger drift angles, the influence of the length of the ship on the width of the path gets larger.

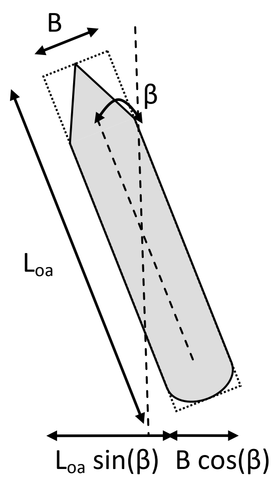


Figure 2.1 - Drift angle

The draught of the ship is mainly used to determine the depth of the channel. A certain underkeel clearance, the distance between the ships hull and the channel bed, must be taken into account. The amount of underkeel clearance will influence the manoeuvrability of the ship, as will be discussed later. Another factor influencing the manoeuvrability is the surface area of the part of the ship exposed to the wind, the so-called windage. Ships with large windage experience a larger drift angle from crosswinds. The windage of the ship depends on the geometry and the freeboard of the ship. Unloaded ships or ships with a low cargo density could have a large windage.

Manoeuvrability

As stated above it is not only important to look at the dimensions of the design ship, but also at the manoeuvrability. The basic manoeuvrability of a ship is determined by characteristics like the shape of the hull, length, beam, draught, mass, propulsive power and rudder area. In general the most important manoeuvering characteristics are the directional stability, the turning ability and the stopping ability. When a ship is directionally stable, it takes up a new straight path when it has

deviated from its initial straight path.
Even without external disturbances the ships path deviates from the theoretical straight course. This is a result of the speed of response of the ship-handler and that of the ship reacting to the rudder. This path shows a sinusoidal course in relation to the straight course and depends in general on the ships characteristics, the skills of the ship-handler and the overall visibility. The deviation from the straight path results in a wider manoeuvering lane than the ships beam, as is shown in Figure 2.2.
The turning ability varies highly among ships and depends on the dimensions, hull shape, speed and propulsion system of the ship. The draught of the design ship and the amount of underkeel clearance has a large influence on the manoeuvrability of the ship. An indication of that influence is given by the depth to draught ratio. When the ratio approaches unity (low underkeel clearance) the ship gets more directionally stable, but the manoeuvrability gets worse. In channel design this could result in a larger channel depth when more manoeuvrability, and therefore a larger underkeel clearance, is required.

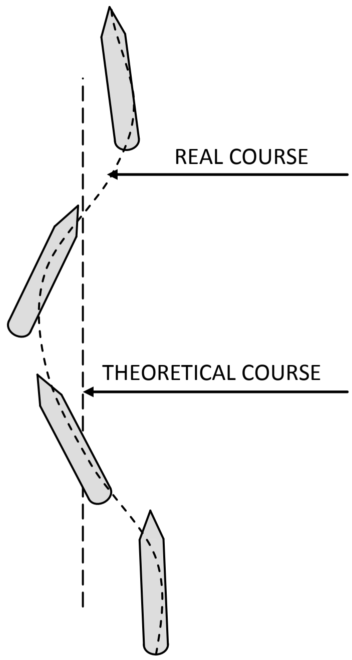


Figure 2.2 - Swept path

Ship speed

The speed of the ship influences the design of a channel in several ways. Especially in shallow waters there is a strong speed to depth relationship. This follows from analyses of the Froude Depth Number (F_{nh}), which quantifies the resistance of an object moving through water. It is defined as:

$$F_{nh} = \frac{V}{\sqrt{g \cdot h}} \quad [-] \qquad (2.1)$$

F_{nh}	*Froude depth number*	*[-]*
V	*ship speed*	*[m/s]*
g	*gravitational acceleration*	*[m/s²]*
h	*undisturbed water depth*	*[m]*

When F_{nh} approaches unity, the resistance gets too high for displacement ships to overcome with the installed power. Non-displacement ships on the other hand, like speedboats, do not have this probkem. As a result a minimum depth limit can be determined from the design ships Froude Depth Number and maximum allowable speed.
The influence of a restricted channel depth and width on the ship speed was studied by Schijf. He developed a method to determine the limiting speed based on the hydrodynamics of a ship sailing in a shallow, restricted waterway. In this method the maximum possible sailing speed is related to the ship and channel cross-section.
Also the manoeuvrability of a ship changes with the speed. In general, the manoeuvrability is better at higher speeds. Ships with bow thrusters can also reach a high manoeuvrability at low speeds. It is clear that manoeuvrability depends largely on the ships characteristics, installed power and propulsion system. The influence of environmental factors also varies with the ships speed, as will be discussed later.

Hazardous cargo

Larger risks must be taken into account when ships with cargo classified as hazardous are expected in the port. Loss of cargo, collisions or running aground of these ships can cause a large impact on the surrounding environment. In the design of the channel often an extra depth or width will be taken into account, depending on the cargo hazard level.

2.2. Environmental factors

The environmental conditions a ship is sailing in have a large influence on the handling and manoeuvrability. The most important environmental influences are discussed below.

Wind

The forces exerted by wind have a large influence on the handling of a ship. The wind acting on the superstructure causes forces in longitudinal and transversal direction and a resulting moment around the ships' centre of gravity. This forces the ship to take up an angle of leeway, moving the ship in the direction the wind is blowing to. To counteract this movement, the ship will have to navigate under a certain drift angle. In this way the exerted wind forces are compensated by the hydrodynamic resistance of the water on the ships hull. The ship will now be able to maintain its course within a certain range. The influence of wind forces on a ship depends on several ship characteristics; the shape and disposition of the superstructure, the shape of the hull, the freeboard of the ship and its speed. Also the intensity and direction of the wind with respect to the sailing direction of the ship play a large role. High freeboard and low draughts result in a heavy wind force and a low resistance by the water leading to a quick respond of the ship to the wind. Small superstructures and deep draughts are less influenced by wind. The effect of wind is greatest at low ship speed.
As seen before, a larger drift angle results in a wider swept path of the ship. Especially in areas with strong winds this effect must be taken into account in the width of the channel.

Currents

The influence of currents on the handling and manoeuvrability depends largely on the direction of the current with respect to the ship. A cross-current has a large effect on the ability to keep course, longitudinal currents influence the manoeuvrability. The channel depth also plays a role, as the ability to react on currents decreases when the depth to draught ratio approaches unity.
Cross-currents make a body of water move at a certain speed, including the area the ship is manoeuvring in. This has no effect on the manoeuvrability, but it does result in a drift sideways. In case of a constant cross-current, this movement is compensated by taking a heading somewhat into the current. Once this angle is set, no additional rudder angle is needed to keep the ship on track. When the cross-current is not constant, a gradient in the current is present. This leads to a rotation in the flow, forcing the ship to turn. In this case a certain rudder angle is required to make a counter-rotation and stay on course [22].
The result of longitudinal currents differs between a current taken at bow or at stern. When the current is taken at bow (direction of the current opposite to the direction the ship is sailing in) it has a positive effect on the manoeuvrability. When a ship travels at a speed of 7 knots against a current of 2 knots, the ships speed relative to the bottom or obstacles is 5 knots. But the speed of the rudder with respect to the water remains 7 knots, which leads to good manoeuvrability compared to the ships groundspeed. A ship traveling with the current will experience the opposite effect. In this situation the manoeuvrability corresponds to a speed which is lower than the actual speed of the ship.

Waves

In the first place waves have an influence on the design of the channel depth by causing a vertical ship motion, called heave. It also has an effect on the handling and manoeuvrability of the ship and therefore on the channel width. Every ship has a natural period of pitch and roll, determined by the ship type, dimensions and loading conditions. Figure 2.3 shows the six degrees of freedom of a ship. Pitching is the rotation of the ship around its transversal axis, rolling is the rotation around the longitudinal axis. When the natural period of pitch and roll coincide with the wave period, resonance occurs. The effect of resonance is depending on the wave period, the ship speed and the angle between the ship and wave direction. The resonance affects the stability of the ship leading to a loss of rudder control. This could result in the decrease of manoeuvrability and a drift in the wave direction. Changing speed and course could (partly) counter the effect of waves.

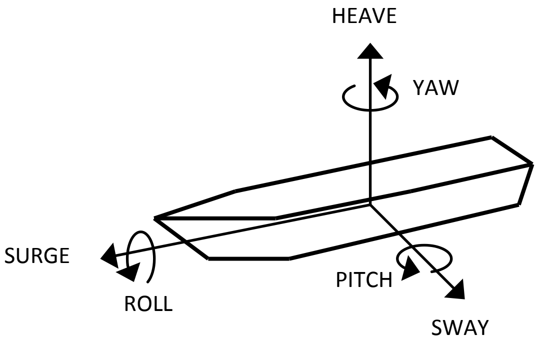


Figure 2.3 - Degrees of freedom

Tides

The influence of the tide is included in the design of a channel in two ways. First of all there is the tidal current, resulting in the effects as discussed before. Second, there is the elevation of the water level. Because of the long wavelength of the tidal wave, the influence of the wave on the handling and manoeuvrability of the ship is very small and often neglected. What should be kept in mind is the influence of the tide height in determining the design water level.

Water density

The draught of a ship depends on the density of the water in which it is traveling. A ships' draught is, in general, measured in salt water in summer conditions. When navigating into water with a lower density, the upward pressure on the ship decreases causing an increase of draught. This could be the case when traveling from salt into fresh water, and should be kept in mind when considering the channel depth.

2.3. Squat

When a ship travels through shallow water it pushes a body of water in front of the bow. This results in a return current around the hull to compensate for the water displacement of the ship. In shallow or restricted waters the return current leads to a decrease of pressure under the ships' hull. This causes a drop of the water level, varying over the length of the ship. It also leads to a vertical downward movement (heave) of the ship, called sinkage, and a rotation around the ships horizontal transversal axis (pitch), which is called trim. The combined effect of sinkage and trim due to the

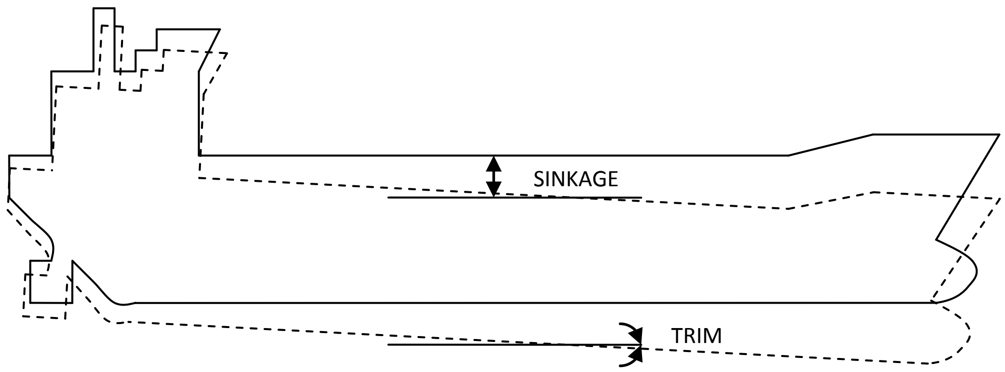


Figure 2.4 - Sinkage and trim

forward speed of the ship is called squat. Sinkage and trim cause a decrease in underkeel clearance, which can influence the steering of the ship or cause grounding.
In the past years a lot of research is done on how to predict the amount of squat in a given situation. The most important findings are discussed below [2].
In a channel, the amount of squat is depending on the ship characteristics and the configuration of the channel. The ship characteristics mainly influencing squat are the ships' draught, shape of the hull and the ships' speed. Also the length and beam of the ship are of importance. The draught and shape of the hull are taken into account by the block coefficient (C_B), which is the shape of the hull relative to an equivalent rectangular volume with the same dimensions. The block coefficient gives an idea about how much of the volume of a block, defined by the length, draught and beam of the ship, is filled by the ships' hull.
The channel characteristics are involved by means of the depth and the cross-sectional configuration. As mentioned before, squat is only of importance in shallow water with a channel depth to ship draught ratio smaller than 1.5. For the channel configuration three main types are determined (see Figure 2.5):

- unrestricted channel
- restricted channel
- canal

All three configurations are in shallow water. An unrestricted channel has no banks in the zone influencing the ship, a restricted channel is a channel with an underwater trench and a canal with emergent banks. The following width at the bottom, trench height, bank slopes and cross-sectional area are used to determine the channel influence on squat. Two of the most important parameters determining the interaction between the ship and the channel are the Froude Depth Number (F_{nh}) and the blockage factor. The blockage factor is the ratio of the submerged cross-section of the ship and the channels' wet cross-section.

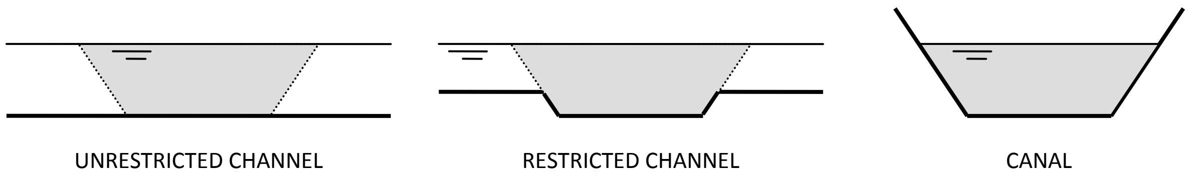


Figure 2.5 - Channel configurations

A first theoretical research on the prediction of squat is done in 1966 by Tuck. In the following years many investigations are done leading to several empirical formulas and graphical methods. The foundations are all based on field data or physical model tests, and therefore come with certain restrictions to where they can be applied. These restrictions are based on the conditions under which the theory is developed. Also, the theories are based on a single vessel sailing along the centerline of a symmetrical channel, which in practice will not always be the case. Attention must be paid to these points when applying one of these methods.

At the moment research is done on situations which deviate from the idealized conditions [4]. Head on passing encounters could lead to an increase on squat of 50% to 100%, also overtaking manoeuvres show higher values of squat. The shape of the hull of the ship also influences the squat. Ships with a flat stern at a right angle to the fore and aft centerline, a so-called transom stern, will experience more squat at the bow than ships with more streamlined sterns. Navigating with an offset and drift angle from the channel centerline also shows an increase of squat. All these influences must be kept in mind when predicting the squat. Which method must be applied depends on the ship and the channel characteristics.

2.4. Restricted water effects

Restricted depth

Navigating through a channel with a restricted depth has several consequences. The shallow water causes an increased resistance of the water on the ship leading to a reduction of speed (Froude Depth Number approaches unity). As seen before, shallow water also has an influence on the underkeel clearance of the ship due to an increase of squat. The ships manoeuvrability is affected by shallow water causing a larger turning radius, a better ability to keep course and a slightly worsened stopping ability.

Bank effects

Bank or wall effects refer to the tendency of the ship to turn towards the bank while navigating eccentrically through a channel. When a ship is navigating through the channel axis, the water flow around the hull of the ship is symmetrical. In practice this will seldom be the case, which results in a different distance between the ship and each bank. At the nearest bank a reduction of the water cross-section will take place, resulting in an accelerated flow and reduced pressure around the hull of the ship. This leads to a decrease of the water level along the ship, but due to the asymmetrical flow the water level decrease will be larger on the side closest to the bank. The difference in water

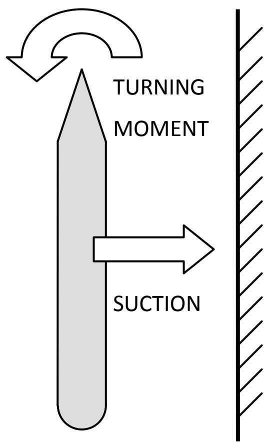


Figure 2.6 - Bank effects

level decrease results in a suction force on the ship towards the bank. The water level depression due to the return current is largest near the stern of the ship. This causes a moment turning the bow of the ship to the centre of the channel (yaw), known as the bow cushion effect, and the stern of the ship towards the bank (Figure 2.6). The rudder of the ship must be used to counter this effect. Parameters determining the bank effects are the ships speed and the distance of the ship to the nearest bank. The channel geometry is also involved in parameters like channel dimensions, slope angles and channel configuration.

2.5. Ship-ship interaction

When two ships start an encountering or overtaking manoeuvre, the ships experience some extra forces causing deviations from the straight course. These effects must be taken into account in the design of a channel with two-way traffic.

Encountering

The behavior of the ships encountering each other is mainly based on the fact that the return currents of the ships during the manoeuvre are in opposite directions. This leads to a partial, and at some point even complete, counteraction of the return currents in between the two ships. As a result the pressure reduction and accompanying water level decrease in between the ships is smaller than between each ship and the channel bank. This has consequences for the hydrostatic pressure forces acting on the ships. In general the encountering manoeuvre can be divided into four phases, determined by the interaction between the two ships and the channel banks [5]. These phases are shown schematically in Figure 2.7, where the colored arrows are the pushing or pulling forces and the black arrows are the bank effects.

1. When the two ships approach each other the ships start to push each other aside. This is an effect of the bodies of water pushed away by the bow of each ship.
2. When the bows of the ship are alongside, the ships turn away from each other. This movement is opposed by the bank suction and bow cushion effect in case of encountering in restricted channels.
3. When the bow approaches the stern of the other ship, it pushes the stern of the other ship aside. Both bows therefore tend to turn towards the centerline of the channel. In the case of a restricted channel, this movement is reinforced by the bank effects.
4. In the last phase of the manoeuvre the sterns are alongside, each stern's suction causes the sterns to turn towards the centerline of the channel. Bank effects oppose this movement.

Overtaking

The factors influencing the overtaking manoeuvre are basically the same as in an encountering situation. The fundamental difference is that this time the return current and water level depression of the two ships are in the same direction and therefore reinforce each other. This results in a larger decrease of water level between the ships than between the ship and the bank, causing the ships to get pulled towards each other. Again four phases can be distinguished [5], as can be seen in Figure 2.8. The red ship is the faster (overtaking) ship and the blue one is the slower ship.

1. When the fastest ship approaches the slower, the bow of the overtaking ship is pulled towards the stern of the ship to be overtaken.
2. Then the faster ship enters the area of water-level depression of the slower ship and gets pulled in.

3. When the ships sail alongside both ships are pulled towards each other.
4. When the stern of the overtaking ship is next to the bow of the other ship, the same situation as in phase 1 occurs. The bow of the faster ship gets pulled towards the bow of the slower ship.

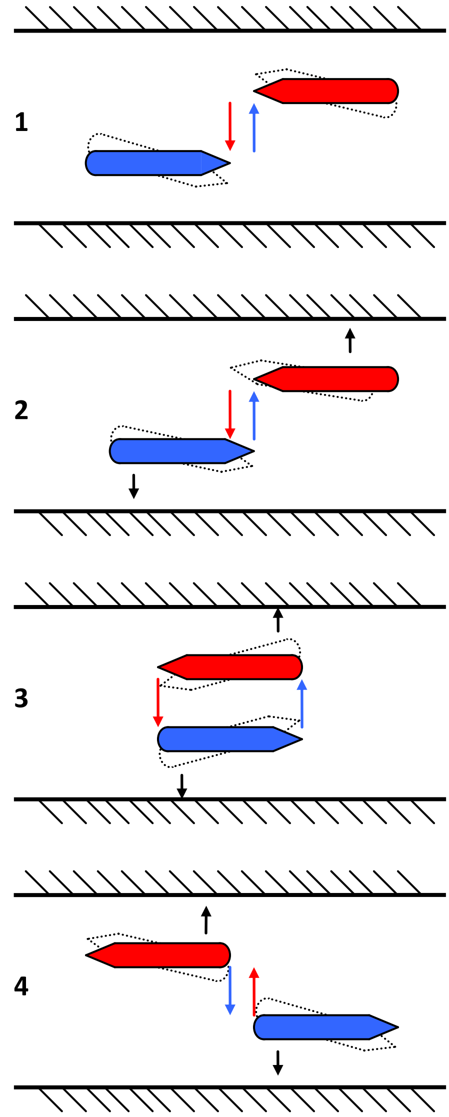


Figure 2.7 - Encountering manoeuvre

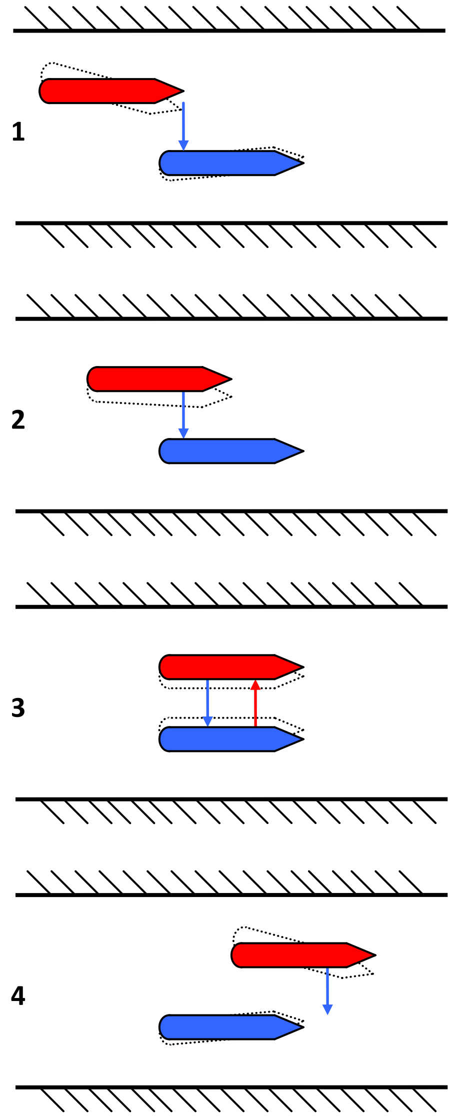


Figure 2.8 - Overtaking manoeuvre

2.6. Aids to navigation

According to the International Association of Lighthouse Authorities (IALA) a marine aid to navigation is a device or system external to vessels that is designed and operated to enhance the safe and efficient navigation of vessels and/or vessel traffic [6]. Ships navigating through a channel are dependent on the aids to navigation to determine the course. The quality of the aid to navigation therefore influences the required width in the design of a channel. Aids to navigation vary from systems on board of the ships, markings along the channels and information sent from the shore. Nowadays there are several systems used, like visual aid to navigation, radio aid to navigation, satellite radionavigation, Automatic Identification System (AIS) and Vessel Traffic System (VTS). These systems, especially the visual aids are considered in the design of a channel and often include leading

lines, buoys and traffic signals. The way they influence the design depends on the effectiveness of the visual aid which is applied. In general, more visual marks will lead to better guidance, but too many marks can lead to confusion.
The position of a ship is often determined using a global satellite navigation system. One of the most accurate systems is DGPS (Differential Global Positioning System). It is based on a global positioning system with an extra feature to increase the accuracy. A system of fixed, land-based reference stations, from which the exact position is known, is used to calculate the difference between the position determined by the GPS and the real position. This information is used to make a more accurate estimate of the position by the satellite.

3. Current guidelines

3.1. Introduction

In this chapter the most commonly used guidelines are discussed. The guidelines made by PIANC (Permanent International Association of Navigation Congresses) can be seen as the international standard, even though it was published in 1997. Several countries developed their own guidelines the last years. In the United States and Canada the guidelines are made by the USACE (United States Army Corps of Engineers) and the CCG (Canadian Coast Guard) respectively. Both are largely based on the guidelines of PIANC. The Japan Institute of Navigation developed their guidelines based on a completely different and more theoretical approach. One of the most recent and most detailed guidelines was presented by the Spanish port authorities in 2007 and is based on a mix between theory and empirical data. The guidelines for the United Kingdom are developed by the BSI (British Standard Institute). The choice of analyzing these specific guidelines is based on either the difference in approach or the differences within the same approach.

3.2. PIANC guidelines [2]

3.2.1. Introduction

In the 1960's the development of deepwater ports called for more attention on the design of approach channels. PIANC therefore set up a working group (no. 2) to research the modern design practice of approach channels, resulting in a first report published in 1973. The report was a product of PIANC and the International Oil Tankers Commission (IOTC) and still contained a lot of uncertainties due to a lack of insight and experience on the factors involved in the design. A review of the report by ICORELS (International Commission for the Reception of Large Ships) resulted in a new report in 1980. In the years following a lot of development was made in the knowledge on ship behavior, guidance systems and computer and physical modeling. Also an increase of experience on the design and use of approach channels made PIANC decide to set up a working group (no. 30) to make a new guideline [2]. The report is a co-operation between PIANC and other international marine organizations and is published in 1997. It is based on the work of earlier working groups and provides guidelines to design an approach channel for any given situation.

The design rules are most of all empirical results of research on existing channels. In the latest edition of the guideline the design rules are being updated with the help of hydrological and ship research institutions and organizations. Also a questionnaire was sent to over 45 port authorities and several other relevant bodies. Analysis of the questionnaire is used to validate the guidelines and models. With that information practical guidelines were set up.

Globally, the guideline is build up in two parts: the concept design and the detailed design. The concept design method gives a quick calculation for an initial estimate of the channel dimensions, and contains safety margins. The detailed design starts where the concept design stopped and uses it as input for a computer simulation model with more extensive and detailed data. To make a fair comparison between the different internationally used guidelines, mainly the concept design rules will be discussed as the detailed design method only gives recommendation on the input of a computer simulation.

The ongoing research on the behavior of ships in restricted channels and the development of naval architecture makes it necessary to keep updating the guidelines. PIANC working group 49 is currently developing a new guideline with advanced computer modeling. The report is expected to be published at the end of 2010. A large contribution to the guidelines will follow from the Spanish guidelines which will be discussed later.

3.2.2. Design guideline

As seen before in the chapter on design considerations, the dimensions of a channel depend on the interaction between ship, environment and channel. The guideline therefore starts with the determination of a design ship. From there on the concept design rules on depth, width, bends and alignment of the channel are given. All the influences taken into account by PIANC are discussed and some examples of channel design are given. Finally the report gives a recommendation on the development of the concept design into a detailed design.

Design ship

The guideline gives recommendations on the choice of a design ship. The ship must either have poor manoeuvrability, large dimensions, excessive windage or carry hazardous cargo. In many cases this will lead to more than one design ship. In a situation where there is no clear view on the ships calling at the port, a traffic analysis must be made to determine the design ship(s).

Channel depth

A first estimate of the channel depth is made according to Figure 3.1. Most of these factors are easy to determine and are already discussed in the chapter on design consideration. The channel depth is mainly based on the draught of the design ship, measured in salt water and summer conditions. The application of a tidal window could have an influence on the determination of the right draught. It could be the case that the ship with the largest draught has a strict tidal window, where a smaller ship is allowed to enter the port continuously and therefore determines the representative draught. For the calculation of squat the PIANC uses the method of ICORELS (1980):

$$S_b = 2.4 \frac{\nabla}{L_{pp}{}^2} \frac{F_{nh}{}^2}{\sqrt{\left(1 - F_{nh}{}^2\right)}} \quad \text{[m]} \qquad (3.1)$$

where ∇ is the ships water displacement, L_{pp} is the length between fore and aft perpendiculars and F_{nh} is the Froude depth number. This formula should not be applied for Froude depth numbers larger than 0.7 and ships with a large block coefficient. The method of ICORELS can only be used in channels configured as unrestricted shallow water (Figure 2.5).

The other considerations mentioned above are not specified further in the guideline. A rule of thumb is given for the estimation of the channel depth based on the depth to draught ratio for cases where no detailed information on the above mentioned influences is available. A minimum depth to draught value of 1.1 should be used in sheltered water, 1.3 in waves up to one meter in height and 1.5 in higher waves. For a more detailed guide to the design of the channel depth, reference is made to the PIANC report "Underkeel Clearance for Large Ships in Maritime Fairways with Hard Bottoms (1985)" [7].

This report gives a detailed description of the calculation of the required underkeel clearance of large ships and discusses the ship-related factors which influence the underkeel clearance. The report contains two different approaches on the calculation, being a deterministic and a probabilistic method. The methods are applicable on all conventional vessel types, like tankers, bulk-carriers, LNG and container ships. The factors influencing the underkeel clearance relate to the water level, design ship and channel bottom.

The response of the ship to the surroundings is included in the gross underkeel clearance, containing an allowance for draught uncertainties, water density effects, squat and influences of waves. The net underkeel clearance is the remaining safety margin in case all other influences are at a maximum. It also shows the difference between the deterministic and the probabilistic approach. The first method is a simple and fast method and uses discrete numerical values for all the influences on the underkeel clearance, supplement with a safety margin. In the calculation maximum values are used which directly leads to one of the disadvantages of this method. By using maximum values overestimation could occur and the question will arise to what extent these values could appear simultaneously. To counter this, the values are interpreted by the designer which could lead to underestimation. A clearer quantification of the variations and uncertainties of the values can lead to an optimum between safety and accessibility. This is done in the second method where the calculation of the gross underkeel clearance is based on mean values of all the influences and a probability allowance. The uncertainties, errors and variations in measurements or observations are taken into account in the probability allowance by means of statistical parameters. In this way for a given channel depth the probability of grounding can be calculated. Reversely, the underkeel clearance can be calculated for a given probability of a ship running aground. As a disadvantage the report states that this method is still in its infancy but, given the report dates from 1985, a further evaluated version of this method can not be ignored nowadays.

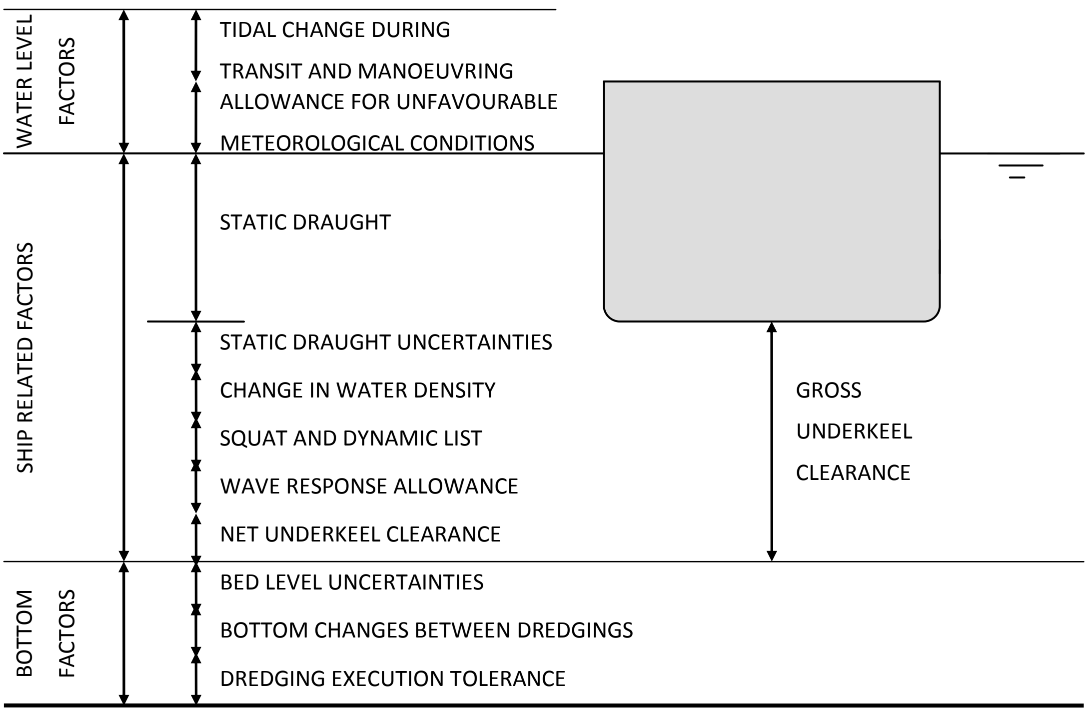


Figure 3.1 - Channel depth according to PIANC [7]

Channel width

For the design of the channel width, there is a more specific method in the PIANC guideline [2]. All sections of the channel width are added up according to the following formula. A distinction is made between a one-way and a two-way channel:

$$W_{one-way} = W_{BM} + \sum_{i=I}^{n} W_i + W_{Br} + W_{Bg} \qquad [m] \qquad (3.2)$$

$$w_{two-way} = 2w_{BM} + 2\sum_{i=I}^{n} w_i + w_{Br} + w_{Bg} + \sum w_p \qquad [m] \qquad (3.3)$$

As can be seen, the width of the one-way channel cross-section is the sum of the basic manoeuvring lane (w_{BM}), additional widths for straight channel sections (w_i) and additional width for bank clearance on the 'red' side (w_{br}) and 'green' side (w_{bg}) of the channel. In case of a two-way channel the influence of the basic manoeuvring lane and straight channel sections are taken twice and an additional width for passing distance (w_p) is added. The basic manoeuvring width is determined by the swept path of the ship and takes the manoeuvrability into account. The influences of the ships' speed, environmental factors and channel characteristics are included in w_i. A buffer for the bank effects and ship-ship interaction are included in w_{br}, w_{bg} and w_p.
The PIANC report provides 4 tables with empirical based parameters to estimate the factors in these formulae. All parameters are multiples of the design ships' beam. A distinction is made between a main approach or inner channel, which lies in relatively sheltered water and a seaway or outer channel, in open water. The main difference is the exposure to wind, waves and currents in the outer channels which is not of any significance in the inner channel.
The first table determines the basic manoeuvring lane and is based on the ship manoeuvrability (Table 3.1). As discussed before the manoeuvrability of a ship depends on a lot of factors and is therefore hard to classify. The report gives a short introduction into some of the factors influencing the manoeuvrability but does not come up with a specific guideline on how to classify the design ship based on the characteristics.

Table 3.1 - Basic manoeuvring lane according to PIANC [2]

Ship manoeuvrability	good	moderate	poor
Basic manoeuvring lane (w_{BM})	1.3B	1.5B	1.8B

The additional width for straight channel sections can be determined using Table 3.2. Several influences discussed in the design considerations are taken into account by PIANC. One of the main influences is the vessel speed. First of all an extra channel width is taken into account for fast vessels (higher than 12 knots) because of the extra risks this speed brings. The effects of the vessel speed on the environmental influences are taken into account by sub-dividing these categories into different speed-classes.
The influence of wind is only taken into account in the direction perpendicular to the ships longitudinal axis (cross-wind). The wind speed is divided into three classes; mild, moderate and severe. The windage, which is an important factor in the reaction of the ship to the wind, is not included. The prevailing currents are split up in cross and longitudinal direction and are also divided into three classes. For the longitudinal currents it is remarkable that there is no distinction between a current with and a current against the ships direction. Currents in the same direction as the ship have a negative influence on manoeuvring, where currents in the opposite direction make the manoeuvrability better. For both wind and currents the additional width increases as wind or current speed gets higher and vessel speed gets lower. The influence of waves is determined by the wave height and the wavelength. Three categories are made based on the significant wave height (H_s), wavelength (λ) and the ship length. Waves with a wave height above one meter and a wavelength smaller than the design ship are not taken into account, where this situation can occur frequently (of course depending on the type of port and location). The additional width of the channel according to

PIANC increases as wave height, wavelength and vessel speed increases.
The last factors taken into account by PIANC are the aids to navigation, the channel characteristics and the ships' cargo. Depending on the type of aids to navigation and the visibility at the location an additional width must be taken into account. The depth of the waterway also has an influence on its width. In shallow water the directional stability increases but the ship will react slowly on changes of course. This is included in the table by an additional width for depth to draught ratios smaller than 1.5. The type of bottom material also plays a role, as a muddy bottom will make the manoeuvrability of the ship worse. On the other hand a rough and hard bottom will increase the amount of damage in case of grounding. The report takes the latter of these into account.

Table 3.2 - Additional widths for straight channel sections according to PIANC [2]

Width (w_i)	Vessel speed	Outer channel	Inner channel
(a) Vessel speed (knots)			
fast > 12		0.1B	0.1B
moderate > 8 – 12		0.0	0.0
slow 5 – 8		0.0	0.0
(b) Prevailing cross wind (knots)			
mild ≤ 15 (≤ Beaufort 4)	all	0.0	0.0
	fast	0.3B	-
moderate > 15 – 33 (> Beaufort 4 – 7)	mod	0.4B	0.4B
	slow	0.5B	0.5B
	fast	0.6B	-
severe > 33 – 38 (> Beaufort 7 – 9)	mod	0.8B	0.8B
	slow	1.0B	1.0B
(c) Prevailing cross current (knots)			
negligible < 2	all	0.0	0.0
	fast	0.1B	-
low 0.2 – 0.5	mod	0.2B	0.1B
	slow	0.3B	0.2B
	fast	0.5B	-
moderate > 0.5 – 1.5	mod	0.7B	0.5B
	slow	1.0B	0.8B
	fast	0.7B	-
strong > 1.5 – 2.0	mod	1.0B	-
	slow	1.3B	-
(d) Prevailing longitudinal current (knots)			
low ≤ 1.5	all	0.0	0.0
	fast	0.0	-
moderate > 1.5 – 3	mod	0.1B	0.1B
	slow	0.2B	0.2B
	fast	0.1B	-
strong > 3	mod	0.2B	0.2B
	slow	0.4B	0.4B
(e) Significant wave height H_s and length λ			
$H_s \leq 1$ and $\lambda \leq L$	all	0.0	0.0
	fast	≈ 2.0B	
$3 > H_s > 1$ and $\lambda = L$	mod	≈ 1.0B	
	slow	≈ 0.5B	
	fast	≈ 3.0B	
$H_s > 3$ and $\lambda > L$	mod	≈ 2.2B	
	slow	≈ 1.5B	
(f) Aids to navigation			
excellent with shore traffic control		0.0	0.0
good		0.1B	0.1B
moderate with infrequent poor visibility		0.2B	0.2B
moderate with frequent poor visibility		≥ 0.5B	≥ 0.5B
(g) Bottom surface			
if depth ≥ 1.5T		0.0	0.0
if depth < 1.5T			
smooth and soft		0.1B	0.1B
smooth or sloping and hard		0.1B	0.1B
rough and hard		0.2B	0.2B
(h) Depth of waterway			
≥ 1.5T		0.0	0.0
1.5T – 1.25T		0.1B	0.2B
< 1.25T		0.2B	0.4B
(i) Cargo hazard level			
low		0.0	0.0
medium		≈ 0.5B	≈ 0.4B
high		≈ 1.0B	≈ 0.8B

When two ships encounter each other, it affects the stability of the ships. The third important table in the PIANC report gives the parameters taken into account for this effect, shown in Table 3.3. In the calculation of the width for passing distance the beam of the largest ship must be used according to PIANC, whether it is the design ship or not. For the effect of a ship overtaking another, the values of the table must be increased by 50%. The channel depth has an influence on the passing and overtaking effects but is not included in the table.

Table 3.3 - Additional width for passing distance in two-way traffic according to PIANC [2]

Width for passing distance (w_p)	Outer channel	Inner channel
Vessel speed (knots)		
fast > 12	2.0B	-
moderate > 8 – 12	1.6B	1.4B
slow 5 – 8	1.2B	1.0B
Encounter traffic density		
light	0.0	0.0
moderate	0.2B	0.2B
heavy	0.5B	0.4B

To reduce the bank effects to a controllable minimum a distance between the manoeuvring lane and the toe of the underwater slope of the channel is taken into account. The parameters are shown in Table 3.4 and are based on the influence of the vessel speed and channel bank characteristics. Again the depth of the channel, which also influences the bank effects, is not included.

Table 3.4 - Additional width bank clearance according to PIANC [2]

Width for bank clearance (w_{br} or w_{bg})	Vessel speed	Outer channel	Inner channel
Sloping channel edges and shoals:			
	fast	0.7B	-
	moderate	0.5B	0.5B
	slow	0.3B	0.3B
Steep and hard embankments, structures:			
	fast	1.3B	-
	moderate	1.0B	1.0B
	slow	0.5B	0.5B

Bends and manoeuvring areas

Extra attention must be paid to the bends connecting two straight legs of a channel. The swept path of a ship in a bend is wider than its beam and depends largely on the manoeuvrability of the ship. PIANC provides a graphical method to determine a value for the rudder angle and the width of the swept path in a bend. The figures are based on a single screw, single rudder container ship, so they can not be applied in all cases. Specific design rules on bend width and radius are not included in the report. Only a general rule is given, which says that the width of the channel in a bend should always be larger than that of a straight section. For the design of channel bends the report recommends a manoeuvring simulation in the detailed design procedure.

The design of berthing and swinging areas depends on the specific situation and manoeuvre to be carried out. Design rules are therefore hard to give and the PIANC report again refers to the detailed design and specific simulation studies. A rule of thumb is given for the manoeuvre of ships swinging through 180%. This requires a swinging area consisting of a circle with a diameter of 1.8 to 2.0 times the length of the ship.

Alignment

The design of the channel alignment depends completely on the surroundings and environmental conditions of the port. It is therefore impossible to make a specific guideline on the design of the alignment. The following general design considerations are included in the concept design method of PIANC. First of all the channel designer must strive for the shortest channel length possible. An approach channel always brings risks of grounding or collision which must be kept at a minimum. Also the execution and maintenance costs are increasing with the channel length. From the costs point of view it is also important to avoid obstacles and areas of accretion, which could result in considering a higher channel length. The channel alignment should consist of straight legs connected by bends. The bends must be as smooth as possible and should be avoided close to the port entrance. In between the bends a transition zone of five times the ship length should be taken into account in the idealized case. It is possible for each straight leg to have its own cross-section dimensions and navigation speed. Currents, winds and waves in the direction perpendicular to the channel should be minimized as much as possible. PIANC recommends taking these considerations into account in the concept design phase and evaluating the design with a ship simulation study.
The PIANC report gives a short recommendation with respect to the design of a basin. The basin should be designed as an area sized as a circle with a diameter of 1.8 to 2.0 times the ship length.

3.2.3. Evaluation

The guideline concludes with an analysis of existing approach channel widths. 26 approach channels are studied to check the reliability of the PIANC concept design rules. The results of this study show a good correlation with a slight overestimation of the width by the guideline. The cause of this can be found in the fact that a very general design is made by the concept design rules. In practice there always seems to be a difference between the used design ship and the actual maximum allowable ship visiting the port. Special regulations in the port for the largest vessels are not taken into account in the design. Another cause is the higher safety standards applied by PIANC.

3.3. USACE guidelines [9]

3.3.1. Introduction

The coastal engineering manual provided by USACE contains a complete guideline for every coastal engineering project, divided into five parts. “Coastal Engineering Manual, Part 5, Chapter 5” contains the general design criteria for navigation projects. For the engineering of approach channels the engineering manual “Hydraulic Design of Deep-draft Navigation Projects” is also of importance. In 1999 both reports where evaluated in a technical note on deep-draught coastal navigation entrance channel practice [8]. It concluded that the influence of coastal conditions and ship speed were not included in an accurate way, leading to a very conservative design. Also large differences between the USACE guidelines and international standards, like PIANC [2], were found. The ongoing developments on measurement and modelling techniques resulted in an update of the guidelines presented in 2006 [3] and 2008 [9]. The guidelines are based on research, experience and project studies. Navigation channels worldwide have been examined with real-time simulators to form the guidelines.

3.3.2. Design guideline

Before the actual design rules are given the report handles the preparation of a navigation project: vessel requirement and design ship determination, data needs and data collection techniques and an economic analysis. The determination of a design ship is similar to the procedure in the PIANC guideline [2]. The results of the ship and environmental analysis are used in the design of the channels depth, width and alignment. The guideline makes a difference between deep draught navigation channels with a channel depth larger than 4.6 meters, and shallow draught navigation channels with a depth smaller than 4.6 meters. Another distinction is made in channel configurations between an unrestricted channel (fairway), a restricted channel (trench) and a canal (see Figure 2.5).

Channel depth

The determination of the depth of the channel is quite similar to the procedure in other guidelines. The distance between the mean low water level and the channel bed level includes the following allowances:

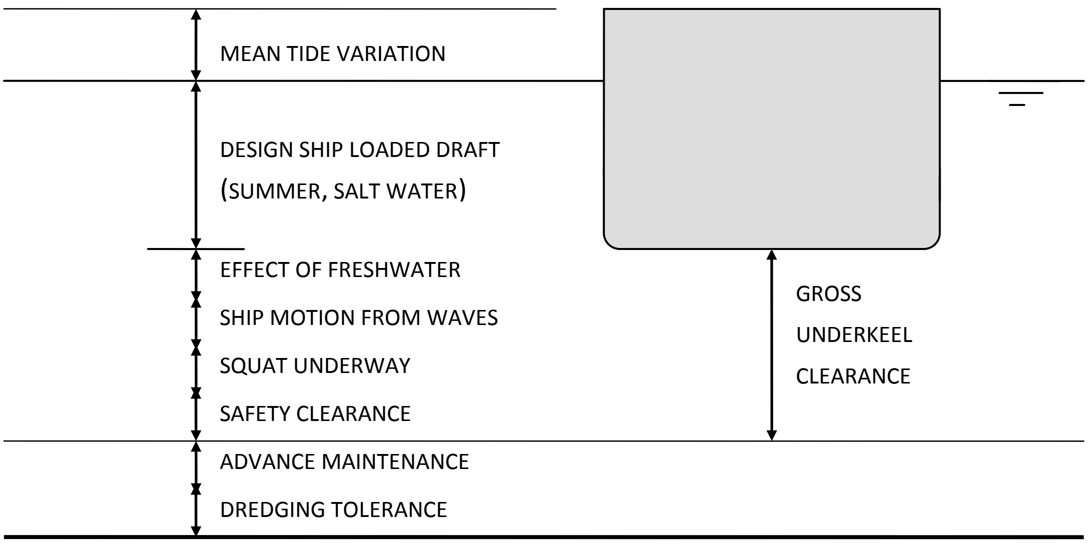


Figure 3.2 - Channel depth according to USACE [9]

The design ship loaded draught should be determined in salt water and summer conditions. The effect of density differences in fresh or brackish water are taken into account by a percentage of the static draught. For the increase of draught between ocean and brackish water of half the salinity 1.3% should be taken into account with a maximum of 0.15 meter. The difference between ocean and fresh water leads to an increase of 2.6% or a maximum of 0.3 meter. These percentages are based on a unit weight of 1025.84 kg/m^3 for salt water and 998.98 kg/m^3 for fresh water.
The reaction of a ship to waves depends on several factors. The wave characteristics, ship properties, channel dimensions and configuration, wind, currents and pilot strategy all contribute to the vessels motion. Also the direction of the waves with respect to the ships course has a large influence. The manual emphasizes that it is very hard to make a simple analytical estimation of the ships reaction to waves and the resulting allowance on the channel depth. Therefore it recommends making an estimation based on studies on ship response, real-time simulation, physical models and on-board ship measurements. For a first indication the manual refers to the rules of thumb made by PIANC [2]:

$$\frac{h}{T} \geq 1.3 \quad \text{for } H \leq 1\text{m} \qquad\qquad \frac{h}{T} \geq 1.5 \quad \text{for } H > 1\text{m} \tag{3.4}$$

The manual provides a short introduction on the phenomenon of ship squat and provides a method for prediction. The method is based on research by Norrbin (1986):

$$Z = 0.01888 \cdot C_b \frac{B}{L_{pp}} \frac{T}{h} V^2 \qquad [\text{m}] \tag{3.5}$$

The maximum ship squat is given by Z and is based on the ships beam (B), length between perpendiculars (L_{pp}), draught (T) and channel depth (h), all given in meters. The ships speed (V) should be entered in kilometres per hour and is included quadratic. The method should only be applied for Froude depth numbers smaller than 0.4 and is therefore rather limited in its application.
The above mentioned factors can be predicted by calculations. To ensure safe navigation a safety clearance is added to these factors to arrive at the gross underkeel clearance. The safety clearance depends on the type of bottom; for a hard bottom (rock, consolidated sand or clay) 0.9 meters is used, for soft soils 0.6 meters.
The exact level of the channel bed is also subject to some uncertainties. During the construction of the channel the dredging works always lead to some inaccuracies of the bed level. This is taken into account in the channel depth by adding a dredging tolerance of 0.3 to 0.9 meters. In between the maintenance dredging events sedimentation of the channel bed occurs. An extra safety margin to maintain navigation in this period is added by the factor advance maintenance. A depth of 0.6 to 0.9 meters is added. These last two factors are influenced by the environment and management of the channel. More exact values of these factors should follow after further research.
The influences of trim and shallow water effects are not taken into account by USACE. The conditions determining the ships trim are largely based on operational decisions and are therefore very difficult to quantify in the design of the channel depth. The same holds for the shallow water effects which are highly depending on the ship and channel characteristics.

Channel alignment and width

The USACE provides some recommendations on the design of the channel alignment. The channel should be aligned with natural channels as much as possible to minimize the dredging works. Also

the directions of wind, waves and currents must be included in the design of the alignment. Bends and turns should be avoided as much as possible, straight sections with a minimum length of five times the design ship length are preferred.
The guideline makes a distinction between inner channels and entrance channels. The first type contains protected waters and harbour areas, the second apply to waters exposed to strong waves and currents. The width of an inner channel is mainly based on the traffic pattern in the channel, one-way or two-way, and the dimensions of the design ship. Also the shape of the channel cross-section, the speed and direction of currents and the characteristics of the aids to navigation should be taken into account according to the manual. The width of the channel is defined as the distance between the side slopes of the channel at its design depth. First of all the manual gives a traditional method to determine the channel width. Empirical results are given to determine the basic manoeuvring lane, bank clearance and ship clearance. For a one-way channel the width contains the basic manoeuvring lane and twice the bank clearance. Another manoeuvring lane and a ship clearance width are added for a two-way channel. The empirical factors are all multiples of the design ships beam, and are presented in Table 3.5.

Table 3.5 - Traditional criteria for channel width according to USACE [9]

Vessel controllability	Very good	Good	Poor
Straight manoeuvring lane	1.6B	1.8B	2.0B
Ship clearance	0.8B	0.8B	0.8B
Bank clearance	0.6B	0.6B	0.6B

A channel width calculated with this method gives a very conservative design. All influences are taken into account by choosing a level of vessel controllability. In 1998 USACE developed a new design method based on new ship simulator studies. This resulted in a more detailed table with empirical factors based on ship properties, currents and channel characteristics (Table 3.6). For situations with currents above 3 knots the manual recommends a simulation study. In situations when ice is present in the channel, the handling of the ship is influenced largely. In this case a 50 to 100% width increase should be taken into account. Also the channel depth must be increased by an extra standard wave allowance.

Table 3.6 - Criteria for channel width according to USACE [9]

One-way traffic, constant cross-section, best aids to navigation			
Maximum current	Unrestricted channel	Canal	Restricted channel
0.0 to 0.5 knots	3.0B	2.5B	2.75B
0.5 to 1.5 knots	4.0B	3.0B	3.25B
1.5 to 3.0 knots	5.0B	3.5B	4.0B

One-way traffic, variable cross-section, average aids to navigation			
Maximum current	Unrestricted channel	Canal	Restricted channel
0.0 to 0.5 knots	3.5B	3.0B	3.5B
0.5 to 1.5 knots	4.5B	3.5B	4.0B
1.5 to 3.0 knots	5.5B	4.0B	5.0B

Two-way traffic, constant cross-section, best aids to navigation			
Maximum current	Unrestricted channel	Canal	Restricted channel
0.0 to 0.5 knots	5.0B	4.0B	4.5B
0.5 to 1.5 knots	6.0B	4.5B	5.5B
1.5 to 3.0 knots	8.0B	5.5B	6.5B

The tables given above are used for the design of an inner channel. The design of an entrance channel is much more complicated due to the larger influence of the environmental conditions. The manual therefore refers to the table with the conservative values (Table 3.5) for a first design of an entrance channel. This of course gives a very global design and therefore the manual recommends making a detailed design based on physical model studies, simulations and field measurements.

The bends in between the straight legs of a channel should be as wide as possible. The reaction of the ship on a turn leads to an increase of the swept path, which must be taken into account by an additional width. Table 3.7 provides factors to increase the width in a turn, depending on the turn angle and the design radius (R) to ship length (L) ratio. The resulting value of the design radius represents the radius of the channel curve from the channel centre line to the center of the curvature. The length and radius are both in meters.

Table 3.7 - Recommended channel turn configurations [9]

Turn angle (degrees)	R/L	Turn width increase factor
0-10	0	0
10-25	3-5	2.0B – 1.0B
25-35	5-7	1.0B – 0.7B
35-50	7-10	0.7B – 0.5B
>50	>10	0.5B

The USACE guideline gives a description of the design of a turning basin. The dimensions are based on the manoeuvrability of a large ship with pilot and tug assistance. The area of the turning basin is a circle with a minimum diameter of 1.2 times the ships length. In case of a current with a speed of 0.5 to 1.5 knots active in the area, the diameter increases to 1.5 times the length. With currents above 1.5 knots the guideline recommends to make a design based on a simulation study.

3.3.3. Evaluation

Comparing the USACE guideline [9] with the PIANC guideline [2] shows a similarity in the used method. Both are based on data gained from intensively used channels and model tests, and give numerical values to determine the depth and width of a channel. It is remarkable that the USACE guideline provides a very global design for an outer channel, neglecting a lot of important design considerations. It is therefore a very conservative design method.

3.4. Japan Institute of Navigation guidelines [1]

3.4.1. Introduction

Before the "Design Standard for Fairway in Next Generation" [1] was published, the influence of the design ship characteristics and weather and sea conditions were not used in the design of approach channels near the Japanese ports. This led to a request of the Japanese government to analyze the world-wide used guideline of PIANC [2]. Approach channels to Japanese ports were designed with these guidelines and calculations on the manoeuvrability were made. The conclusion of this analysis was that the rules can not be applied in the Japanese cases. The researchers stated that the PIANC rules are simply an summation of influencing elements and are not founded on a clear scientific basis. The rules are also more to be applied on the European, longer channels. In 2003 the Japan Institute of Navigation (standard committee) and the Ministry of Land, Infrastructure and Transport (National Institute for Land and Infrastructure Management, Port and Harbour Department) presented their design standard for approach channels in Japan [1]. The report still has no final character as it is the goal of the Japanese government to keep updating the guidelines.

3.4.2. Design guideline

The guideline starts with emphasizing the difference between navigating in deep, unrestricted waters and navigation in restricted channels. Shallow water effects and heavy traffic often result in alternations to the ships course, having their influence on the design of a channel. The report only treats the design of the channel depth, width and alignment. Because of the early state of the report all design rules are given in a very brief format.

Channel depth

The report makes a distinction between a design without and with a clearly specified design ship. The first method gives a quick first estimate, the second gives an extensive design method. When there is no specified design ship, the depth of the channel only depends on the maximum draught of a ship moored at a berth in still water. The design depth varies between 1.10 and 1.20 times that draught, given the presence of swell inside the harbour basin. When the design ship is well specified the depth follows from equation 2.6.

$$D = T + D_1 + \max\left(D_2, D_3\right) + D_4 \qquad \text{[m]} \qquad (3.6)$$

The factors determining the design depth (D) are the max draught (T) and squat (D_1) of the design ship, the maximum influence of either bow sinking (D_2) or bilge keel sinking (D_3) due to wave response and a depth allowance (D_4). The report further recommends keeping the effects of tides, accuracy and nature of the bottom and pressure and density differences in mind but does not give a clear design rule.

The squat is predicted by the method of Dr. Yoshimura (1986):

$$D_1 = \left[\left(0.7 + \frac{1.5T}{h}\right)\left(\frac{C_b}{L_{pp}/B}\right) + \left(\frac{15T}{h}\right)\left(\frac{C_b}{L_{pp}/B}\right)^3\right]\frac{V^2}{g} \qquad \text{[m]} \qquad (3.7)$$

The formula holds for restricted and canal type channels and gives an estimate for the squat at the bow of the ship. It includes the design ship by its speed (V), draught (T), length (L_{pp}) and block coefficient (C_b) and the channel configuration by its depth (h).
The reaction of a ship to waves causes a heaving, pitching and rolling motion. The combination of heave and pitch results in sinking of the bow and therefore a reduced underkeel clearance. According to the guideline this influence is only of importance if the wavelength is larger than 0.45 times the ship length. An explanation of that factor is not given. The guideline presents a graphical method to determine the value of D_2 for a given wave amplitude, wave length and angle of the wave according to the ship. The method is based on experimental data following from Japanese research. Sinking of the bilge keel of the ship is a result of a heaving and rolling motion due to waves. This motion occurs when the natural period of roll of the ship approaches the meeting period of the design ship and the wave. The design guide provides a formula, based on the research of Dr. Honda, to calculate the resulting decrease of underkeel clearance (D_3). It depends on several wave and ship characteristics like significant wave height, wave slope angle, ships beam, ships rolling angle and the encountering angle between the ship's head and the wave direction. The ships motions can occur at the same time, but their resulting maximum sinking can not. Therefore the maximum of the resulting depressions is taken into account, instead of adding them up.
Because of the shallow water effects occurring in a channel, an extra depth allowance (D_4) is used. The report prescribes an extra depth of 5% of the draught of the design ship, with a minimum of 0.5 meters.

Channel width

Again the report makes a difference between the situation with and without a specific design ship. When the design ship is not clearly defined the width of a one-way traffic channel should be at least 0.5 times the overall length of the ship using it. It is recommended to apply extra safety measures up to a width of 1 time the overall length. In a two-way channel the minimum width is between 1.0 and 2.0 times the overall length of the ship, depending on the length of the channel and the traffic intensity.
For the situation with a clearly defined design ship the report provides some formulas to determine the channel width. Like in other design guidelines the channel width contains a basic manoeuvering lane and 2 times a bank clearance in case of one-way traffic. In two-way channels an extra ship clearance width is added.
The basic manoeuvering lane is split up into a width to counter environmental influences and a width to take the deflection from the theoretical course into account.
The effects of wind and currents are determined by the angle of the ship due to these external influences. These can be divided into an angle to counter the effect of wind (β_1) and currents (β_2) on the ship and an angle to counter drift sideways (γ). The drift angle following from wind depends on the characteristics of the wind and the design ship, resulting in a rudder angle to compensate the influence of wind. The design guide provides tables to determine the accompanying drift angle for several ship types. The influence of currents is calculated by the following formula including the ship speed (V) and current speed (V_c):

$$\beta_2 = \arctan\left(\frac{V_c}{V}\right) \quad \text{[dgr]} \qquad (3.8)$$

Using the total angle ($\beta = \beta_1 + \beta_2$) and the overall length of the design ship (L_{oa}) results in the extra channel width due to wind and currents:

$$W(\beta) = L_{oa} \cdot \sin(\beta) + B \cdot \cos(\beta) \qquad \text{[m]} \qquad (3.9)$$

While navigating through a channel a ship makes a yawing motion resulting in a drift sideways. This motion is a result of the ships characteristics and can be calculated using the ship speed (V), maximum yawing angle (ϕ_0) and yawing period (T_y). The maximum motion sideways is given by:

$$W(y) = \frac{1}{4} \cdot V \cdot T_y \cdot \sin(\varphi_0) \qquad \text{[m]} \qquad (3.10)$$

Because of the yawing motion around the ships longitudinal axis, this extra width should be taken into account on both sides of the ship. All the influences above will lead to the first part of the basic manoeuvring width:

$$W_m(\beta, y) = W(\beta) + 2W(y) = L_{oa} \cdot \sin(\beta) + B \cdot \cos(\beta) + \frac{1}{2} \cdot V \cdot T_y \cdot \sin(\varphi_0) \text{ [m]} \qquad (3.11)$$

The ability to keep a steady course is largely influenced by the navigational aids and is taken into account by the design guide in the factor $W_m(\alpha)$. A more accurate aid to navigation results in a smaller value of $W_m(\alpha)$. The design guide describes several systems like the use of buoys on both sides of the channel, guiding lights ashore and the combination of radar and buoys. It also gives recommendations on the use of GPS and D-GPS. The influence of such systems results in a value for the deflection of the ship from the straight course, which should be added to both sides of the ship in the determination of the channel width. The total width of the basic manoeuvring lane therefore is:

$$W_m = W_m(\beta, y) + 2 \cdot W_m(\alpha) \qquad \text{[m]} \qquad (3.12)$$

The deflection of course due to bank effects must be minimized in such a way that a maximum rudder angle of 5 degrees should be enough to counter these effects. Therefore a distance between the basic manoeuvring lane and the bank (W_b) is taken into account. The distance depends on the force resulting from the bank suction effect and the moment resulting from the bow cushion effect. The design guide provides figures to determine the distance for a given force, moment and ship length. The figures are based on the theory of Dr. Kijima and are based on a bank configuration of a vertical wall reaching above the water level. This is not always the case and therefore the design guide provides a correction factor which takes the influence of the slope angle and the water depth outside the channel into account.

For a channel containing two-way traffic an additional ship clearance must be added to the channel width. The interaction of two ships encountering or overtaking each other results in a drift angle of both ships. This must be compensated and the design guide again allows a maximum rudder angle of 5 degrees to do this. The drift and rudder angle result in a minimum distance between the two ships. The determination of this distance is comparable to the method used for the bank effects. The forces and moments resulting from the interaction are used in a graphical method together with ships length.

Alignment

The alignment of the channel is discussed briefly in the design guide. Only some recommendations are given. A formula for the calculation of the radius of a turning circle is given, based on the manoeuvrability, length, rudder angle and speed of the ship. Also the angle between two straight sections should not exceed 30 degrees. For more information and design rules on the alignment of a channel, the design guide refers to the PIANC guidelines [2].

3.4.3. Evaluation

The Japanese guideline shows a completely different approach on channel design as seen in the guidelines made by PIANC and USACE. The Japanese guideline provides design rules in the form of formulae and graphs, not in numerical values. The design rules are based on Japanese research on ship hydrodynamics and have a more scientific background. The Japanese guideline does not contain any rules on the design of a turning basin.

3.5. Spanish Port Authority guidelines (ROM) [10]

3.5.1. Introduction

In 1987 the ROM-program (Recommendations for Maritime Works) started with assigning the first technical committee on behalf of the Spanish government. The goal of the program is to provide reports on the latest, advanced technologies in maritime works. Eventually the reports will serve as guidelines for designers, engineers and constructors in the maritime sector. Since the publication of the first recommendation in 1990 several reports appeared and have been updated.
The guidelines for the design of the maritime configuration of ports, approach channels and habour basins are included in ROM 3.1-99 [10], published in 2007. The guidelines are drawn up under supervision of the Spanish port authorities (Puertos del Estado) and are used in port design worldwide. To reach a safe and reliable design the factors influencing the manoeuvrability of a ship are taken into account from 2 points of view: the ship characteristics and the physical environment.

3.5.2. Design guideline

The ROM provides a very detailed guideline, including not only approach channels and basins but also harbour entrances, manoeuvring areas, anchorage, outer harbours, quays, emergency areas and special facilities.
The guideline starts with a thorough explanation of the ships manoeuvring characteristics and the influence of external actions on a ship. From that background the guideline gives information on navigation and manoeuvring of a ship resulting in the requirements of the channels cross-section and layout.

Channel depth

The channel depth is built up in 3 parts. The first part include the vessel related factors and result in the lowest level any point on the vessel can reach according to the ship properties, waves, currents and wind. The second part consists of the water level related factors like tides and resonance phenomena resulting in the design water level. The last part of the channel depth is the seabed related factors. Figure 3.3 shows a schematization of the channel depth.
The ship related factors starts with the static draught of the design ship. An increase of depth due to water density changes can be added depending on the situation. The guideline also gives a recommendation on the increase of draught due to an unevenly distributed load on the ship. Depending on the ship type this factor varies between 0.0015 and 0.0025 times the length of the design ship. For the prediction of squat the guideline uses the empirical formula of Huuska (1976) and Guliev:

$$s_b = 2.4 \frac{\nabla}{L_{pp}^{\ 2}} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}} K_s \quad \text{[m]} \qquad (3.13)$$

This formula shows large resemblance with the formula of ICORELS (1980) used by PIANC [2] but has a correction factor K_s to include restricted channels and canals.
The determination of the channel depth continues with the motions of a ship caused by waves. The response of the ship is determined by the response amplitude operator, which gives the ratio between the vertical motion of the ship and the wave height. A table with the resulting vertical displacement for a given ship length and wave height is included in the guideline.

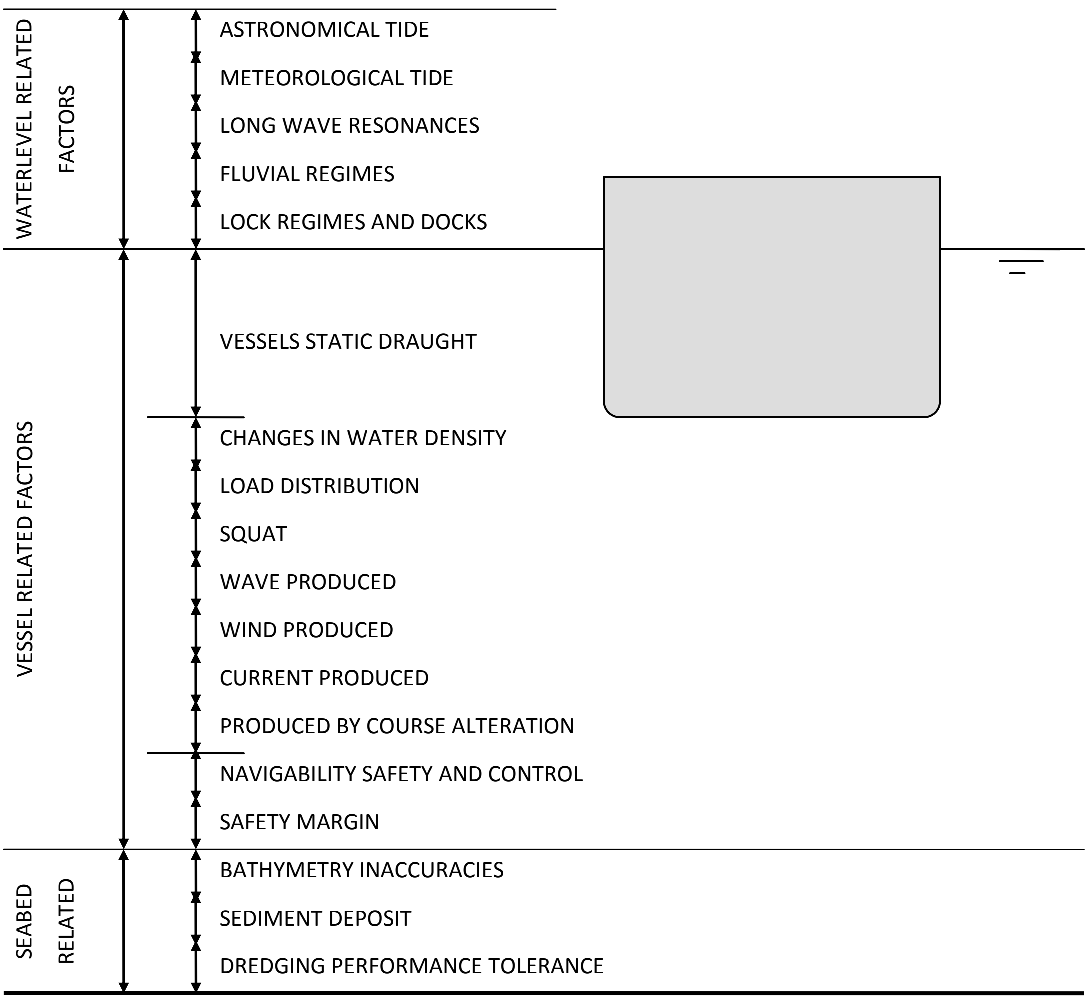


Figure 3.3 - Channel depth according to ROM [10]

The influence of wind and currents on a ship and its reaction to alterations of course causes a rotation of the ship. This leads to a heeling motion and results in an additional draught. The guideline provides formulae to determine the rotation and extra draught in these cases, for flat bottomed ships. The last factor taken into account is a safety margin to maintain navigation control in case all other factors are at their maximum value. A table is given where the margin can be found for a given ship type, bottom material and ship speed.

When all factors are known, the ship related depth can be calculated according to two methods. The first method provides the draught at the ships centerline, the second method at the ships port and starboard sides. The largest value of the two should be taken into account.

The design water level is determined by the water level related factors. First of all the astronomical tide is taken into account. The guideline provides information on the tidal wave in Spanish waters and gives recommendations on the application of a tidal window. The influence of wind and changes in atmospheric pressure are added by the meteorological tide. In case of a confined enclosure the guideline recommends to study the effect of long wave occurrence due to resonance.

The measurement of the seabed bathymetry always results in a certain inaccuracy. The error could be in the recording equipment, but also in the motion caused by waves while taking measurements. A margin for this effect must be taken into account. The guideline presents values for this margin for

inner or outer waters, for a measuring system with or without wave compensation. Another seabed related factor is the sediment deposit in between two dredging campaigns. The guideline recommends making a forecast based on littoral or fluvial dynamic studies. Also an indication for the dredging performance tolerance is given for a soft ground or a rocky bottom.
All three categories together form the design depth of the channel. The guideline also gives an empirical method to make a quick estimate of the ship related channel depth, as a multiplication factor of the design ships draught. The factors vary from 1.10 to 1.50 depending on the degree of protection to waves.

Channel width

Globally the design of the channel width is based on the design ships characteristics and manoeuvrability, the available aids to navigation and a certain safety margin to prevent collisions with the channel boundaries. These factors result in the nominal width of the channel. The design of the nominal channel width is divided into eight different situations. A distinction is made between one-way and two-way traffic, straight and curved sections, constant and varying environmental conditions. The basic formula for the determination of the channel width is given by the expression for a one-way, straight channel section with constant environmental conditions:

$$B_n = B + b_d + 2(b_e + b_r + b_b) + (rh_{sm} + rh_{sd})_i + (rh_{sm} + rh_{sd})_d \quad \text{[m]} \quad (3.14)$$

The formula is based on the width of the design ship B. An additional width for navigation under a certain drift angle due to external influences is given by b_d. The quality of aids to navigation and possible errors in the marking system are given by b_e and b_b. The factor b_r takes the time between the detection of a deviation in course and the ships response into account. The bank effects and an additional safety margin between the bank and the ship are given by rh_{sm} and rh_{sd} for both banks separate.
The extra width of a ship navigating under a drift angle β can be expressed by (see Figure 2.1):

$$b_d = L_{pp} \cdot \sin\beta \quad \text{[m]} \quad (3.15)$$

The drift angle is caused by external forces on the ship. The most important influences on the drift angle are given by wind, currents and waves. The guideline also provides a method to determine the drift angle caused by tug-boat action. The drift angle due to wind action is determined by the shape of the ships hull, expressed in a coefficient K_v, and the windage of the ship given by a coefficient C_v. Also the wind speed relative to the ship (V_{vr}), ship speed relative to the water (V_r) and the angle between the wind and the ships direction (α_{vr}) are included in the formula:

$$\beta_{wind} = \arcsin\frac{K_v \cdot C_v \cdot V_{vr} \cdot \sin\alpha_{vt}}{V_r} \quad \text{[dgr]} \quad (3.16)$$

The drift angle due to current action is calculated in a similar way. This time the current speed (V_c), speed of the ship relative to the bottom (V) and the angle between the current and the ships direction (α_{cv}) are included:

$$\beta_{current} = \arctan\frac{V_c \cdot \sin\alpha_{cv}}{V + V_c \cdot \cos\alpha_{cv}} \quad \text{[dgr]} \quad (3.17)$$

The last important influence is caused by the response of the ship on wave action. A coefficient K_w is introduced which depends on the shape of the ships hull, the ratio of the water depth (h) and the ships draught (T) and the angle between the wave propagation and the ships direction (α_w). The significant wave height is included by H_s.

$$\beta_{wave} = \arcsin\left(K_w \cdot \sqrt{\frac{g}{T}} \cdot \frac{H_s}{V_r}\right) \qquad \text{[dgr]} \qquad (3.18)$$

As discussed before, the influence of wind, currents and waves is largest for low ship speeds. This also follows from the formulae given above. Also the angle between the wind, current or wave and the ships direction has an important influence on the drift angle. For an α close to 90^O the drift angle is at a maximum and for an α closer to 0^O or 180^O the drift angle is at a minimum.
The combined influence of wind, current and waves can be found by:

$$\sin\beta = \sin\beta_{wind} + \sin\beta_{current} + \sin\beta_{wave} \qquad (3.19)$$

The guideline also provides a calculation method for the drift angle due to the forces exerted by a tug-boat. The influence of tug-boats will not be discussed here.
The additional width b_e is based on positioning error of the ship caused by a deviation between the ships real position and the position estimated by the navigational systems. The value of this deviation depends on the type of aids to navigation and the presence of a pilot or the experience of the captain. The guideline provides a table with values depending on these factors. For the use of D-GPS the distance is 10 meters. This is remarkably high, as the position of a ship can be determined within one meter using a D-GPS system.
An error in the positioning of the navigation marking systems, like buoys, should also be taken into account. The value of this additional width (b_e) should follow from detailed information on the marking systems used in a particular situation.
When a deviation of the course is being observed the ship needs to response. This takes some time in which the ship is still deflecting from its course. This phenomenon is taken into account by adding a width b_r. The guideline gives a table to determine this width depending on the ships characteristics and a risk factor. If the risks accompanied with a course deviation are large, the width increases.
The influence of bank suction or rejection effects is included in the factor rh_{sm}. On top of this value a safety margin (rh_{sd}) is taken into account which represents the minimal horizontal clearance which must always be available between the ship and the banks. The guideline provides empirical values for both parameters, based on the channel configuration and ship speed.
The above mentioned factors must be taken into account in case of a one-way, straight section with constant environmental conditions. When the environmental conditions vary over the track an additional width b_{dv} must be added to the width of the swept path. This extra width is determined by the ships speed and the relation between the maximum drift angle in the varying conditions and the drift angle before or after this area.
In case of a curved stretch in the channel an additional width (b_{dc}) is taken into account to compensate for the increase of swept path in a bend. This factor is based on the ships characteristics and the radius of the curve.
In case of two-way traffic the influences of overtaking or encountering of ships must be taken into account. This leads to the following formula for a straight section with constant conditions:

$$B_n = 2\left[B + b_d + 2\left(b_e + b_r + b_b\right)\right] + b_s + \left(rh_{sm} + rh_{sd}\right)_i + \left(rh_{sm} + rh_{sd}\right)_d \quad \text{[m]} \quad (3.20)$$

Most of the parameters are already discussed above except for the passing distance b_s. This additional width is based on the ships speed, traffic density and the degree of protection against environmental influences. The guideline provides a table with empirical values of b_s. In case overtaking is allowed, the values must be increased by 50%. The additional widths for curved sections and varying environmental conditions can also be applied in case of a two-way channel.

Channel alignment

Because of the large influence of local conditions a clear design procedure for the channel alignment can not be given. The guideline therefore provides some general recommendations. Bends must be avoided as much as possible, especially S-curves. If bends are necessary, a single bend is better than a sequence of bends following each other. The radius of a bend has a minimum of 5 to 10 times the length of the design ship and the length of a bend is restricted to half the bend's radius. In between the bends, the length of the straight section must be at least 10 times the design ship length. The channel should be aligned in the direction of the currents to minimize cross-currents and their effect on ships. Aligning the channel such that storms are taken abeam must also be avoided. If this leads to conflicting requirements a compromise must be found. Areas of sediment accretion must be avoided to keep the maintenance costs at an acceptable level.

Turning basin

The Spanish guideline contains a chapter on the design of turning manoeuvring areas. A distinction between manoeuvres with and without tug-assistance is made. In this thesis only the situation without tug-assistance is of importance. The dimensions of the turning area are based on the area a ship needs to turn around reversing its direction of navigation. The area is a circle with radius R_{sr} which is calculated by the following formula:

$$R_{sr} = R \cdot \tan 30 + K \cdot L + 0.35 \cdot L \quad \text{[m]} \quad (3.21)$$

The factor R is the minimum radius of the ships path in the turning manoeuvre. As a rule of thumb the guideline gives values for R as a multiple of the ship length, based on the water depth to draught ratio. For shallow water smaller than 1.2 times the ships draught a value of 5 times L_{pp} is given. The factor K is the distance from the vessels pivot point to the stern, as a fraction of the ships length. A recommended value of 0.5 is given for ships with large displacements. The value of 0.35 in the formula is a safety coefficient. All the factors are shown in Figure 3.4.

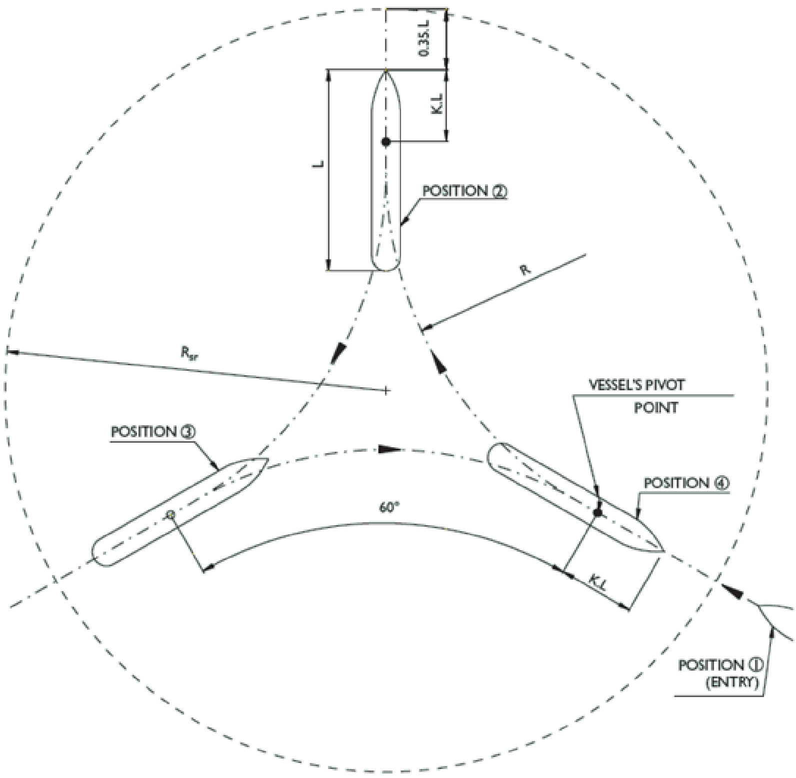


Figure 3.4 - Area for turning without tug-boat assistance [10]

3.5.3. Evaluation

The Spanish guideline shows a combination of a theoretical and an empirical approach on channel design. The guideline takes more influences and safety factors into account than the other guidelines, and could therefore lead to an overestimation of the channel dimensions. The design rules are accompanied with extensive background information on ship movements and environmental influences. The ROM is the only guideline that gives a detailed guide for the design of a turning basin. A disadvantage of this method is that the influence of bow thrusters on the turning manoeuvre are not included, leading to an overestimation of the basin dimensions.

3.6. Canadian Waterway National Manoeuvring guidelines [11]

3.6.1. Introduction

The guidelines for channel design in Canadian waterways are provided by the Canadian Coast Guard (CCG). The CCG works as a special operating agency under the governmental department of Fisheries and Oceans Canada. To ensure safe navigation in the Canadian waterways these organizations set up a program for waterway development. This resulted in the document "Canadian Waterway National Manoeuvring Guidelines: Channel Design Parameters" [11], from which the latest version is revised in June 1999. The guideline provides design rules for a first design for large commercial traffic and can not be used in a final design stage. The rules are based upon the operational requirement for ships in the Canadian waterways. The channel design parameters that can be determined with the guideline are width, depth, side slopes, curvature and alignment.

3.6.2. Guideline

The guideline starts with providing information on which data should be used for the determination of the minimum channel dimensions. A baseline study must result in input data on the design ship, traffic in the channel, weather conditions and waterway characteristics. From there one the guideline provides a design procedure on the channel width, depth, side slopes and bends. Also a chapter on bridge clearance is include, which will not be discussed in this thesis.

Channel width

The guideline provides two methods to determine the channel width. The first is based on the procedure in an earlier version of the guideline in 1995. The procedure is expanded for the report of 1999 by using a greater variety and more detailed parameters, leading to method 2. Only the second method will be discussed here, as it provides a more detailed and optimized design of the channel width.

The total channel width is based on the design width and safety allowances. The design width is based on the manoeuvring lane and additional widths for the effects of interaction between meeting and passing ships, crosswinds, cross currents, bank suction and navigational aids. The procedure shows a large resemblance with the design rules of PIANC [2]. All widths are based on empirical relations and are given as a factor multiplied with the beam of the design ship. The manoeuvring lane is determined by the manoeuvrability of the design ship, classified as excellent, good or poor. The ship clearance taken into account for the hydrodynamic interaction between ships should be at least 30 meters. If the beam of the design ship is larger than 30 meters, this beam should be used as ship clearance. In case of moderate (1 – 3 ships per hour) or heavy (more than 3 ships per hour) traffic an extra width must be added. Numerical values are given in several tables, which are combined in Table 3.8. The influence of wind and currents depends largely on the ballast condition of the ship, and the resulting manoeuvrability. The wind and current severity are divided into categories as well as the manoeuvrability of the ship. For each situation an additional width is given. For the determination of the additional width for bank suction effects, first an estimation of the severity of these effects must be made. This estimate is based on distance of the ship from the bank, depth to draught ratio, ship speed and channel configuration. From here on the bank suction severity can be categorized as low, medium or high and an additional width can be found depending on the ship manoeuvrability. Also a table with additional widths is provided based on the quality of the navigational aids. Finally a category of other allowances is given. This includes the effect of the level of cargo hazard, shallow water, bottom surface material and ship speed.

Table 3.8 - Channel width requirements according to CCG [11]

		Channel width
Manoeuvrability		
excellent		1.3B
good		1.5B
poor		1.8B
Traffic density		
light (0 – 1 vessel/hour)		0.0B
moderate (1 – 3 vessel/hour)		0.2B
heavy (>3 vessel/hour)		0.4B
Wind severity	Manoeuvrability	
	excellent	0.0B
low (<15 knots)	good	0.0B
	poor	0.0B
	excellent	0.3B
moderate (15 – 33 knots)	good	0.4B
	poor	0.5B
	excellent	0.6B
severe (>33 knots)	good	0.8B
	poor	1.0B
Current severity	Manoeuvrability	
	excellent	0.1B
low (0.2 – 0.5 knots)	good	0.2B
	poor	0.3B
	excellent	0.5B
moderate (0.5 – 1.5 knots)	good	0.7B
	poor	1.0B
	excellent	0.7B
severe (>1.5 knots)	good	1.0B
	poor	1.3B
Bank suction severity	Manoeuvrability	
	excellent	0.5B
low	good	0.75B
	poor	1.0B
	excellent	0.75B
medium	good	1.0B
	poor	1.25B
	excellent	1.0B
high	good	1.25B
	poor	1.5B
Navigational aids		
excellent		0.0B
good		0.1B
moderate with infrequent poor visibility		0.2B
moderate with frequent poor visibility		0.5B
Cargo hazard level		
low		0.0B
medium		0.5B
high		1.0B
Shallow water effects (depth / draught ratio)		
D/d > 1.50		0.0B
1.15 ≤ D/d ≤ 1.50		0.2B
D/d < 1.15		0.4B
Bottom surface (only for D/d < 1.5)		
smooth and soft		0.1B
smooth or sloping and hard		0.1B
rough and hard		0.2B

Channel depth

As can be seen in Figure 3.5, the channel depth according to the CCG is based on the ships static draught with extra allowances for trim, squat, exposure, fresh water adjustment, bottom material and overdepth. For the influence of trim due to the loading conditions of a ship, the guideline provides a rule of thumb of 0.25 meter extra depth per 100 meters of ship length. The squat is predicted by a dimensionless form of the Eryuzlu equation (1994):

$$S_b = 0.298 \frac{h^2}{T} \left(\frac{V}{\sqrt{gT}} \right)^{2.289} \left(\frac{h}{T} \right)^{-2.972} K_b \qquad [-] \tag{3.22}$$

with $K_b = \frac{3.1}{\sqrt{\frac{w}{B}}}$ when $\frac{w}{B} < 9.61$ and $K_b = 1$ when $\frac{w}{B} \geq 9.61$

This formula is based on model tests on ships with a block coefficient larger than 0.8, a length to beam ratio of 6.7 – 6.8 and a beam to draught ratio of 2.4 – 2.9 [2]. The method is applicable for all channel configurations.

For the influence of exposure to environmental conditions the guideline recommends to make an estimate based on local information. A table with typical values in Canadian waterways is given in the guideline. A depth increase of 2-3% should be taken into account for the change of density for ships in fresh water. The bottom material allowance contains a safety margin to prevent ships running aground. The value is based on the bottom material and varies from 0.25 meters for a soft bottom to 0.90 meters for rock. To maintain safe manoeuvrability the guideline states that the sum of the exposure allowance and bottom material allowance should be at least 1 meter. An average value of 0.3 meters should be used for the overdepth allowance due to dredging tolerances and sedimentation.

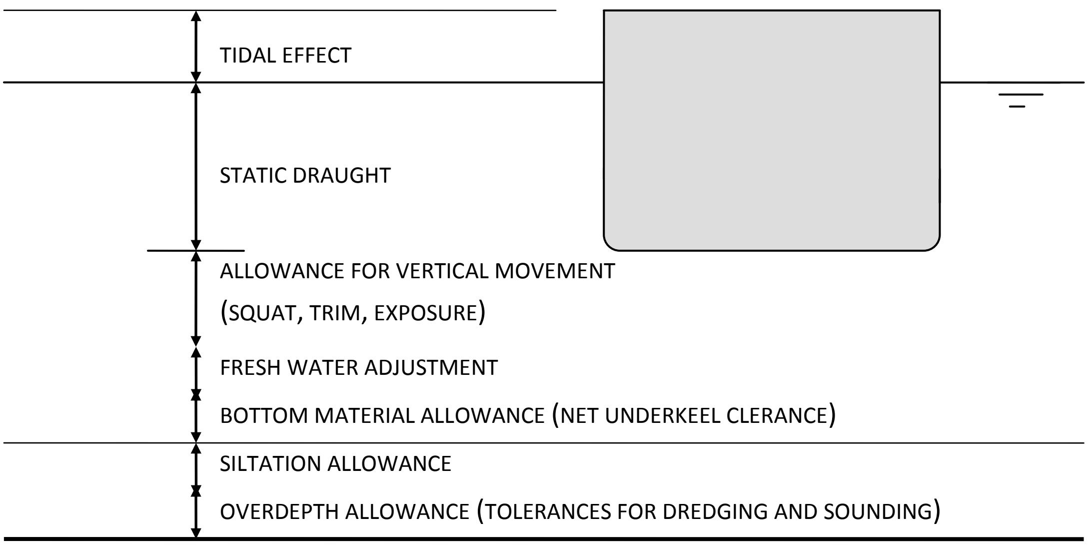


Figure 3.5 - Channel depth according to CCG [11]

The guideline provides some recommendations on the side slope of the channel. To allow the ships to move up the channel bank for a small distance in case of an emergency, the use of a completely vertical bank is excluded. The minimum side slope is set to 1:1 and is recommended for rock and other firm bottom materials. To ensure the stability and prevent sliding, the recommended side slope decreases as the bottom materials get less firm and softer, eventually resulting in a side slope of 8:1 for mud and soft silt.

Channel alignment

A clear guideline for the design of the alignment of the channel is not given. Instead recommendations on the design of bends are included in the report. Depending on the angle of the turn the guideline gives a radius of the curvature as a multiple of the design ship length. Because of the wider swept path of a ship in a bend, an additional width should be taken into account. Model studies in a basin have led to a formula for the determination of the extra width ΔW:

$$\Delta W = \frac{0.9144 \cdot \phi \cdot V^2 \cdot L^2 \cdot F}{R_t \cdot C_c \cdot S} \quad \text{[m]} \qquad (3.23)$$

This formula contains the angle of the turn (*Φ*), ship speed (v_s), ship length (L), turning radius of the bend (R_t), coefficient of ship manoeuvrability (C_s), unobstructed sight distance (S) and a coefficient for one or two-way traffic (F).

The CCG guideline does not contain any rules on the design of a turning basin.

3.6.3. Evaluation

The guideline provided by the Canadian Coast Guard is clearly based on the design rules by PIANC. The method provides tables with empirical values to determine the channel width. All influences taken into account by the PIANC are used in the guideline of the CCG. The Canadian guideline is the only one that gives a calculation method for the extra width of the channel in a bend.

3.7. British Standard: Maritime structures [12]

3.7.1. Introduction

The British standard on maritime structures consists of 8 parts. The standard gives general recommendation on the design, planning, construction and maintenance of structures in the marine environment. Part 1, code of practice for general criteria [12], includes the design rules on approach channels and was published in 2000. The document mainly provides information on which factors to consider during design. It therefore does not provide information and design rules as detailed as in the guidelines described in the previous part of this chapter.

3.7.2. Guideline

The design standard emphasizes that nowadays the final design of an approach channel should include the use of a simulation model. Real-time and fast-time computer models and physical scale models give detailed and reliable information on the handling of a ship in a narrow channel.

For the preliminary design the guideline provides some general rules. The depth of the channel is mostly determined by the draught and underkeel clearance of the largest ship expected in the channel. In the first stage of the design a value of 10% of the ships draught can be used as underkeel clearance. This includes the effect of squat, draught and sounding uncertainties and a safety margin. When the channel is not in a sheltered environment the influence of waves should also be taken into account. In this case the underkeel clearance must increase to up 30% of the ships draught. The hydrodynamic effects following from ship-ship and ship-bank interaction also contribute to an increase of underkeel clearance. For more detailed formulae on all these effects, the British standard refers to the rules made by PIANC [2].

For the design of the channel width the standard again refers to the PIANC [2] for a preliminary design and to computer simulations for the detailed design. The standard only provides some general rules of thumb. For a channel with one-way traffic a width of 4 to 6 times the beam of the largest ship should be used. In two-way traffic this factor increases to 6 to 8 times the beam. For large tankers up to 300000 dwt in a one-way channel the width should be 5 to 7 times the beam. Two-way traffic involving large tankers should be avoided. In case of a detailed study based on computer simulation, attention also must be paid to other operational aspects like wind, waves, channel geometry and traffic.

The British standard only gives an overview of the factors taken into account in the design of a channel. For design rules it fully refers to the PIANC guidelines [2]. The British standard will therefore not be discussed further.

3.8. Discussion

3.8.1. General

In the foregoing the most commonly used guidelines for the design of a channel were discussed. Only the concept design rules for the depth, width and alignment are studied. In case the guideline gives a design rule for a turning basin, these are also given. Based on this literature study, the main differences, advantages and disadvantages of the guidelines can be discussed.

Channel depth

In all guidelines the determination of the channel depth is handled in less detail than the channel width. To determine the channel depth, roughly all guidelines take the same factors into consideration. The most important factors are the draught, squat and vertical movements of the design ship. Some other allowances based on the environment, channel and ship characteristics are added. For the prediction of squat every guideline uses different methods, which all have their own limitations and restrictions. The most important characteristics of the guidelines are:

- The PIANC guideline only gives a rule of thumb to determine the channel depth and refers to another report for a more detailed description. In this report all factors determining the channel depth and their influence are discussed, but no values or formulae are given. The PIANC report also provides an extensive research on different methods of squat prediction.
- The guidelines of USACE and CCG provide some rules of thumb and tables based on empirical relations.
- The Japanese guidelines provides a fully analytical method to calculate the channel depth. The guideline presents formulae based on hydrodynamic studies on ship behavior.
- The Spanish guideline combines an analytical with an empirical method. The guideline presents formulae and tables containing empirical data.

Channel width

The differences in the determination of the channel width can be found in the amount of influences taken into account, the level of detail and the approach on the calculation method. Some main distinctions can be made:

- PIANC, USACE and CCG determine the channel width using a table with empirical values, which results in a multiplication factor of the beam of the design ship. The table contains parameters influencing the movement of a ship through a channel.
- The Japanese and Spanish guidelines are based on a more theoretical foundation. According to these two guidelines the width of a channel is largely based on the ships drift angle resulting from external influences. Both guidelines provide a different method to calculate this drift angle.
- The values in the guideline by PIANC are divided into several categories, mainly based on the manoeuvrability and speed of the design ship. PIANC makes a distinction between an inner and an outer channel by giving different empirical values.
- USACE also makes a distinction between an inner and an outer channel. For the design of an outer channel the guideline only gives an empirical relation based on the manoeuvrability of the design ship. The influence of currents and the channel configuration are included in determining the width of an inner channel. Also a table with additional widths in bends is given. Other important influences are not taken into account, like wind and waves, and therefore a very global design is provided.

- The design rules of the CCG are almost similar to the PIANC rules, but are a little less detailed and only based on the ship manoeuvrability, not the speed. CCG is the only guideline that gives a formula to determine the extra width in a bend.
- The Japanese guideline provides a fully theoretical approach on the design of the channel width. The method determines a maximum allowable rudder angle for the design ship and provides formulae and graphs to calculate the accompanying drift angle. This is done for the influence of waves, currents, ship-ship interactions and bank effects. No detailed explanation or backgrounds on the method are given, which makes it hard to determine what the influences of the design considerations on the channel width are.
- The Spanish guideline provides formulae for the calculation of drift angles based on the characteristics of the design ship due to wind, waves and currents. The other factors influencing the channel width are included in tables with empirical values. The Spanish guidelines are very detailed and provide extensive background information on the design considerations taken into account.

Alignment

The design of the channel alignment is fully depending on the layout of the surrounding area and is therefore hard to capture in general rules. All guidelines give recommendations and rules of thumb. It is always recommended to use a simulation model to determine the final alignment.

Turning basin

The design of a turning basin is given by the area of a circle. The diameter of the circle is a multiple of the design ships length. The PIANC report only gives a global recommendation of this diameter, the USACE report gives a recommendation based on the prevailing currents in the area. The only detailed calculation method for the diameter of the turning basins is given by the Spanish guidelines. It gives a formula based on the length of the design ships and the radius of its swept path during the turning manoeuvre. The guideline also makes a distinction between making the manoeuvre with or without tug assistance. The Japanese and Canadian guidelines do not provide a design method for a turning basin.

3.8.2. Example

To make a quantitative comparison of the used guidelines, a numerical example of the design of a channel will be made. All the discussed guidelines will be used to make a concept design. The example will be based on a channel used in the construction of the New Doha International Airport by a consortium including Boskalis in Qatar. Some basic assumptions regarding the design ship and channel are made. The design ship is a TSHD with the following dimensions:

- Length (L_{pp}) 209.5 m
- Beam (B) 32 m
- Loaded draught (T) 13.5 m

The ship has a high manoeuvrability and excellent onboard aids to navigation, including a DGPS system and detailed information of the project site. The ship will be the input in the design of a straight section of a two-way channel, which will only be used by ships of the building consortium. The location of the channel is sheltered leading to the following environmental conditions.

- The maximum significant wave height to take into account is 1 meter.
- A longitudinal current of at most 1.5 knots and a transversal current of 0.5 knots perpendicular to the channel can occur.

- The average wind speed is 15 knots (Beaufort 4) with a maximum of 30 knots (Beaufort 7) in a direction of 45 degrees to the channel.
- The bottom surface consists of smooth and hard rock, in which a channel slope of 1:2 will be made.
- The surrounding water depth is 7 meters, which leads to a restricted channel configuration.

With this information the depth and width of the channel is determined based on the guidelines. This resulted in the following dimensions.

Table 3.9 - Calculated dimensions of the channel

Guideline	Depth (h)	Width (W)	h/T	W/B
PIANC	15.09 m	256 m	1.12	8
USACE	14.98 m	166 m	1.11	5
Japanese	14.87 m	173 m	1.10	5
Spanish	15.49 m	321 m	1.15	10
CCG	14.99 m	230 m	1.11	7

Channel depth

As seen before, the channel depth is in general determined by the ships draught, squat and allowances for external influences. The draught of the design ship is equal in all five designs. Taking a look at the allowances, a large resemblance can be found (see Table 3.10). The methods of PIANC, USACE, CCG and the Spanish guideline all take the same value into account. This is actually very logical as all these guidelines refer to the PIANC report in case of these allowances. Only the Japanese guideline uses its own method, based on a percentage of the ships draught. In this example it leads to a smaller amount of underkeel clearance compared to the other guidelines. This is not always the case, as the Japanese allowance increases for larger draughts and the others are constant values.

Table 3.10 - Calculated channel depth allowances

Guideline	Draught (T)	Squat (s)	Other allowances	Total channel depth
PIANC	13.5 m	0.55 m	1.05 m	15.09 m
USACE	13.5 m	0.43 m	1.05 m	14.98 m
Japanese	13.5 m	0.54 m	0.83 m	14.87 m
Spanish	13.5 m	0.94 m	1.05 m	15.49 m
CCG	13.5 m	0.44 m	1.05 m	14.99 m

Squat

It can be concluded that the largest contribution to the variation in channel depth can be assigned to the differences in squat calculation. In this example the squat is calculated with a constant speed of 8 knots, the result of the calculations are given in Table 3.11. The squat calculations show large differences which can be explained by looking at each method.

Table 3.11 - Squat calculations

Guideline	Method	Squat	Percentage of draught
PIANC	ICORELS	0.55 m	4.0 %
USACE	Norrbin	0.43 m	3.2 %
Japanese	Yoshimura	0.54 m	4.0 %
Spanish	Huuska / Guliev	0.94 m	6.9 %
CCG	Eryuzlu	0.44 m	3.3 %

All methods of squat prediction are based on model or full-scale measurements. This leads to certain restrictions for the use of each method. One of the conditions for using a method is based on the channel configuration. According to PIANC [2] the method of ICORELS can only be applied in unrestricted shallow water. The methods used in the USACE, Japanese and Spanish guideline have no limitations with respect to the channel configuration. Other limitations in using a certain method are mostly based on the ships block coefficient or the Froude depth number.

- The formula of ICORELS should not be applied for large block coefficients and Froude depth numbers larger than 0.7.
- Predicting squat with the method of Norrbin is only valid for situations where the Froude depth number is smaller than 0.4, which makes the method rather limited.
- No limitations are given for the method of Yoshimura and not much about the realization of its formula is known.
- For calculation of squat according to Huuska and Guliev the channel depth to draught ratio must lie within the range of 1.1 to 1.5. According to Briggs [13] the method of Huuska and Guliev should not be used for Froude depth numbers larger than 0.7.
- The method of Eryuzlu can be used in unrestricted shallow waters and restricted channels, but only if the ships block coefficient is larger than 0.8.

These restrictions show that the squat prediction depends largely on the channel characteristics, ship type and their interaction. The calculation methods all try to give reliable results for a wide range of ship types and channel configurations. This makes it hard to apply these calculations on a specific case like a TSHD in a restricted channel.

In the numerical example a restricted channel is designed. The ships design speed of 8 knots leads to a Froude depth number of 0.36. The block coefficient is 0.87 and the channel depth to draught ratio of all concept designs are between 1.1 and 1.2. Based on these parameters some conclusions can be drawn on the reliability of some of the squat calculations in this example. According to the criteria the calculation made by the PIANC gives an invalid result based on the channel configuration, as this method is not valid for a restricted channel. All other methods can be applied in a restricted channel configuration. However, there is a large difference in how much the influence of a restricted channel is taken into account. A parameter in giving a detailed description of this influence is the cross-sectional area of the channel. The only method that includes this parameter is the method of Huuska / Guliev. Squat increases in a more restricted channel, which explains the high value of squat compared to the other methods which only include the channel depth. Which method is best for the prediction of squat for a TSHD will be discussed later.

Channel width

Just like in channel depth calculation, the channel width also varies between the several guidelines. However, in the channel width the differences can not be found in one influence. The differences here depend on the background of the complete method. First of all the differences can be made clear by analyzing the calculated example. In general every design can be reduced to a basic form containing an allowance for the basic manoeuvring lane, bank clearance and passing distance. The total width of the channel, in case of two-way traffic, is then determined by:

$$W_{total,\ 2\text{-}way\ traffic} = 2 * W_{basic\ manoeuvring} + 2 * W_{bank\ clearance} + W_{passing\ distance} \qquad [m] \qquad (3.24)$$

In Table 3.12 these allowances are given in meters for each guideline, in Table 3.13 these results are given with respect to the ships beam.

Table 3.12 - Calculated channel width allowances (in meters)

Guideline	Manoeuvring lane	Bank clearance	Passing distance	Total channel width
PIANC	70 m	32 m	51 m	256 m
USACE	51 m	19 m	26 m	166 m
Japanese	52 m	22 m	24 m	173 m
Spanish	87 m	45 m	58 m	321 m
CCG	67 m	32 m	32 m	230 m

Table 3.13 - Calculated channel width allowances (with respect to the ships beam)

Guideline	Manoeuvring lane	Bank clearance	Passing distance	Total channel width
PIANC	2,2 B	1,0 B	1,6 B	8 B
USACE	1,6 B	0,6 B	0,8 B	5 B
Japanese	1,6 B	0,7 B	0,8 B	5 B
Spanish	2,7 B	1,4 B	1,8 B	10 B
CCG	2,1 B	1,0 B	1,0 B	7 B

The empirical methods of PIANC and CCG show rather similar results. This seems logical as the CCG guideline is mainly based on the PIANC report. The only difference can be found in the passing distance, which is larger in the PIANC design. In the PIANC report the passing distance is determined based on the ships speed and the traffic intensity, where in the CCG method it is one constant value. The third fully empirical method by USACE gives smaller values for all the allowances, resulting in a much smaller channel width. This could be explained by the low amount of influences taken into account by the USACE.

Comparing the two theoretically based methods, the Japanese and the Spanish guidelines, give the same conclusion. The large difference between these methods is a consequence of the degree of detail used in the calculation. The Japanese guideline gives a brief calculation method based on a maximum rudder angle. The Spanish guideline provides a very detailed calculation involving much more influences than any other guideline reviewed in this thesis. Another explanation of the large difference is given by the fact that the Japanese guideline is fully based on research projects in Japan. As stated in the guideline these situations can not be compared with the general design of a channel in any arbitrary part of the world. As a reason for this, it is stated that the European channels are longer than the Japanese channels. This is remarkable as the length of the channel is not included specifically in the other world-wide used design guidelines.

Varying conditions

Besides looking at the differences between the guidelines for a specific example, it is also useful to analyze the results of the channel design for varying input parameters. This immediately shows the largest disadvantage of the three empirical methods (PIANC, USACE, and CCG). The channel widths calculated by these methods are all based on multiplication factors of the ships beam, divided into several categories. These categories consist of a certain range of the influence. The PIANC guideline for example, is mainly based on the ships speed divided into slow (5 to 8 knots), moderate (8 to 12 knots) and fast (above 12 knots). If the PIANC method is used for the project in Qatar based on a speed of 7.9 knots, it results in a channel width of 224 meters. If a speed of 8 knots is used a width of 256 meters is found, while in practice the speeds are almost the same. It shows that the method does not give a continuous result and attention must be paid for over- or underestimation of the channel width. The same holds for the influences of wind, currents and waves for all three guidelines. The Spanish and Japanese guidelines provide a continuous increase of channel width for increasing level of environmental influence. This is clearly shown in Figure 3.6.

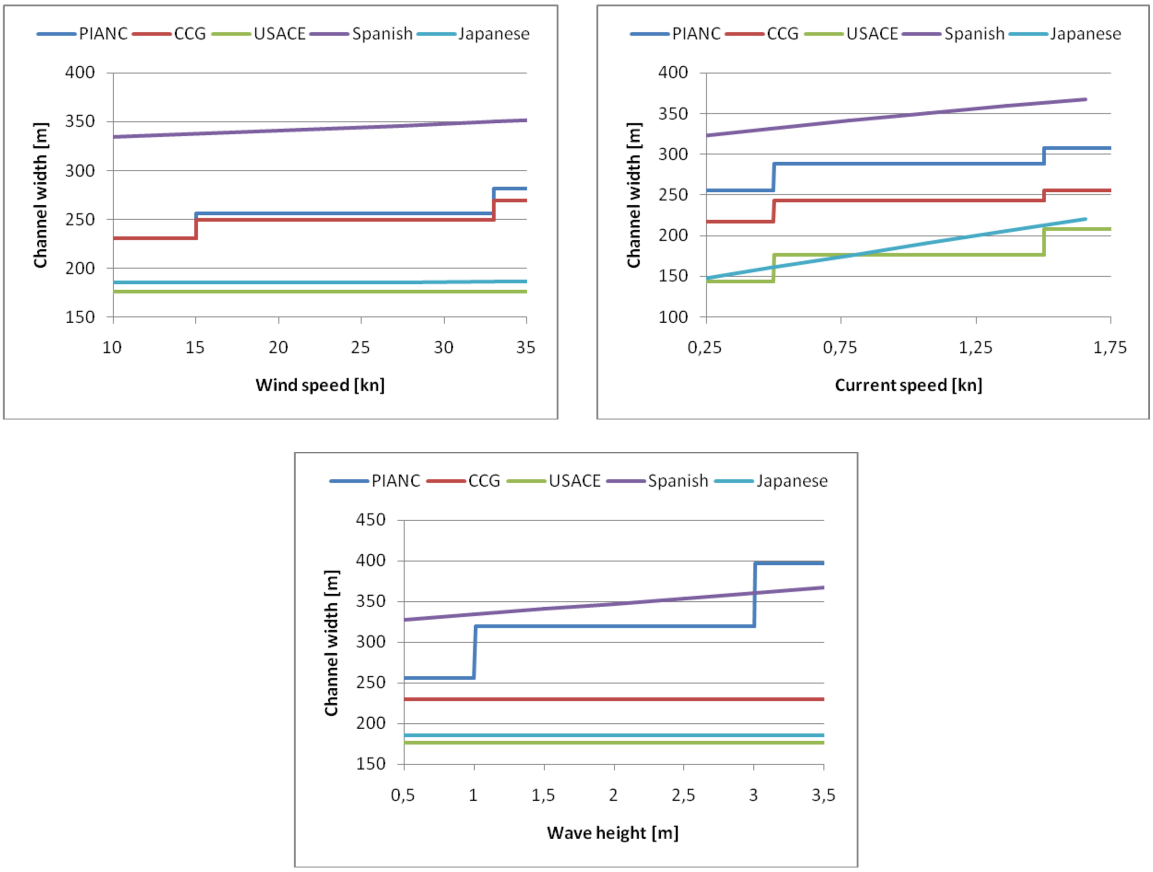


Figure 3.6 - Channel width calculation for increasing environmental influence

The figures clearly show the influence of an environmental factor on the channel width. Increasing wind speed gives an increased channel width for the guidelines by PIANC, CCG and Spain. The Japanese guideline takes the influence of wind into account in a continuous way, but in this example it leads to an almost negligible increase of channel width. This shows a large difference with the method used by the Spanish guideline which shows a clear increase of channel width. The guideline by USACE does not take the wind speed into consideration. The influence of currents is the only environmental factor that is taken into account by all guidelines. All guidelines show a rather similar increase in channel width for increasing current speed. The Japanese guideline shows the largest increase, the guideline by CCG shows the smallest increase. The influence of wave height on the channel width is only taken into account by the PIANC and Spanish guidelines. Especially the PIANC shows a large increase of channel width for increasing wave height.

Practical application

Of course, the widest channel is not per definition the best design and the smallest channel is not always the cheapest. All designs lead to their own considerations regarding construction and use of the channel. In the example project a channel width of 170 meters was designed by Boskalis based on the PIANC guidelines. This shows a large difference with the 256 meters given above which can be assigned to the empirical background of the method as stated before. The prevailing wind and currents and the ship speed are all exactly on the borderline between two categories. In the calculation given above the design is based on the safe side of this border, where the project engineers did not. Eventually the channel was constructed with a width of 200 meters. This dimension is based on the experiences of the helmsman of the TSHD sailing through the channel. The prevailing wind and currents resulted in a too high drift and the manoeuvrability of a loaded TSHD was lower than expected and therefore the width of 170 meters was not sufficient. However, the width of 256 meters would have resulted in a too wide channel.

3.8.3. Conclusion

This example shows that it is very hard to predict the optimal dimensions of a channel based on the concept rules discussed before. The main problem is that all methods are based on conventional ships and the design is made for a channel that has to last for a design life of several years. The situation of a TSHD in a temporary work channel is a completely different situation.

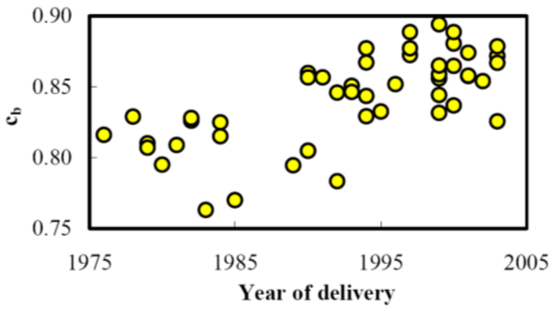
But how could an optimal design of a temporary work channel be designed? First of all, more insight in the behavior of a TSHD in restricted water is needed. It is clear that the channel depth is mainly based on the calculation of squat. It is therefore necessary to determine a squat prediction method that fits the characteristics of a TSHD and is applicable in shallow and restricted waters. Looking at the design of the channel width, it is clear that a fully empirical method has some disadvantages. It is not continuous in varying conditions and is very dependent on the data it is based upon. Looking at the theoretical methods, the Japanese guideline takes a limited amount of influences into account. This method therefore leads to very small dimensions of the channel. The Spanish guideline provides more backgrounds and takes many influences into account. A large disadvantage is that it overestimates the channel width in the situation of a TSHD in restricted waters. The empirical method of PIANC results in dimensions in between the Japanese and Spanish method. Because of these differences, the design method for a work channel used by a TSHD will not be based on only one of the discussed guidelines. It will be a combination of some of the theories lying under the guidelines and experiences from the past.

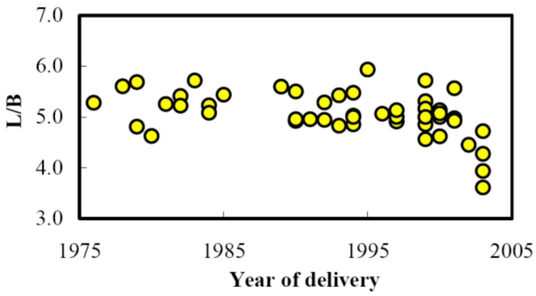
4. Trailing suction hopper dredger

To make an optimal design for a work channel specifically for TSHD's, more backgrounds of these ships is needed. A TSHD has to operate in situations where a great variety of water depths occur. The area where it is active often contains shallow and restricted waters, which have an impact on the manoeuvrability of the ship. However, the activities of a TSHD require a high manoeuvrability. These requirements all have their influence on the characteristics of a TSHD and its use in shallow and restricted waters.

4.1. Characteristics

Like other types of ships, the TSHD has its own typical characteristics. Based on the purpose and the cargo of the ship some typical dimensions and shapes can be found in the design of a TSHD. As seen before in the design of a channel, the most import parameters of the ship are the dimensions (length, beam, draught) and the block coefficient.
The block coefficient can be seen as a measurement of the fullness of the ship. In general a ship will strive for an optimum between the ship speed, the amount of cargo and the resulting fuel consumption. For most of the ship types this leads to a block coefficient around 0.6. A loaded TSHD however has a much higher block coefficient of about 0.8 or larger. This is a result of the relatively small loaded sailing distance which makes it cost-effective to sail with a high degree of loading.
A TSHD often operates on a construction site with limited space available for manoeuvring and a restricted water depth. This has several consequences for the dimensions of the TSHD. First of all the limited manoeuvring space requires a small length, to decrease the swept path and turning circle. Operating in shallow water requires a small draught to realize an acceptable underkeel clearance. To maintain a large carrying capacity the dimension of the beam must increase, which is typical for a TSHD. These requirements lead to a large length to beam ratio, and a small beam to depth ratio.
These typical dimensions are also found in practice looking at some of the TSHD build in the last years. In the master thesis of M.J. Kuiper [14] the tendency in TSHD design from 1965 to 2005 is described, the results are shown in Figure 4.1. The average length to beam ratio decreased from 5.5 to 5 and the average beam to draught ratio increased from 2.7 to 3. The average block coefficient increased from 0.81 to 0.85, with values of 0.87 occurring frequently. Also an increase of Froude depth number is observed from 0.21 to 0.23, which means that at a constant water depth the ship speed has increased.





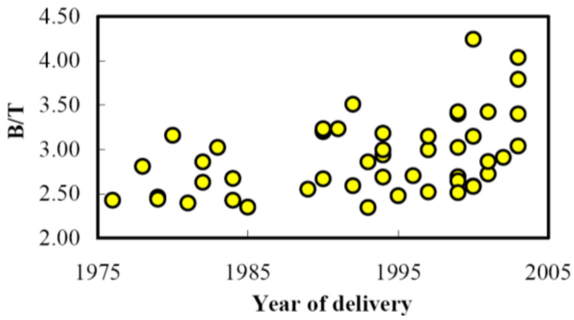


Figure 4.1 - Tendencies in TSHD design [14]

The increase in block coefficient and speed of the TSHD also has a consequence for the design of the shape of the ship. It leads to a higher resistance of the water on the ship and therefore a higher propulsive power is needed. The high block coefficient also has a negative effect on the produced wave pattern while sailing and the reaction of the ship on external influences at sea. These effects can be reduced by applying a bulbous bow. A bulbous bow changes the flow around the hull of the ship leading to less resistance, higher speed and more stability. Nowadays almost all TSHD's are built with a bulbous bow.

4.2. Squat

As seen before in the analysis of the current guidelines for channel design, the prediction of squat has a large influence on the channel depth. It is therefore very important to find a calculation method that fits the characteristics of a TSHD in shallow and restricted water. A squat prediction method exactly made for this situation does not exist. Also there are no measurements of the squat of a TSHD in a shallow restricted water. Therefore, a method must be found that approaches this situation as close as possible.

4.2.1. The HOSWA-project

In 2006 a research project was initiated by IHC, Ballast HAM (now Van Oord), Boskalis and MARIN to gain more insight in the manoeuvrability, course keeping and squat behavior of TSHD's in shallow unrestricted water. In this project, called HOSWA, some model and full scale tests were done to obtain measurements of squat. Analyzing the results of these tests showed that the typical form of the TSHD has a large influence on the amount of squat in shallow water. The longitudinal distribution of the volume of the ship and the local shape of the fore body, often a bulbous bow, influence the squat directly. There also seems to be a relation between the drift angle and the decrease of underkeel clearance.

The full scale measurements of squat in the HOSWA-project are done on the TSHD *Coastway*. The test results give insight in the squat of a TSHD in shallow, unrestricted water. Therefore, these results can not be used to check the calculation of squat in a shallow restricted water. However, it does show if a calculation takes the typical shape of a TSHD into account.

4.2.2. Squat prediction methods

PIANC [2] provides several methods to calculate squat. Only four of these methods can be used in restricted channel configurations. A method that is not proposed by PIANC, but takes a very detailed hull shape into account is the method by Ankudinov [14]. This method can also be applied in all channel configurations. The test results from the HOSWA project will be checked with the following five calculation methods [2], [15]. First a short description of each method is given.

Barras I (1979)

The first method of Barras is an empirical formula based on ships and model test with a block coefficient of 0.5 to 0.9.

$$S_b = 3.75 \cdot C_B \cdot S_2^{3/4} \cdot \left(\frac{V}{V_s} \right)^{1/2} \cdot \frac{V^2}{2g} \qquad (4.1)$$

S_b	*squat at bow*	*[m]*
C_B	*block coefficient*	*[-]*
S_2	*velocity return factor*	*[-]*
V	*ship speed*	*[m/s]*
V_s	*ship service speed*	*[m/s]*

Barras II (1981)

The second method of Barras is a modified and simplified version of his first method.

$$S_{\max} = \frac{C_B \cdot S_2^{2/3} \cdot V_k^{2.08}}{30} \qquad (4.2)$$

S_{max}	*maximum squat*	*[m]*
C_B	*block coefficient*	*[-]*
S_2	*velocity return factor*	*[-]*
V	*ship speed*	*[knots]*

Huuska / Guliev (1976)

The method of Huuska is based on an earlier method by Hooft (1974). Huuska modified the equation to get a better correlation with his model tests.

$$S_b = 2.4 \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} K_s \qquad (4.3)$$

S_b	*squat at bow*	*[m]*
∇	*ship volume of displacement*	*[m^3]*
L_{pp}	*ship length between perpendiculars*	*[m]*
F_{nh}	*Froude depth number*	*[-]*
K_s	*correction factor (=1 for unrestricted channels)*	

Römisch (1989)

This empirical method is based on extensive model investigations and is based on the critical ship speed.

$$S_b = C_V \cdot C_F \cdot K_{\Delta T} \cdot T \qquad (4.4)$$

$$C_V = 8 \cdot \left(\frac{V}{V_{cr}}\right)^2 \left[\left(\frac{V}{V_{cr}} - 0.5\right)^4 + 0.0625\right] \tag{4.5}$$

$$C_F = \left(\frac{10 \cdot C_B \cdot B}{L_{pp}}\right)^2 \tag{4.6}$$

$$K_{\Delta T} = 0.155 \cdot \sqrt{\frac{h}{T}} \tag{4.7}$$

$$V_{cr} = 0.58 \cdot \left(\frac{h}{T}\frac{L}{B}\right)^{0.125} \sqrt{gh} \tag{4.8}$$

S_b	*squat at bow*	*[m]*
T	*ship draught*	*[m]*
v	*ship speed*	*[m/s]*
C_B	*block coefficient*	*[-]*
B	*ship beam*	*[m]*
L_{pp}	*ship length between perpendiculars*	*[m]*
h	*channel depth*	*[m]*

Ankudinov (2009)

The method of Ankudinov is developed in 2000 and was recently updated. The large advantage of this method is that it is very detailed and can be applied to all the channel configurations. The method approaches squat as a combination of midpoint sinkage and trim.

$$S_b = L_{pp}(S_m - 0.5 \cdot Trim) \tag{4.9}$$
$$S_s = L_{pp}(S_m + 0.5 \cdot Trim) \tag{4.10}$$

S_b	*squat at bow*	*[m]*
S_s	*squat at stern*	*[m]*
L_{pp}	*ship length between perpendiculars*	*[m]*
S_m	*midpoint sinkage*	*[-]*
Trim	*ship trim*	*[-]*

The method consists of 16 equations to calculate the values of S_m and Trim. The calculation can be seen as a function of various input parameters:

$$S_m = f(B, T, L_{pp}, C_B, F_{nh}, h, h_t, A_s, A_{ch}) \tag{4.11}$$
$$Trim = f(B, T, T_{ap}, T_{fp}, C_B, F_{nh}, h, h_t, A_s, A_{ch}) \tag{4.12}$$

B	*ship beam*	*[m]*
T	*ship draught*	*[m]*
T_{ap}	*ship draught at aft perpendicular*	*[m]*
T_{fp}	*ship draught at front perpendicular*	*[m]*
L_{pp}	*ship length between perpendiculars*	*[m]*
C_B	*block coefficient*	*[-]*
F_{nh}	*Froude depth number*	*[-]*
h	*channel depth*	*[m]*
h_t	*depth channel to top of trench*	*[m]*

A_s	*cross-sectional area of the ship*	$[m^2]$
A_{ch}	*cross-sectional area of the waterway*	$[m^2]$

A detailed description of the method is given in appendix A.

4.2.3. Comparison with test results

To obtain measurements of the squat, four tests are done with TSHD *Coastway*. The tests are made with varying sailing speed and water depth. An overview is given in Table 4.1.

Table 4.1 - Overview test conditions

Test	1	2	3	4
Draught [m]	7.0	6.9	6.9	7.0
Water depth [m]	11.9	15.5	10.2	12.8
Sailing speed [kn]	11.66	12.13	12.11	11.66
Froude depth number [-]	0.56	0.51	0.62	0.53

The results of the tests can be compared with the calculated values according to the five methods given above. The test results and calculations are given in Figure 4.2. The vertical axis gives the measured or calculated amount of squat in meters, the horizontal axis gives the Froude depth number.

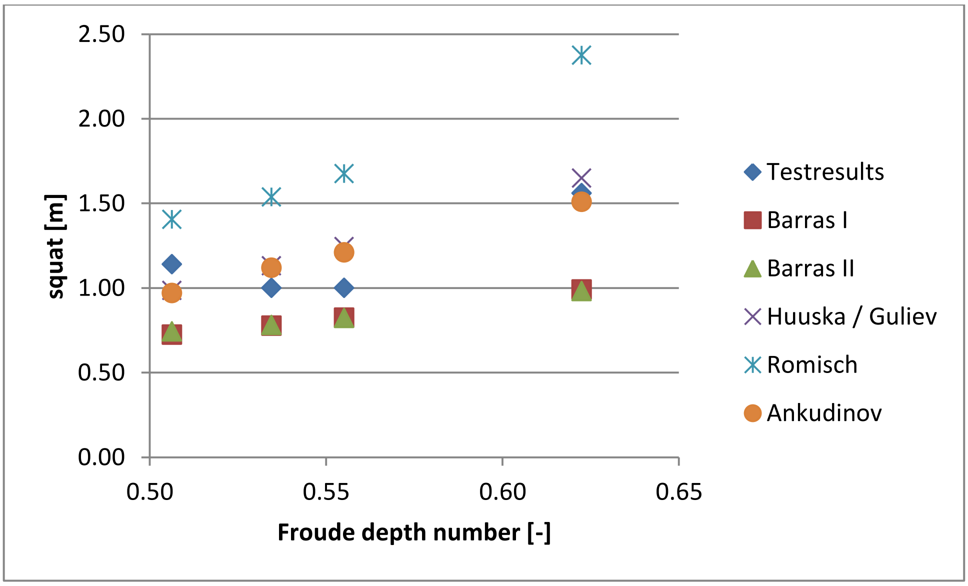


Figure 4.2 - Measured and calculated squat results in meters

The calculated squat values all seem to increase for increasing Froude depth number. This is logical as the squat increases for higher ship speeds or smaller channel depths. The test results do not follow the same trend. This could be explained by the fact that not all four tests are done at the exact same location and time. Environmental conditions and local bathymetry also have an influence on the squat. The calculated values are all based on a situation with a perfectly smooth bottom and no environmental influences. To have a clear overview of which method gives the closest approach to the test results, the calculated squat is computed as a percentage of the measured squat. These results are given in Figure 4.3. Positive values represent an overestimation, negative values give an underestimation.

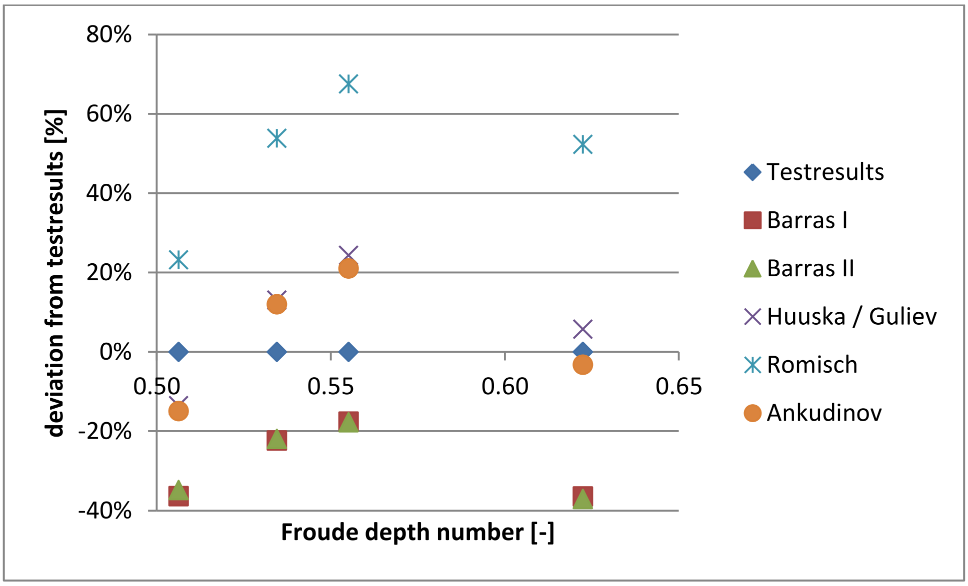


Figure 4.3 - Calculated squat in percentages of test results

The methods of Huuska / Guliev and Ankudinov both show a good correlation with the test results. The other methods all show a large deviation from the measured values. Barras I and II give an underestimation, Römisch gives an overestimation. A choice between Huuska / Guliev and Ankudinov must be made. According to Figure 4.3, the results of Ankudinov gives a smaller deviation from the test results for higher Froude depth numbers, compared to the results of Huuska / Guliev. The situation of a TSHD in a work channel often involves high Froude depth number, as the sailing speed is high and the water depth is low. The method of Ankudinov seems to be the best squat prediction method for a TSHD in a work channel. Also, a validation is made for the application of the method of Ankudinov in restricted channels in the paper of Briggs and Daggett [16]. Such a validation is not available for the method of Huuska / Guliev.

Based on comparing the test results with calculated values, it can be concluded that the method of Ankudinov takes the typical TSHD characteristics into account and gives good results in the situation of a TSHD in shallow water. The method can also be applied for shallow waters with a restricted width and will therefore be used to calculated the squat of a TSHD in a work channel. How the method reacts on a restricted channel width can not be concluded from these test results.

4.2.4. Ankudinov squat prediction method

From the above analysis follows that the method by Ankudinov gives the best results for the situation of a TSHD in shallow water. The method takes several factors influencing the squat into account. An overview of the method is given in Figure 4.4 on the next page, where the green and purple boxes are the input parameters of the method. A detailed description including all formulas is given in appendix A.

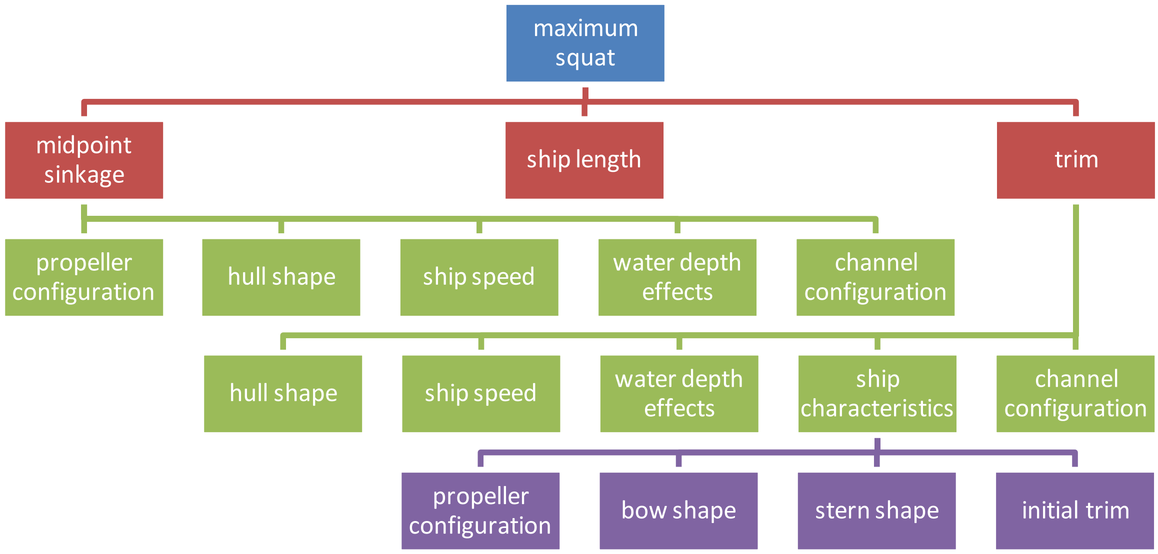


Figure 4.4 - Overview of the Ankudinov squat prediction method

Restrictions

One of the disadvantages of the Ankudinov squat prediction method is the restriction based on Froude depth number. The method does not hold for values of the Froude depth number larger than 0.6. However, there are situations where a Froude depth number of 0.6 or higher occurs. The Froude depth number can be higher than 0.6 (and up to 1.0) for cases with a high speed and a low water depth as could be the case for an empty hopper in the shallow part of a channel. In these situations a prediction of squat must also be made.

After investigating several methods it can be concluded that a reliable and widely applicable squat prediction method for Froude depth numbers between 0.6 and 1.0 is not available. However, some research is done by Gourlay [18] which resulted in a method for predicting the maximum squat of slender body ships at high speeds. This research concluded that the maximum squat in the range of Froude depth numbers between 0.6 and 1.0 lies at 0.8% of the ships length. This maximum is found at a Froude depth number of 0.9. During the HOSWA project also some model scale tests were done at a Froude depth number up to 0.8 which also showed a squat of around 0.8% of the ships length. When the squat in this range of Froude depth numbers is calculated with the method of Ankudinov, the same maximum of 0.8% is found. This means that although it is not advised to use this method for Froude depth numbers above 0.6, it does give a good estimate for the squat in the range of 0.6 to 0.9. Therefore, in the design tool the method will be used for all Froude depth numbers.

Validation

There are no measurements of the squat of a TSHD in a shallow restricted channel available, simply because that particular case has never been researched. It is therefore not possible to compare the calculated values with measured values. Also the captains could not give an indication of the amount of squat, because they mainly look at the underkeel clearance. However, the method has been validated in two cases. The first validation is made to check if the method of Ankudinov takes the typical shape of a TSHD into consideration. The results are shown in Figure 4.2 and Figure 4.3 and are discussed in the previous paragraph. It is concluded that there is a good correlation between the calculated values and the measured values of a TSHD in shallow water. This gives an indication of the accuracy of the method for a TSHD, but does not take the influence of a restricted channel into consideration. Second of all, the report published by M.J. Briggs and L. Dagget [16] shows the results of laboratory tests for a Post-Panamax containership in a range of channel configurations. All three channel configurations were tested: unrestricted channel, restricted channel and canal (See Figure 2.5). A series of physical model experiments with self-propelled models of Panamax and Post-Panamax containerships were done. Comparing the results of the Ankudinov method with the field measurements in the different channel configurations will tell more about the accuracy of the method in restricted waters compared to an unrestricted water. The model tests with the containerships showed that the predictions according to the method of Ankudinov give the best results for a restricted channel configuration. The canal-type configuration showed the worst results. This means the squat prediction method of Ankudinov can be used in a restricted channel.

Remarks

The measurements in the restricted channel configurations did show a slight overprediction of squat for all cases. This means the calculations are always on the conservative side. How this relates to the case for a TSHD in a shallow, restricted water can not be told due to the absence of measurements for that particular case. However, a slight overestimation seems to be useful as there are other phenomena that increase squat. Based on conversations with H.J. de Koning Gans (TU Delft), the following must be taken into account:

- Sailing with a drift angle increases the squat
- Sailing eccentric through a channel increases squat
- Encountering another ship increases squat

The increase of squat due to a drift angle can be explained by the increase of the channel blockage [21]. As a consequence, the same amount of water has to flow through a smaller gap leading to a higher return velocity. This leads to a decrease of pressure which lowers the water level as well as the ship. The increase of channel blockage also occurs when two ships encounter each other in a restricted channel. Another consequence of sailing with a drift angle is a higher flow velocity under the keel of the ship which results in an extra suction force. This higher velocity is assigned to the fact that the water has to flow over a larger distance from one board to the other. Finally, the velocity at one board will increase, while the velocity at the other board will decrease. This leads to a pressure gradient and an extra flow under the ships keel, which also results in an increase of squat.

At this moment, there is no squat prediction method that takes these influences into account. It is not possible to determine the influences of drift, eccentric sailing and encountering in a quantitative way, as research on these subjects is still ongoing. Therefore an overestimation of the squat is not such a bad idea, as these situations are likely to occur in a temporary work channel.

4.3. Manoeuvrability

The typical characteristics of a TSHD have their influence on the manoeuvrability. Of course, this all depends on the specific ship type and the conditions it is sailing in. In the HOSWA project, the effect of shallow water on the manoeuvrability of a TSHD was also investigated. Several model and full scale tests were done to obtain more insight in the shallow water effects. The full scale tests showed a loss of course stability when the ship speed was reduced. This effect gets larger in more shallow water. Also the effect of currents on the manoeuvrability of a TSHD is very large in shallow water. The research in the HOSWA-project resulted in a larger insight in the manoeuvrability of a TSHD in shallow water. The effects of a waterway bounded in the width are not investigated. It is therefore very hard to predict the exact behavior of a TSHD in a shallow, narrow work channel. Track logs and field data of executed projects will have to provide more insight in this subject in the future.

5. Analysis of projects

To gain more insight in the currently used design procedure for a temporary work channel, some projects are analyzed. The projects are all executed by Boskalis or a consortium including Boskalis. First of all the design stage is investigated by collecting calculations, reports, drawings and by interviewing the involved engineers or project managers. Next, the situation as it has been constructed is analyzed. In the end, experiences of the final user are collected by interviewing TSHD captains.

5.1 Design and construction

While making an inventory of projects it became clear that there is no standard design procedure for a temporary work channel and basin. Therefore not all information was available for every project, but enough information was collected to get a clear overview of some of the temporary work channels that were constructed. The projects with the most complete information available are discussed below. An overview of the main dimensions of the TSHD's used in the projects is given first.

Table 5.1 - Main dimensions TSHD's

Trailing Suction Hopper Dredger (TSHD)	Length [m]	Beam [m]	Max. draught [m]
Queen of the Netherlands	230.71	32.00	13.67
Fairway	209.50	32.00	13.50
Prins der Nederlanden	156.00	28.00	12.02
Gateway	137.00	28.00	10.00
Willem van Oranje	137.00	28.00	10.00
Barent Zanen	133.58	23.13	8.81
Alpha B	115.50	21.40	6.37
Coastway	97.70	23.00	6.58
HAM 309 (van Oord)	124.10	19.63	6.49

5.1.1 Dilmunia Health Island, Bahrain

The Dilmunia-project involved the construction of an island for the coast of Bahrain. For the construction of the island a temporary work channel and handling basin was needed. The design of the width of the channel was made according to the PIANC guidelines and was calculated for two categories of sailing speeds. The TSHD's operating on this project are the *Coastway* and the *Alpha B*.

According to the guideline a vessel speed of 12 knots or higher resulted in a channel width of 92 meters, a speed of 5 knots or lower gave a width of 106 meters. For the depth of the channel an assumption was made of 7.5 meters, which leads to an underkeel clearance of 10% based on the *Coastway*. For the design of the turning basin no clear design calculation was found. The different sailing speeds lead to the advice to make the channel somewhat narrower at the beginning and wider at the end, near the basin. This is based on the fact that in the entrance of the channel the TSHD has a higher speed than at the end of the channel, where it needs to stop at the basin. Another possibility that was advised is to use a constant channel width of 100 meters. This last option was adopted for the final construction after conversations with the TSHD captain. This advice was based on the experience of the captain on another project with similar environmental conditions which lead to a high drift angle in the first part (near the entrance) of the channel.

The bottom material on the project site consists of bedrock and therefore the channel was constructed by a cutter suction dredger (CSD). From a financial and construction point of view a box-cut profile was made, with a width of 100 meters and a depth of 8 meters below chart datum (CD). In this project the CD is defined 1.55 meters below mean sea level (MSL). This resulted in comments from the captains of the TSHD's using the channel. The strong NW-winds in the area resulted in a large drift angle of the TSHD's in the channel, which approached the channel banks closely. The steep box-cut profile of the channel increased the bank suction effects, making the drift angle worse. As a solution a slope of 1:3 was dredged in the profile between -8.0 m and -6.5 m CD. An extra width of 20 meters was constructed to create more space for the ships and to decrease the bank suction effects.

5.1.2 New Doha International Airport, Qatar

For the construction of the new international airport of Doha, a temporary work channel was designed. The design was made according to the PIANC rules. Several calculations were made based on different TSHD's, one-way or two-way traffic and local environmental conditions. The largest TSHD's used in this project are the *Fairway* and the *Prins der Nederlanden* and are therefore the design ships. Squat calculations were made based on the method of Huuska/Guliev and resulted in a squat of 1 meter at a speed of 8 knots. Therefore a speed limit of 8 knots is applied for a loaded design ship. For an empty TSHD no speed restrictions are used. The depth of the channel is assumed at -14.8 m CD. The PIANC rules suggest a channel depth of 1.1 time the draught of the design ship. This results in a maximum draught of 13.5 meters, which means the *Fairway* cannot always enter the channel loaded at its dredging load line. Of course this will depend on the tide at that moment and should be considered on site. For the design of the channel width first a calculation of a one-way channel was made. Using the PIANC rules with heavy weather conditions as input resulted in a channel width of 120 meters based on the loaded *Fairway*. For this project it was recommended to use two-way traffic to reach a high productivity. For that case the one-way channel will be widened with a more shallow part for an empty TSHD returning from the basin to the borrow area at sea. The water depth in the shallow part is assumed at -10.3 m CD. Several channel width calculations are made for different environmental conditions. This resulted in the following conclusions. A width of 120 meters for the deep part of the channel is enough to let the loaded *Fairway* enter under all environmental conditions. When the width of the shallow part is 40 meters, so a total width of 160 meters, the channel should be wide enough to let the *Prins der Nederlanden* and the *Fairway* pass each other in calm weather conditions. For moderate weather conditions the shallow part needs to be 50 meters which should result in smaller delays. This last option was proposed in the final project plan.

Eventually the channel was constructed with a channel width of 200 meters; a 65 meters wide shallow part with a depth of 10.3 meters and a 135 meters wide deep part with a depth of 14 meters. This was done after comments of the captains of the TSHD's operating in the channel. When entering and leaving the channel, the currents and wind resulted in a larger drift angle and lower TSHD manoeuvrability than expected. In that case it was too dangerous to let two large TSHD's, like the *Fairway* and the *Prins der Nederlanden*, pass each other.

5.1.3 North Bahrain New Town, Bahrain

For the construction of an island in the North of Bahrain a temporary working channel was needed. No detailed calculation of the channel design was found while analyzing the project. The project plan and accompanied drawings did show the dimensions of the channel and the turning basin. The channel was designed with a depth of -9 m NSD (National Survey Datum) and a width of 125 m. The channel width at the bottom is 75 meters, the width of each bank is about 25 meters. The largest TSHD working on the project was the *HAM 309* (van Oord). Making a calculation for the channel width according to the PIANC guidelines results in a width at the bottom of 78.5 meters.

The construction of the channel did not completely go according to the plan. Due to the fact that the bottom material differed from the assumed material for the calculation, it was not possible to construct the channel as it was designed. It was decided to use the maximum cutting width of the available CSD as the width of the channel. This resulted in a box-cut profile with a width of approximately 90 meters. From interviews with the involved engineers and project managers followed that this small channel width, in combination with strong prevailing cross currents, lead to some collisions of TSHD's against the channel banks. The exact amount of damage or resulting costs were not investigated.

5.1.4 Porto Dubai, United Arab Emirates

A temporary work channel was also needed for the land reclamation of Porto Dubai. The channel was designed for the TSHD's *Queen of the Netherlands* and *Prins der Nederlanden*. No detailed design was found in the analysis of the project. A channel depth of - 12 m CD and a width of 120 m were found in drawings and reports. CD is here defined at 0.4 m below MLLW (mean lower low water). This means both TSHD's could not enter the channel with a fully loaded hopper and therefore had restrictions with respect to the amount of sand they were carrying.

At a later stage of the project, the depth of the channel was adjusted. For economical reasons the channel was constructed with a depth of -10 m CD, which is shallower than the design depth. Research pointed out that in this situation making the channel deeper with a CSD leaded to higher costs than sailing with a more restricted load in the TSHD.

5.1.5 Brass, Nigeria

The LNG project in Brass, Nigeria is still in the design stage at the moment of this thesis. A temporary work channel had to be designed for the TSHD's *Barent Zanen* and *Gateway*. The design of the channel is made according to the PIANC design rules, which resulted in a channel width of 80 meters and a depth of 10 meters. These dimensions are based on the calculation for the *Barent Zanen*. For the *Gateway* the depth is increased to 10.5 meters because of its larger draught. However, the *Gateway* also has a larger beam than the *Barent Zanen* and should therefore (following the PIANC rules) be the design ship for the channel width. Nonetheless, the design of the channel is discussed with the captains of the TSHD's and both agreed. They did remark that the channel width and depth are at an absolute minimum now. Because of the better manoeuvrability of the *Gateway* compared to the *Barent Zanen* it was accepted to base the calculations on the smaller ship. Besides that, the captain of the *Gateway* is willing to take more risks due to the soft and muddy bottom material, where touching the ground will probably not lead to immediate damage.

5.1.6 Overview

The above analysis shows that most of the work channels within Boskalis are designed based on the guidelines of the PIANC. Table 5.2 gives an overview of the analyzed projects. For each project the width and depth of the channel is given for a calculation according to the engineers and the width and depth as the channel was eventually constructed. For the project of Brass the dimensions of the constructed channel could not be given as the project was not constructed yet during the writing of this thesis.

Table 5.2 - Overview channel dimensions for all analyzed projects

Project	Depth [m]			Width [m]		
	engineered	constructed	ratio	engineered	constructed	ratio
Dilmunia	7.5	8.00	1.1	100.0	120.0	1.2
Doha	14.8	14.00	0.9	170.0	200.0	1.2
NBNT	9.0	9.00	1.0	75.0	90.0	1.2
Porto Dubai	12.0	10.00	0.8	120.0	120.0	1.0

From this overview follows that the channel depth engineered according to the PIANC guidelines varies between an overestimation and an underestimation with respect to the eventually constructed channel depth. This is explained by the fact that the eventual depth of the channel is often adjusted during the construction of the work channel. These adjustments can have varying causes. The TSHD that is eventually using the channel could be different from the design TSHD. The depth of the channel can also be adjusted to the construction method of the work channel. For example, it can sometimes be financially interesting to adjust the depth of the channel to the maximum depth of the CSD that is constructing the channel. However, the engineered depth does not lead to a deviation from the constructed depth larger than 20%.

The engineered channel width according to the PIANC never shows an overestimation with respect to the eventually constructed width. In all cases the constructed channel width is equal to, or larger than the engineered values. It is remarkable that in three of the four cases the constructed width is exactly 20% larger than the engineered width.

It must be noted that the channel in the NBNT project is eventually constructed as a box-profile. It is therefore hard to compare the channel width in this project with the other projects. The channels in the Dilmunia, Doha and Porto Dubai project are all constructed with sloping channel banks.

5.2 Experiences of captains

As seen in the analysis of projects, the influence of the end user of the temporary work channel on the dimensions is very large. To gain more insight in the experiences of captains on this subject interviews with captains of TSHD's were done. The following TSHD's and captains are involved:

- *Willem van Oranje* A. Verloop
- *Prins der Nederlanden* F. Suurs
- *Queen of the Netherlands* G. Swan

All captains emphasized that sailing through a shallow, restricted channel is mostly a matter of experience. It is therefore hard to quantify all influences in the design of a channel. First of all the interaction between the TSHD and the channel and their influence on the design is discussed. After that a view on the human factor is given.

The depth of a channel is mainly determined by the underkeel clearance (UKC) of the TSHD. The UKC is the vertical distance between the lowest part of the ships hull and the top of the channel bottom. A distinction is made between the "net UKC" and the "static UKC" [19]. The static UKC is the

underkeel clearance measured when the ship is not in motion and lying in calm water. The net UKC is the underkeel clearance that is present when the ship is in motion and under the influence of environmental conditions. The net UKC is found when the water depth is subtracted by the ships draught, squat and response to environmental conditions.
On board of a TSHD, a system is used that predicts, measures and monitors the net UKC during navigation. As a rule of thumb a net UKC of 1 meter is found to be acceptable. This means that the squat is also of great importance, but because of the monitoring of the UKC a specific system to measure the squat is not used on a TSHD. It is also possible to feel the bottom when the net UKC gets too small, as the ship will start to vibrate. In that case the speed of the ship can be lowered which will lead to a decrease of squat and an increase of net UKC. This also emphasizes the importance of the bottom material. In soft muddy material touching the bottom will not necessarily give a problem, where in a hard rocky bottom damage will be almost inevitable. Therefore the amount of net UKC is also depending on the bottom material. The indicated value of 1 meter holds for hard, rocky bottoms where touching the ground will lead to immediate damage to the TSHD's hull.

Damage to the hull of the TSHD is not the only problem that occurs at small UKC. Also the manoeuvrability of the ship is largely affected. The thesis of Y. Abdelouarit [20] discusses failure-mechanisms due to insufficient UKC in the harbor basins of the Port of Rotterdam. A conclusion of the report is that, in the case of the Port of Rotterdam, not the touching of the bottom but the resulting decrease in manoeuvrability is the normative failure-mechanism. It must be noted that these conclusions hold for ships manoeuvring within a harbor basin. This means the sailing speed is lower and there is more protection to environmental influences compared to a TSHD in a temporary work channel. Therefore the vertical motions of the ship inside a harbor basin are smaller which makes the risk of touching the bottom lower. However, the Port of Rotterdam also takes the value of 1 meter of net UKC into account to create a safe situation.

An indication of the ships speed on which the squat is still acceptable is 6 to 8 knots for a loaded TSHD and 14 to 16 knots for an empty ship. These speeds are given by all of the interviewed captains and can therefore be representative as the design ship speed. To reach an acceptable net UKC it is very important to know the exact draught of the TSHD. For a loaded TSHD the draught at the dredging load line must be taken into account. Loading the hopper beyond this dredging load line is not allowed. The last important parameter in the design of the channel depth is the reference water level. Also the effects of swell must be taken into account when determining the normative water level. This design water level is determined by the workability desk based on an acceptable amount of downtime of the TSHD.

In a narrow channel, the captains try to keep course in the center of the channel as much as possible to reduce the influences of the channel banks. The sinusoidal movement around the channel axis will therefore be reduced as much as possible and will not have a large influence on the design of the channel width. This means the channel width is mainly determined by the ships drift angle due to wind and currents, which also followed from the literature and guidelines. As an indication, the *Queen of the Netherlands* has a maximum drift angle of approximately 20 degrees in a cross current of 3 knots and at a sailing speed of 8 knots. The drift angle following from wind depends largely on the surface area and lay-out of the ship. It is therefore hard to make a general rule for the calculation. The captains all state that the influence of wind on the drift angle is very small compared to the influence of currents. Also the relation with the ship speed is very important. A higher speed

often results in a smaller drift angle, but also in lower manoeuvrability.
Next to the basic manoeuvring lane based on the drift angle, some allowances for bank influences and passing ships must be taken into account. As an indication for the bank clearance a distance of 20 to 30 meters is used, based on the *Prins der Nederlanden*. A safe passing distance used by the *Queen of the Netherlands* is approximately 50 meters. These distances correspond to respectively 1 and 1.5 times the ships beam.

The basins used by the TSHD's are completely different from the turning basins in a harbor seen in some of the guidelines. The basins are not only used to turn, but also to connect to a pipeline used to pump the dredged material ashore. The TSHD are all highly manoeuvrable and are equipped with bow thrusters, which makes it able to turn around their own axis. The turning basin therefore can have the minimum dimensions of a circle with the diameter of the ships length and an extra safety margin. As a safety margin often half the ship length is used. It is also recommended that the TSHD has enough space to turn with the currents when it is connected to the pipeline while discharging. This could result in the need for some extra space in the direction of the prevailing currents.

With respect to bends in a temporary work channel, the captains did not have any experience. It seems that most of the channels are straight on. All captains mentioned that there are no differences between a TSHD or another ship type when it comes to navigating through a bend.

Visual aids to navigation, like buoys or light-lines, are not applied in temporary work channels so far. All TSHD's are equipped with a DGPS system. These systems are provided with up to date maps and survey data of the project site. This gives a very detailed description of the surrounding area. A large disadvantage is the dependency of the TSHD's on this system. When an error occurs or the system shuts down entirely, most of the time all activities of the TSHD needs to be stopped to prevent accidents. Especially in a situation with poor visibility, like fog, shut down of the system could lead to large problems as one of the captains had experienced.

As mentioned before, the way a ship navigates through a shallow restricted channel depends largely on the captain. Since every captain has its own method and experiences on how to handle the TSHD, it is very hard to quantify the behavior of the captain in the design of a channel. However, it must be kept in mind during the design. One of these factors is the level of risk that is taken. In the end the captain is responsible for the TSHD. Therefore clear communication between the captains of the TSHD's on the project site is very important. On the other hand this could also influence the risks taken. When a TSHD has a higher productivity, another TSHD could take higher risks to reach that same level of production. Another example is when a captain thinks it is not safe enough to enter the channel due to a too small channel width and too large cross currents. This verdict can be adopted by other captains, even if it is safe to enter the channel. All these factors must be kept in mind in the design of a work channel and basin.

5.3 Discussion

From the analysis of projects followed that the design of a work channel by Boskalis is currently based on the guidelines of PIANC, supplemented with experiences of captains. The level of detail in the design of a channel varies between a calculation on the one hand, and a rule of thumb complemented with experiences of captains on the other hand. A calculation for the dimensions of the basin was found in none of the projects.

One of the largest problems in the design of a work channel is that there are a lot of uncertainties during the design phase. Due to the flexibility of the TSHD's it is not always clear which TSHD('s) will be on the project. In the design phase the TSHD is determined on which all calculations will be based. When eventually another TSHD is used on the project, the dimensions of the work channel will be adjusted. Also the local conditions, like bottom material, bathymetry and environmental conditions, can differ from the data used in the design. From the analysis of the projects followed that it is sometimes hard to get reliable information concerning the input for the channel design. All these uncertainties can lead to the design of a channel which does not meet the requirement for the TSHD's. Also it can lead to a situation where the channel is not constructed according to the design. Eventually the TSHD's are not able to use the work channel as it is supposed to, and adjustments must be made.

The calculations for the channel dimensions within Boskalis are all based on the design guideline made by PIANC. This guideline prescribes a channel depth of 1.1 to 1.3 times the draught of the design ship. In the analyzed projects this is often done the other way around. A channel depth is assumed based on the bathymetry of the project location and on the characteristics of the dredging equipment that will be used to construct the channel. From there on, the maximum draught of the design ship is calculated to meet the PIANC requirements. This places large responsibilities at the TSHD captains as they must decide till what level the hopper must be loaded.
The width of the channel follows from the dimensions of the beam of the TSHD and the allowances following from the PIANC tables. As seen before in the analysis of the guideline, several influences are taken into account. From the experiences of the captains follows that not all influences are important. The drift angle of a TSHD is mainly determined by the cross-currents in that area, wind and waves hardly influence the width of the swept path of the TSHD.

5.3.1. Channel width

The calculation of the channel width according to the PIANC guidelines can lead to different results. As seen before in the analysis of the guideline, it does not provide a continuous change in channel width for increasing environmental conditions. All influences are divided into categories which are all subdivided into certain ranges of magnitude. When the input data also consists of a certain range (like: the prevailing cross-currents are in the order of 1 to 2 knots) this forces the engineer to make a choice between a wide and less wide channel. To find out how the engineers interpret the PIANC guidelines, for every project a new PIANC calculation is made from scratch. An overview of the differences in channel width for the projects is given in Figure 5.1. The blue bars represent the new calculation according to PIANC, the red bars show the calculation of the engineers and the green bars give the eventual constructed width. To make a good comparison, the channel width is divided by the beam of the design ship. In case of a two-way channel (Doha) the total channel width is divided by the sum of the two design ships. The calculations are given in Table 5.3.

Table 5.3 - Calculation ratio channel width to TSHD beam

Project	Beam	Channel width			Ratio width / beam		
	TSHD	PIANC	engineer	constructed	PIANC	engineer	constructed
Dilmunia	23	117	100	120	5.1	4.3	5.2
Doha (two-way)	32+28	256	170	200	4.3	2.8	3.3
NBNT	20	79	75	90	4.0	3.8	4.5
Porto Dubai	32	128	120	120	4.0	3.8	3.8
Brass	28	112	80	-	4.0	2.9	-

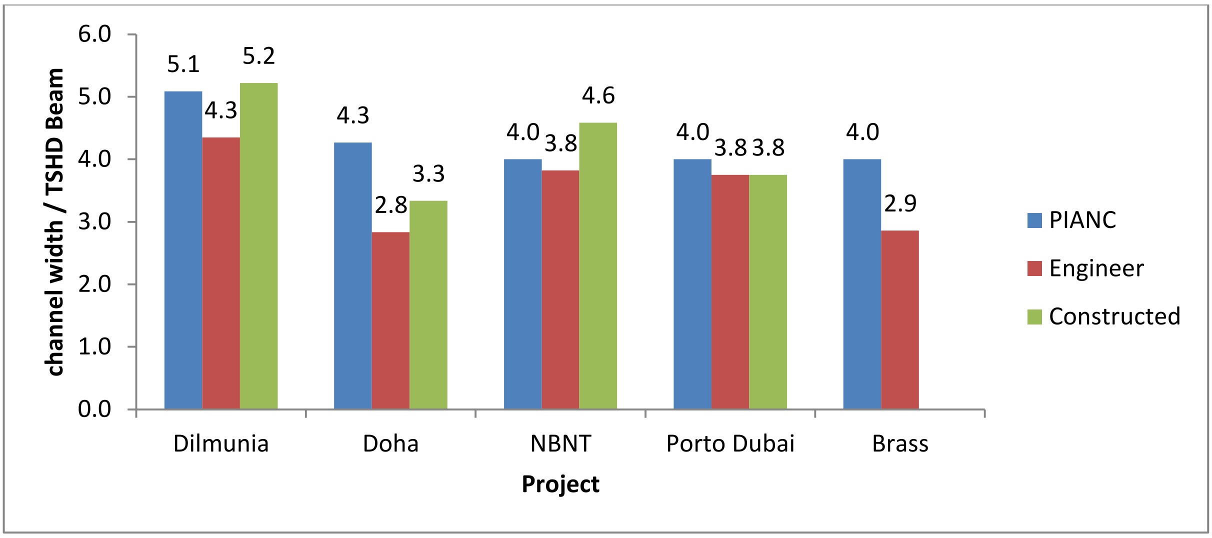


Figure 5.1 - Overview ratio channel width to TSHD beam

It is clear that the calculations of the project engineers give the smallest channel width. This can be explained by different interpretations of the input values. The engineers choose the allowances in such a way that the minimum channel width can be reached. This is done from a commercial point of view. A smaller channel results in lower costs which could be the difference between losing or winning a tender. The channel width as constructed shows the adjusted width after comments of the captains on the project or after adjusting the construction method. It is clear that in all cases the design of the engineers was too small. The design resulting from the safe side of the PIANC rules gives a slight overestimation for the Dilmunia and Doha project. The constructed width in the North Bahrain New Town (NBNT) project seems to give a larger width than the PIANC method. It must be remarked that the channel for this project is eventually constructed as a box-cut profile, which means it has vertical banks. The other channels all have sloping banks which result in a relatively larger wet cross-section compared to the box-cut profile. In general it can be concluded that the PIANC method as it is interpreted by the Boskalis engineers leads to an underestimation of the eventual channel width. Interpreting the PIANC guidelines more strictly leads to a channel width closer to the eventually constructed channel.

5.3.2. Channel depth

The same analysis can be made for the channel depth, by calculating the channel depth to TSHD draught ratio. The blue bar in Figure 5.2 represents the rule of thumb made by PIANC of 1.1 times the ships draught. The red bar again shows the result of the channel depth designed by the engineers and the green bar gives the channel depth to TSHD draught ratio as the channel was eventually constructed. The calculations are given in Table 5.4.

Table 5.4 - Calculation ratio channel depth to TSHD draught

Project	Draught TSHD	Channel width PIANC	engineer	constructed	Ratio width / beam PIANC	engineer	constructed
Dilmunia	6.58	7.2	7.5	8.0	1.1	1.1	1.2
Doha	13.5	14.9	14.8	14.0	1.1	1.1	1.0
NBNT	6.49	7.1	9.0	9.0	1.1	1.4	1.4
Porto Dubai	13.7	15.0	12.0	10.0	1.1	0.9	0.7
Brass	10.0	11.0	10.5	-	1.1	1.1	-

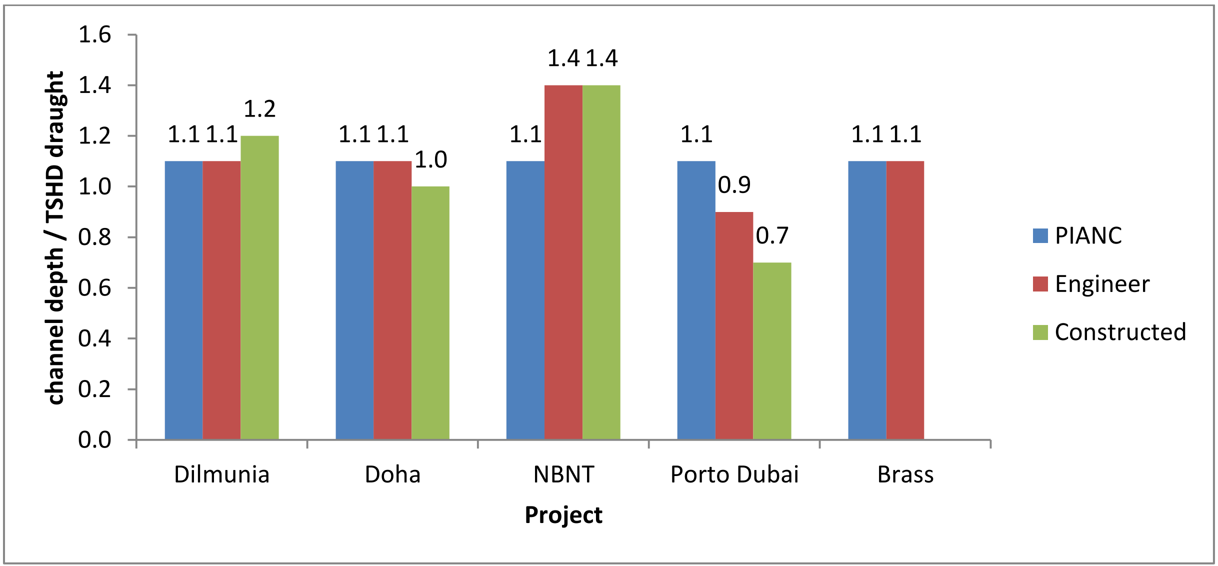


Figure 5.2 - Overview ratio channel depth to TSHD draught

For the determination of the channel depth no clear trend can be found. This can be explained by the fact that in most of the projects the channel depth is not calculated according to the TSHD's maximum draught. As seen in the analysis of the projects, this is often done the other way around. In other words: the PIANC calculates the channel depth by multiplying the maximum draught of the ship with a factor between 1.1 and 1.3. The engineers determine the most ideal channel depth, based on bathymetry or construction method, and calculate the maximum draught of the TSHD. This calculation is made by dividing the channel depth by a factor between 1.1 and 1.3. This method is applied for the projects Dilmunia, Doha and Porto Dubai and NBNT. For the project of Brass a calculation following the PIANC rules was made.

The fact that in some of the projects, the channel design had to be adjusted after construction implies the need of input from the TSHD captains in the design tool. This was also confirmed in the interviews with the TSHD captains. Discussing the design with the TSHD captain can also clarify some of the factors that are hard to quantify in the design, like the risks a captain is willing to take. On the other hand it is not always clear which TSHD or captain will be operating on the project.

Finally the analysis shows that often a two-way channel is applied to increase productivity. An optimization is often made by constructing a stepped profile: a deep fairway for the loaded TSHD's and a shallow fairway for empty TSHD's. When the bottom consists of hard material, like bedrock, the channel design is often influenced by the CSD that is used to construct the channel. This could result in a box-cut cross section. The experience is that this profile has a large negative influence on the use of the channel, mainly with respect to the influence of bank suction effects. It is therefore common practice that side slopes are constructed afterwards to reduce bank suction.

5.4 Conclusions

The analysis of the projects showed that there is a great variation between the design of the dimensions of a channel and the eventual constructed dimensions. There is often even a difference between the design made by an engineer within Boskalis and a design which strictly follows the PIANC guidelines. For the width of the channel this results in a variation between 2.8 and 5.2 times the beam of the design ship. The channel depth varies between 0.7 and 1.4 times the draught of the ship. From the five analyzed projects can be concluded that the designs made by the engineers all show an underestimation of the channel width within a marge of 20%. Strict interpretation of the PIANC guidelines however, approaches the eventually constructed width closer. All the calculations of the channel dimensions within Boskalis are based on the design method of PIANC. The problem that occurs for the channel width is that the method of PIANC is not continuous for changing conditions (see Figure 3.6). Also the rules can be widely interpreted. For the channel depth the PIANC only gives a rule of thumb. The large differences between the designs and the construction of the channel call for a design method that is specifically made for the situation of a TSHD in a temporary work channel.

Based on the analyzed projects and used guidelines, some starting points can be set up to come to a new design method. Within a range of 20% the PIANC guideline gives a good estimation of the channel dimensions. However, there are some disadvantages to this method:

- The guideline is made for the design of an approach channel to a port used by a wide variety of ships, not specifically for a TSHD in a work channel
- The calculation of the channel depth is only based on a rule of thumb
- The calculation of the channel width can be interpreted widely resulting in different channel dimensions for the same input parameters
- The calculation of the channel width is not continuous which, for a certain range of input parameters, could lead to the same channel dimensions for increasing environmental influences.

For a new design method especially for TSHD's in a work channel, the PIANC guideline will be used as a starting point. The disadvantages given above will be improved and only the factors that have an influence on a TSHD in a work channel will be taken into account. For the channel depth this must lead to a more extensive method than just a rule of thumb. All factors that are important according to the end-user of the channel (the TSHD captain) must be included. For the calculation of the channel width, it is important that the new design tool provides a continuous design for changing conditions. The differences in interpretation of the input data must be excluded, the input data must lead to only one design. For the channel width also holds that only the factors that are important for the case of a TSHD in a temporary work channel are included in the design tool. In the next chapter the formation of the design tool will be discussed.

6 Design tool

From the previous chapters followed that there is a clear need for a guideline concerning the design of a temporary work channel and basin used by a TSHD. As seen before in the analysis of the executed projects, the PIANC guideline give a good estimate of the channel dimensions. However, this method has some disadvantages. The new design tool is based on the PIANC guidelines but will be specified for the situation of a TSHD in a work channel. Also the disadvantages of the PIANC guideline are illuminated.

As seen in other guidelines, the design tool computes the channel depth based on the draught and squat of the TSHD and some allowances for environmental influences. The width of the channel is build up as in the PIANC method: a basic manoeuvring lane with an allowance for bank suction on both sides. In case of a two-way channel an allowance for ship-ship interaction is added. Only the factors that influence a TSHD are taken into account. The choice for which factors are taken into account, is based on the experiences of captains and engineers. To reach a continuous and unambiguous design, empirical relations are used as less as possible. Only when no reliable theories are available, an empirical formula is used based on the experiences of the captains. To get a reliable tool, the theories will be checked with the values following from experiences whenever this is possible. This will also be done the other way around.

First of all an overview of the design tool is given. After that, the way the calculation of the channel dimensions is build up is discussed. Finally the calculation method of each factor influencing the channel dimensions is given and all theories or assumptions are checked with experiences.

6.1 Overview design tool

Figure 6.1 represents a flow-diagram of the tool. The design tool is made in the spreadsheet-software Microsoft Excel. In the flow diagram the blue, green and red boxes are the input parameters of the design tool. Blue are the ship characteristics, green are the environmental influences and red are the channel characteristics. The starting values of the channel dimensions are given in the red boxes. The purple boxes represent the calculations made by the design tool, the eventual channel dimensions are given in the orange boxes.

The calculation of squat requires the wet cross-sectional area of the channel. Therefore a first estimate of the channel depth is computed by the design tool. Iteration of these values leads to the final channel depth.

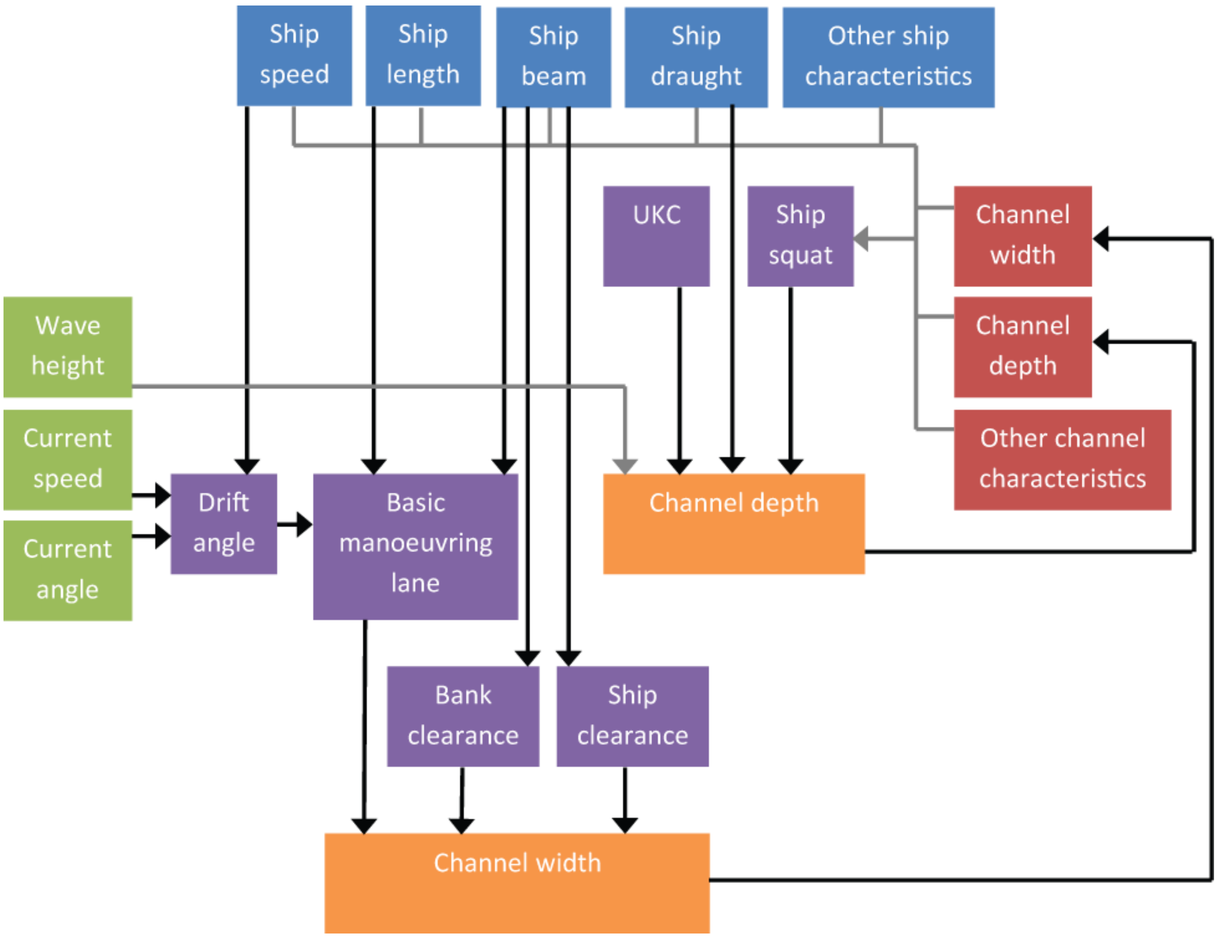


Figure 6.1 - Flow diagram calculation tool

The channel depth is a combination of the ships draught, wave response, the maximum occurring squat and an allowance to reach an acceptable static UKC. The width of the channel is build up from a basic manoeuvring lane. After that an extra width for bank clearance and, in case of a two-way channel, an allowance for ship-ship interaction is added. In the next paragraphs the most important factors in the design tool will be discussed and checked with the theoretical background. After that, all input parameters will be discussed and an overview of the formation of the channel depth and width is given.

6.2 Channel dimensions

The main results of the design tool are the dimensions of the channel. All influences taken into account lead to the calculation of the depth and width of a temporary work channel specially designed for a TSHD. The input parameters can be divided into ship, channel and environmental characteristics. How to calculate the channel dimensions and how to treat the input parameters is discussed in the following section. An overview of the input parameters is given on the next page in Table 6.1.

In the design tool the set of input values is used to calculate three cases: a loaded TSHD in a one-way channel, a loaded TSHD in the deep part of a two-way channel and an unloaded TSHD in the shallow part of a two-way channel. Because of the difference in channel cross-section area, both loaded TSHD's can not be seen as the same case.

Table 6.1 - Input parameters design tool

TSHD parameter		Unit	Remarks
Length	L_{oa}	[m]	*Insert the length of the design TSHD* [1]
Beam	B	[m]	*Insert the beam of the design TSHD* [1]
Draught empty	T_e	[m]	*Insert the draught of a TSHD with an empty hopper* [1]
Draught at dredging load line	T_l	[m]	*Insert the draught of a TSHD loaded at the dredging load line* [1]
Block coefficient empty	$C_{b,e}$	[-]	*Insert the block coefficient of the empty TSHD, as an estimate use 0.85*
Block coefficient loaded	$C_{b,l}$	[-]	*Insert the block coefficient of the loaded TSHD, as an estimate use 0.85*
Empty ship speed	$V_{e,k}$ $V_{e,s}$	[kn] [m/s]	*Insert the sailing speed of an empty TSHD, as an estimate use 16 knots* [2]
Loaded ship speed	$V_{l,k}$ $V_{l,s}$	[kn] [m/s]	*Insert the sailing speed of a loaded TSHD, as an estimate use 8 knots* [2]
Initial trim fore perpendicular Initial trim aft perpendicular	T_{fp} T_{ap}	[m] [m]	*Insert the initial trim at the bow or stern of the TSHD due to an unevenly distributed load*
Propeller configuration	X_p	[-]	*Choose between single or twin propellers*
Bow configuration	X_b	[-]	*Choose between a bulbous bow or no bulbous bow*
Stern configuration	X_s	[-]	*Choose between a transom stern or no transom stern*[3]

[1] *in case of multiple design ships, take the largest value*

[2] *to convert knots into meters per second, use 1 kn = 0.514 m/s*

[3] *a transom stern is a flat, truncated stern*

Channel parameter		Unit	Remarks
Surrounding water depth	h_t	[m]	*Insert the water depth surrounding the channel* [4]
Bank slopes 1:n	n	[-]	*Insert the steepness of the bank slopes*
Channel configuration	X_c	[-]	*Choose between an unrestricted channel (U), a restricted channel (R) or a canal (C) configuration* [5]

[4] *use the water depth with respect to the normative water level*

[5] *see Figure 2.5*

Environmental influence		Unit	Remarks
Bottom material	X_{bm}	[-]	*Choose between hard (rock) or soft (mud) bottom*
Current speed	$V_{c,k}$ $V_{c,s}$	[kn] [m/s]	*Insert the speed of the prevailing current* [2]
Current angle	α_c	[dgr]	*Insert the angle of income of the current with respect to the TSHD's sailing direction, where 0 degrees is at bow and 180 degrees is at stern*

6.2.1 Channel depth

The depth of the channel is determined by five parameters: the reference water level, the static draught, the amount of squat, the response on waves and an extra allowance based on the bottom material.

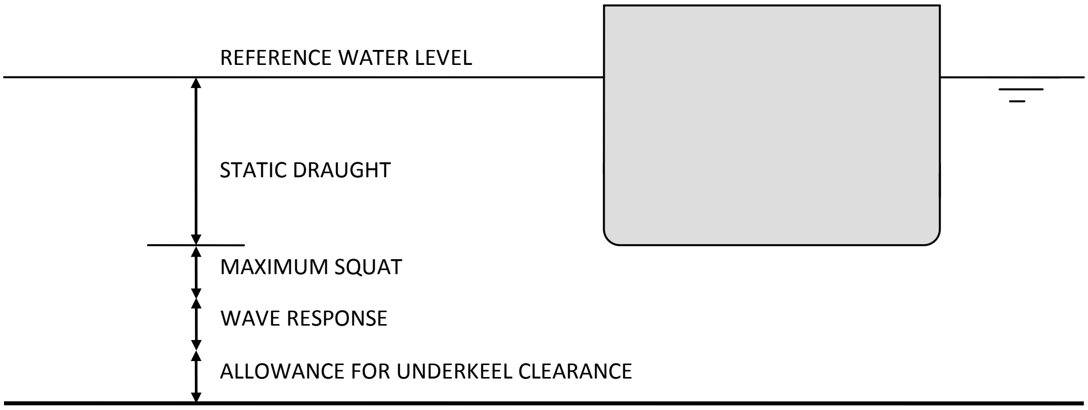


Figure 6.2 - Channel depth calculation

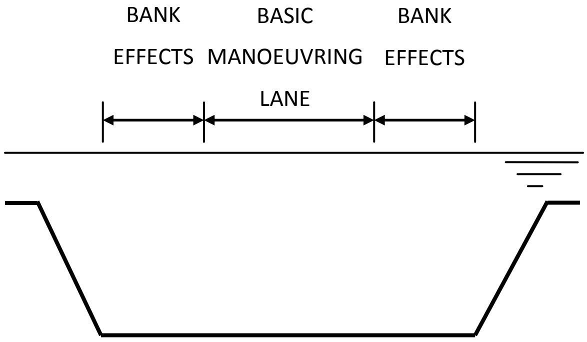
The design tool calculates a channel depth with respect to the reference water level. This water level must be determined based on an acceptable downtime of the TSHD when the water level in practice gets below this value. The calculation of this water level is not considered in the design tool. In engineering practice this water level is determined by the productivity department and the workability desk.

From this reference water level first the static draught of the TSHD is subtracted, depending on the case that is calculated, the loaded or empty draught is used. To compensate for the movement of the TSHD in shallow water, the maximum amount of squat following from the method of Ankudinov is added to this draught. This results in the maximum draught of the TSHD when sailing through the channel. Two extra allowances are also added. The first one is based on the maximum response of the TSHD on incoming waves, which is assumed to be half the significant wave height. Second, based on interviews with the TSHD captains, an extra allowance for net underkeel clearance is added depending on the bottom material. For soft muddy material no allowance is taken into account, for a hard rocky bottom 1 meter is added. Also an intermediate option is included which adds 0.5 meters of net UKC.

All input parameters concerning TSHD and channel in Table 6.4 are used for the calculation of the channel depth. The calculation of squat requires the area of the channel cross-section, which means a first estimate of the channel depth is computed by the design tool. This first estimate is used as an input value to calculate the final channel depth by means of iteration. Based on the analyzed projects, interviews with captains and currently used guidelines an average value is used. The channel depth is estimated at 1.1 times the loaded draught for the deep part of the channel and 1.3 times the empty draught for the shallow part.

6.2.2 Channel width

Basically the channel width is determined by the maximum width of the TSHD's swept path and allowances for bank effects and ship-ship interaction. An overview is given in Figure 6.3.



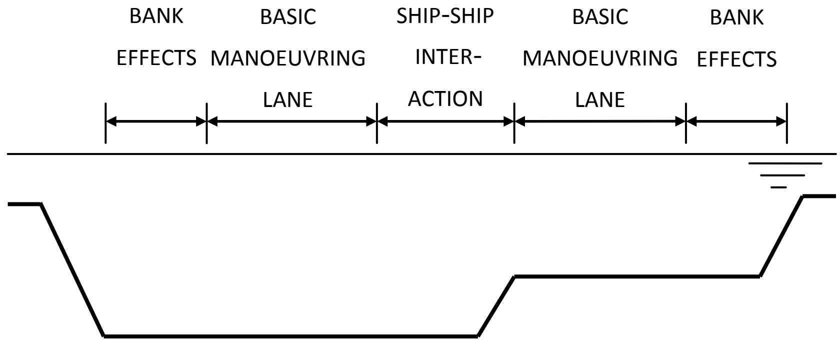


Figure 6.3 - Channel width calculation for one-way (top-left) and two-way traffic (bottom-right)

The most important parameter influencing the channel width is the drift angle of the TSHD due to the prevailing currents. This drift angle β, together with the length and beam of the TSHD, determines the maximum width of the basic manoeuvring lane. This is calculated as follows:

$$W_{BM} = L_{oa} \cdot \sin(\beta) + B \cdot \cos(\beta) \quad \text{[m]} \qquad (6.1)$$

L_{oa}	*ships overall length*	*[m]*
B	*ships beam*	*[m]*

On both sides of this basic manoeuvring lane the allowance for bank suction effects is added, which constists of 1.0 times the TSHD's beam. In case of two-way traffic an extra allowance for ship-ship interaction is taken into account in between the two basic manoeuvring lanes. The width of this buffer is 1.5 times the TSHD's beam. In case of a bend in the channel, an extra width is calculated based on the length of the TSHD and the radius of the bend.

6.2.3 Channel alignment and turning basin

A design method for the alignment of the work channel is not included in the design tool. Of course all the considerations mentioned in the analysis of the current guidelines must be kept in mind, but they are of less importance for a temporary work channel. Strong currents perpendicular to the channel must be avoided as much as possible. However, most of the time the alignment of the channel will be based on the shortest distance between the sand borrow area and the re-handling location. Also the bathymetry of the project location must be investigated closely, as the shortest distance between the sand borrow area and re-handling location does not always result in the shortest channel length. This will often lead to an optimization between the dredging-cycle times and construction costs of the work channel.

The design tool also gives a recommendation for the dimensions of the turning basin, based on the interviews with the TSHD captains. The eventual shape of the basin depends on its function. Often the location of the mounting point with the pipelines, which transports the dredged materials ashore, have a large influence on the shape of the basin. The design tool therefore only gives the minimum dimensions of the basin. This will be a circle with a diameter of 1.5 times the length of the design TSHD.

6.3 Calculation method

This paragraph discusses the actual calculation of all of the influences given above. When the calculation is based on theories developed in the past, the outcome of the calculations will be checked with values given by the captains for some examples. When the magnitude of an influence is based on values indicated by the captains, these values will be checked by the available theories. Off course this can only be done when there are reliable theories available which can be applied on the situation of a TSHD in a work channel.

6.3.1 Ship speed

One of the most important input parameters is the ship speed. It has a large influence on the manoeuvrability and squat of the ship, and therefore on the width and depth of the channel. The captains of the hoppers indicate maximum speeds of 6 to 8 knots for a loaded hopper and 14 to 16 knots for an unloaded hopper. The ship speed is influenced by hydraulic phenomena resulting from movement through a restricted shallow channel [5].

To check the values based on the experiences of the captains, calculations of the limiting speed according to the method of Schijf are done. Schijf's theory is based on the method of preservation of energy and only holds for self-propelled ships in shallow, restricted waters. All currents along the ships hull are schematized into a one-dimensional current. It is assumed that the ship has no trim and that its sinkage is equal to the water level depression in the channel. In a ship-fixed coordinate system continuity conditions are applied on a channel cross-section in front of the ship and in the middle of the ship. This leads to the following continuity equation:

$$Q = V_s \cdot A_c = (V_s + U_r) \cdot (A_c - A_s - W \cdot z) \qquad [\mathrm{m}^3/\mathrm{s}] \qquad (6.2)$$

V_s	*ship speed*	*[m/s]*
U_r	*return current velocity*	*[m/s]*
A_c	*area channel cross-section*	*[m^3]*
A_s	*area ship cross-section*	*[m^3]*
W	*channel width*	*[m]*
z	*water level depression*	*[m]*

Schijf used this theory of preservation of energy to compute a natural limiting speed, a maximum ship speed following from the influences of a restricted channel depth and width. Due to the waterlevel depression (a result from the ships forward movement), the return current along the hull of the ship increases until it reaches a maximum. When the ship speed is increased even more, this results in a change of the flow along the hull from subcritical to critical. This leads to an accumulation of water in front of the bow, which a displacement ship can not overcome. The ship speed at which this occurs is referred to as the limiting speed.

Applying a combination of the continuity equation and Bernoulli's law leads to the following equation for the limiting speed:

$$1-\frac{A_s}{A_c}+\frac{1}{2}\left(\frac{V_{\lim}}{\sqrt{g\cdot \bar{h}}}\right)^2-\frac{3}{2}\left(\frac{V_{\lim}}{\sqrt{g\cdot \bar{h}}}\right)^{2/3}=0 \qquad \text{(canal configuration)} \qquad (6.3)$$

The formula can be simplified for situations with an unrestricted channel width. In that case the cross-sectional area of the channel is very large compared to the area of the ship, which means that A_s / A_c approaches zero. For these cases follows:

$$V_{\lim}=\sqrt{g\cdot \bar{h}} \qquad \text{[m/s]} \quad \text{(unrestricted channel configuration)} \qquad (6.4)$$

V_{lim}	*limiting ship speed*	*[m/s]*
h	*channel depth*	*[m]*

V_{lim} in these equations is maximum possible ship speed. In practice the speed will be lower as sailing at the maximum possible speed results in high costs. As a rule of thumb, the maximum sailing speed in practice is assumed at 90% of the calculated limiting speed.

To check the values given by the TSHD captains, the limiting speed of the five analyzed projects from chapter 5 will be calculated according to the method of Schijf. The results will give an answer to the question if the theoretical values meet the values indicated by the captains. As can be seen in equation 6.2, the limiting speed mainly depends on the cross-sectional areas of the TSHD (A_s) and the channel (A_c). Because of the fact that the hull of the TSHD is not fully blocked, a value of 0.98 times the beam times the draught of the TSHD is used for the cross-sectional area. All the work channels in the analyzed projects have a restricted channel configuration, which means the channel banks do not reach the water surface but are surrounded by a certain water depth. This results in the fact that it is hard to calculate the exact wet channel cross-section of influence, because it is not clear which width of the surrounding water still has an influence on the limiting speed. The influencing width of the surrounding water is referred to as the effective width (Figure 6.4). The method of Schijf does not provide a value for this effective width. The results of the calculations below are based on an effective width of the surrounding water of 8 times the beam of the TSHD. This value is often used in the calculation for the effective width in squat prediction methods given in the PIANC guidelines [2], where this same problem occurs for an unrestricted channel configuration. The input values and results of the calculations are shown in Table 6.2.

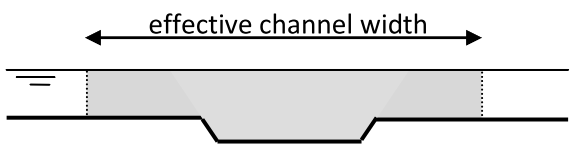


Figure 6.4 - Defenition effective channel width

Table 6.2 - Limiting speed calculations for loaded TSHD's

Project TSHD Condition		Dilmunia Coastway loaded	Doha Fairway loaded	NBNT HAM 309 loaded	Porto Dubai Prins loaded	Porto Dubai Queen loaded
Beam	[m]	23	32	19.63	28	32
Draught	[m]	6.6	13.5	6.49	13.5	13.67
TSHD cross section	[m^2]	149	423	125	370	429
Effective width	[m]	184	256	157	224	256
Channel width	[m]	120	200	90	120	120
Channel depth	[m]	8	12.15	9	10	10
Surrounding depth	[m]	4	4	4	4	4
Bank slopes 1:	[-]	2	2	0	2	2
Channel cross section	[m^2]	1248	2787	1078	1688	1816
A_s / A_c	[-]	0.12	0.15	0.12	0.22	0.24
Limiting speed	**[m/s]**	**5.22**	**5.88**	**5.59**	**4.47**	**4.28**
Limiting speed	**[kn]**	**10.15**	**11.44**	**10.87**	**8.69**	**8.32**
90% limiting speed	***[kn]***	***9.14***	***10.29***	***9.78***	***7.82***	***7.49***

The calculations show a maximum sailing speed between 7.5 and 10.3 knots. This is slightly higher than the 6 to 8 knots indicated by the captains, but it does show that a speed of 6 to 8 knots can be reached in a channel. The lower indication can be explained by the fact that the maximum sailing speed is not only depending on the hydraulic phenomena that are used in the method of Schijf. Also the manoeuvrability and amount of squat of the TSHD are influenced by the sailing speed. These influences can be the reason for the captains to use a lower sailing speed.

Calculations regarding situations with an unloaded hopper are also made to check if the indicated values of 14 to 16 knots can be reached in those cases. The input values and results of the calculations are shown in Table 6.3.

Table 6.3 - Limiting speed calculations for unloaded TSHD's

Project TSHD Condition		Dilmunia Coastway unloaded	Doha Fairway unloaded	NBNT HAM 309 unloaded	Porto Dubai Prins unloaded	Porto Dubai Queen unloaded
Beam	[m]	23	32	19.63	28	32
Draught	[m]	4	6.5	4	6.5	6.5
TSHD cross section	[m^2]	90	204	77	178	204
Effective width	[m]	184	256	157	224	256
Channel width	[m]	120	200	90	120	120
Channel depth	[m]	8	12.15	9	10	10
Surrounding depth	[m]	4	4	4	4	4
Bank slopes 1:	[-]	2	2	0	2	2
Channel cross section	[m^2]	1248	2787	1078	1688	1816
A_s / A_c	[-]	0.07	0.07	0.07	0.11	0.11
Limiting speed	**[m/s]**	**6.01**	**7.38**	**6.39**	**6.07**	**5.95**
Limiting speed	**[kn]**	**11.67**	**14.35**	**12.42**	**11.80**	**11.58**
90% limiting speed	***[kn]***	***10.51***	***12.91***	***11.18***	***10.62***	***10.42***

The resulting maximum sailing speed for an unloaded TSHD lies between 10 and 13 knots. This is lower than the 14 to 16 knots indicated by the captains. This can be explained by the fact that the calculations are based on the part of the channel closest to the basin. This is the part of the channel is surrounded by the smallest water depth, which also followed from the analysis of the projects. A smaller surrounding water depth results in a smaller channel cross-section. The cross-sectional area of the TSHD remains the same and so a lower limiting speed is found. However, in this part of the channel the TSHD does not have such a high sailing speed because it is just leaving the basin and needs to gain speed. The parts where the maximum speed can be reached are further down the channel, in the direction of the open sea. The surrounding water depth also increases in this direction. When the surrounding depth increases, the channel gets less restricted. This means the cross-sectional area of the channel increases, leading to a higher limiting speed further down the channel. Eventually the simplified formula given by equation 6.3 will be used. From this formula follows that a 90% limiting speed of 14 knots is reached at a water depth of 6.53 meters and a speed of 16 knots at a depth of 8.5 meters. It can be concluded that the limiting sailing speed in this case is depending largely on the surrounding water depth and therefore varies among the projects. In general, the sailing speeds indicated by the captains can be reached at a surrounding water depth of approximately 6.5 to 8.5 meters.

6.3.2 Squat

For the prediction of squat, the method of Ankudinov is used. An explanation of this choice is given in chapter 4.2. The following parameters are used in the design tool to calculate the squat:

- Length between perpendiculars of the TSHD
- Beam of the TSHD
- Draught of the TSHD in loaded and in ballasted condition
- Block coefficient of the TSHD in loaded and in ballasted condition
- Sailing speed of the TSHD in loaded and in ballasted condition
- Initial trim of the TSHD at the fore perpendicular
- Initial trim of the TSHD at the aft perpendicular
- Propeller configuration: choice between single or twin propellers
- Bow configuration: choice between a bulbous bow or no bulbous bow
- Stern configuration: choice between a flat, truncated stern or a curved stern
- Surrounding water depth
- Bank slopes of the work channel
- Channel configuration: choice between an unrestricted channel, restricted channel or canal configuration (see Figure 2.5)

The design tool will calculate the squat in three cases. A loaded TSHD in a one-way channel, a loaded TSHD in a two-way channel and an empty TSHD in a two-way channel. Because of the variation in channel cross-section, ship cross-section and sailing speed all three cases will result in different values of squat.

6.3.3 Wave response

From the interviews with the TSHD captains followed that the influence of waves on the drift angle of a TSHD can be neglected. Therefore the influence of waves are not taken into account in the calculation of the channel width. However, waves do have an influence on the vertical motion (heave) of a TSHD. To calculate the motions resulting from an incoming wave, the response amplitude operator (RAO) can be used. This is a transfer function which determines the effect of a certain sea state on the motions of a ship. These calculation require extensive input parameters regarding the ships characteristics. The calculations are often performed by computer programs because of the complexity of the calculation and the interaction between all six degrees of freedom of the ship (see Figure 2.3). However, for the vertical movement of the ship a generalization is made by giving some graphs for the general cases. Looking at those graphs shows that the maximum RAO for a ship manoeuvring in shallow water lies at 1.0. This RAO value is given as the ratio of the vertical ship movement to the incoming wave amplitude.

Because of the fact that the design tool has to be easy and fast in use, a calculation based on extensive input parameters will not be used. An extra allowance of 1.0 times the wave amplitude will be added to the channel depth, which corresponds with 0.5 times the wave height.

6.3.4 Drift angle

The most important factor determining the channel width is the drift angle of the ship. As seen before, a larger drift angle results in a wider swept path of the ship. The main influences on the drift angle are the cross-currents and cross-winds. Both will be analyzed to see their impact on the total drift angle and a calculation method will be determined and checked. Also the sinusoidal movement of the ship around its ideal course can result in a drift angle. The influence of waves will not be taken into account, as this has no significant impact on the ships drift angle according to the experiences of the captains.

Sinusoidal movement

As seen before in chapter 2.1, a ships actual course can be seen as a sinusoidal movement around its theoretical straight course. This is a result of the environmental influences , the speed of response of the captain and that of the ship reacting to the rudder. This movement results in a drift angle with respect to the straight course. The amount of drift angle is depending on the manoeuvrability of the ship. From the interviews with the TSHD captains followed that the sinusoidal movement of a TSHD is very small due to the high manoeuvrability. The captains stated that the resulting drift angle can be neglected compared to a drift angle resulting from environmental conditions. The design tool therefore does not take the sinusoidal movement into account by means of a drift angle. The deviation of the course will be adapted by an allowance in channel width which will be explained later on in this chapter.

Currents

From the interviews with the captains followed that the impact of the current should be the largest. A cross current of 2 to 3 knots at a sailing speed of 8 knots should result in a drift angle of approximately 20 degrees, which is the maximum drift angle allowed by the TSHD captains. The resulting drift angle due to currents can be calculated with some goniometrical rules. The incoming current can be resolved in a component in the direction of the ships speed, and in a component perpendicular to that. Due to this first component, the ships speed could show a slight increase or decrease (or none at all) depending on the currents angle of income. This new forward speed of the ship combined with the cross-component of the current, results in the drift angle. A schematization is shown in Figure 6.5.

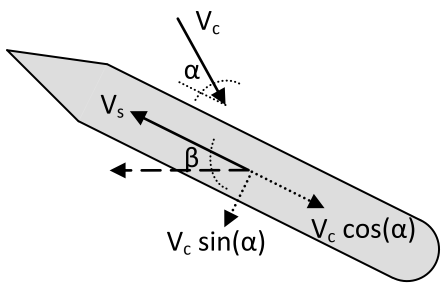


Figure 6.5 - Schematization drift angle due to currents

The ships forward speed is given by V_s and the current speed is given by V_c. α_c represents the angle of income of the current with respect to the ships forward speed. The resulting drift angle is given by β. To calculate this drift angle, the schematization results in the following formula:

$$\beta = \arctan\left(\frac{V_c \cdot \sin(\alpha_c)}{V_s - V_c \cdot \cos(\alpha_c)}\right) \qquad \text{[dgr]} \qquad (6.5)$$

β	*drift angle*	*[dgr]*
V_c	*current speed*	*[m/s]*
V_s	*ship speed*	*[m/s]*
α_c	*angle of income of the current*	*[dgr]*

Up to a current angle of 90 degrees the cosines results in a positive value, therefore decreasing the total forward ship speed by the minus sign in the formula. For larger angles, and negative cosines, the ship speed is increased. An example calculation with a current speed of 3 knots and a ship speed of 8 knots is made. The calculation is made for all current angles from 0 to 180 degrees. This resulted in a maximum drift angle of 22.0 degrees at a current angle of 68 degrees. A cross-current at 90 degrees resulted in a drift angle of 20.5 degrees. The distribution of the drift angle for varying current angle is given in Figure 6.6. These results show a good agreement with the value of 20 degrees given by the hopper captains.

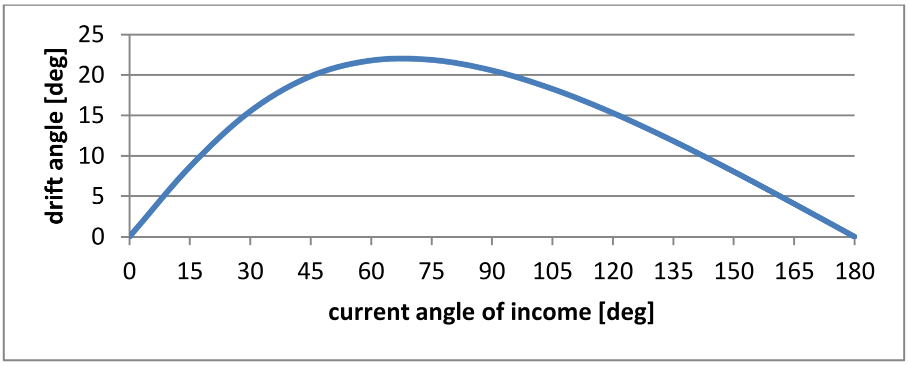


Figure 6.6 - Distribution of the drift angle for a sailing speed 8 knots.

The current angle of income which results in the maximum drift angle varies with the current and ship speed. In practice the normative current direction is often given as a certain range, for example 35 to 45 degrees. In that case it is very helpful to know where the maximum is located. For that purpose, the design tool will display the distribution of the drift angle over the current angle of income.

Wind

The drift angle due to wind force on a ship is a result of the pressure caused by the wind on the part of the ship above the waterline and the resistance of the water on the submerged part of the ships hull. The resulting drift angle is therefore largely depending on the area and position of the superstructure and draught of the ship. The differences in density between water and air also have an influence as the water resistance is often very large compared to the wind force. The superstructure of a TSHD has a small area and is very open which leads to a small drift angle due to wind. According to the captains the influence of the wind on a TSHD is negligible and will therefore not be taken into account in the design tool.

6.3.5 Other allowances

As seen before the so-called basic manoeuvring lane of a channel is determined by the ships swept path caused by a drift angle. Next to the basic manoeuvring lane, the channel needs a safety margin to take the bank suction effects into account. This margin is also used to take other deviations from the center of the channel into account, like the sinusoidal movement of the TSHD. In case of two-way traffic, an extra width between the two basic manoeuvring lanes will be used to guarantee safe encountering of ships.

Bank suction

The past few years some research is done on the influence of the channel banks on the manoeuvrability of a ship [17]. It is clear that the bank effects can be divided into a sway force and a yaw moment. The theories used to calculate these forces are all based on model tests and are therefore rather restricted in use. A method based on TSHD's is not available. Besides that it is hard to judge when a captain thinks the bank influences are of the magnitude that it influences the manoeuvrability too much. Based on the experiences of the captains a distance of one times the beam of the largest ship will be used in the design tool.

Ship-ship interaction

The same as indicated above also holds for ship-ship interaction. Some research is done, based on model tests not including a TSHD. A general conclusion is that the forces and moments decrease with increasing lateral distance between the ships. Also an increasing ships draught and decreasing underkeel clearance results in higher interaction forces. The distance taken into account by two ships encountering head-on is also depending largely on the situation. The experience of the captains and their mutual communication plays a large role. As a rule of thumb for TSHD's in a work channel a ship clearance of 1.5 times the ships beam is taken into account, where ship clearance is defined as the distance between the two basic manoeuvring lanes.

6.3.6 Bends

Sailing through a bend in a channel leads to some differences compared to a straight section. First there is the oblique position of the ship with regard to the centerline of the channel. Second, the drift angle of the ship increases to compensate the centrifugal force. Due to this oblique position and increase in drift angle, the swept path of the ship becomes larger. This could result in a larger required channel width. From interviews with TSHD captains followed that there is no difference in the behavior in a bend between a TSHD and a conventional ship. All captains also stated that they have no experiences with the situation of a bend in a temporary work channel. From the analysis of projects and interview with engineers at Boskalis also followed that a bend in a temporary work channel is seldom applied. However, this situation could occur and therefore the design of a bend is included in the design tool.

Several studies have been done leading to formulae to calculate the extra required channel width in a bend. All the formulae can be reduced to one general formula [5]:

$$\Delta W = 0.50 \cdot \frac{L}{R} \qquad \text{for unloaded ships} \qquad [m] \tag{6.6}$$

$$\Delta W = 0.25 \cdot \frac{L}{R} \qquad \text{for loaded ships} \qquad [m] \tag{6.7}$$

ΔW	*channel width increase*	*[m]*
L	*ship length*	*[m]*
R	*bend radius*	*[m]*

The radius of the bend is depending on the angle of the turn, which is defined as the angle between the two straight parts the bend is connecting (see Figure 6.7).

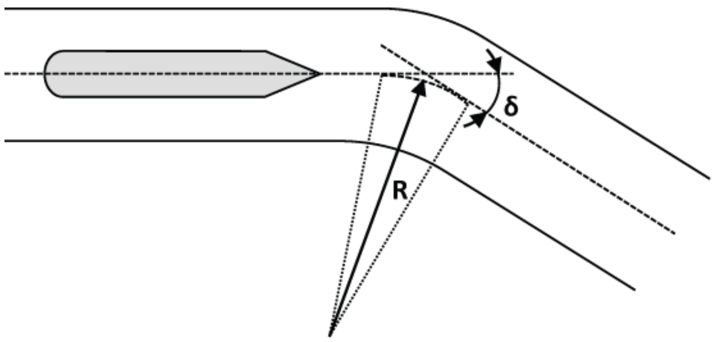


Figure 6.7 - Bend configuration

In the design of the bend, the values for the bend radius given in Table 6.4 can be used [9].

Table 6.4 - Bend radius for given turn angle

Turn angle (δ) [dgr]	Bend radius (R) [m]
< 10	0
10	3.0 L
25	5.0 L
35	7.0 L
50	10.0 L
> 50	> 10.0 L

7 Fast-time simulation (SHIPMA)

The previous chapter described the method used in the design tool to calculate the dimensions of a temporary work channel for a TSHD. The next step is to make sure that the resulting design will suffice in a practical application. A good method to make this check, is by applying a computer simulation model. These models can generally be divided into two categories: real-time and fast-time simulators. The most important difference between the two is the input. In a real-time simulator the ship is actually steered by the person controlling the model, which in the most ideal situation is an experienced helmsman. A fast-time simulator is controlled by an autopilot which follows a pre-set course. The main advantage of the real-time simulator is that it gives a very reliable presentation of the real situation. It can show how a captain would respond in the simulated situation. This also means that if the model is used by a person without any shipping-skills, the results are rather useless. The largest disadvantage is that it is very time-consuming and expensive. The fast-time simulation on the other hand, often requires short computation time which makes it easy to make small changes in the simulated situation without losing too much time.

For testing the design tool the fast-time simulation model “SHIPMA” is used. First of all a description of the model is given in the next paragraph. After that the input of the model is discussed by choosing a project case, representative TSHD and environmental characteristics. This input also results in the dimensions of a work channel according to the design tool. Eventually the results will be analyzed and an assessment of the design of the channel, and therefore of the design tool, will be made.

7.1 Description of the fast-time simulation model SHIPMA

The fast-time simulation software SHIPMA is developed by Deltares and MARIN (Maritime Research Institute Netherlands). The model is used for the design of ports and fairways and gives insight into the restrictions of ships, infrastructure and environmental conditions. SHIPMA uses an autopilot which is capable to follow a pre-set course or perform several manoeuvres within a port. The input of the model can be roughly divided into four parts: the ship, the location, the environmental conditions and the desired course or manoeuvre. This also follows from the main screen of the program shown in Figure 7.1.

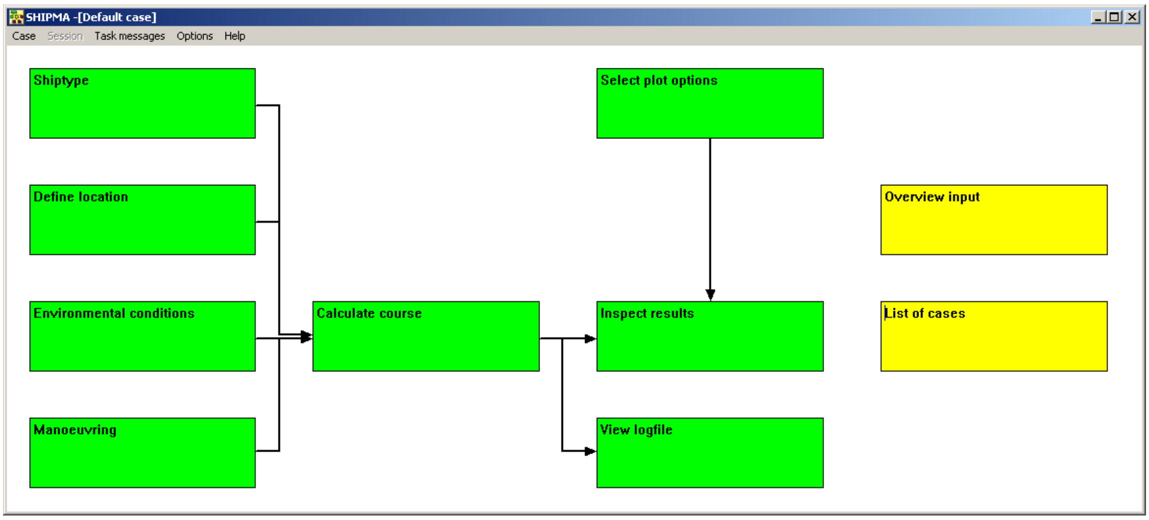


Figure 7.1 - Main screen of SHIPMA

The model of the ships are made by MARIN and consist of hydrodynamic derivatives which are specifically determined for each ship and follow from model scale tests or hydrodynamic calculations. These hydrodynamic derivatives represent the manoeuvring characteristics of the ship. Besides that the ship is described by characteristics like dimensions, mass and windage area.

The input-data concerning the project site is defined by selecting the correct layout, bottom bathymetry, bank suction lines, flow-, wave-, wind- and swell-conditions. All the input files can be adjusted to the users preferences.

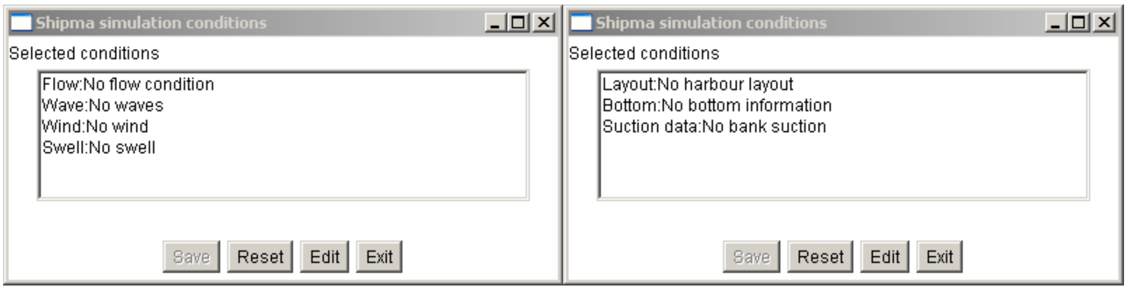


Figure 7.2 - SHIPMA input screens for environmental conditions and layout

The autopilot is configured in a file called the manoeuvring-file, which contains information concerning the nature of the manoeuvre, desired track, starting position and (if necessary) tug-properties.

When all input-files are configured in such a way that it approaches the simulated situation, the course can be calculated and the results can be inspected. Several output-data can be selected, such as:

- Track, position, course and heading of the ship
- Course deviation and distance to the desired track
- Rudder angle and number of propeller revolutions
- Characteristics of the environmental conditions and their resulting forces on the ship

Especially the data concerning the deviations with respect to the desired track, rudder- and drift angle can be of great importance in the analysis of the design of a work channel.

7.2 Simulation project: Bahrain

As a test case for the design of a work channel according to the design tool, a fictive project is used. For the location the analyzed project of chapter 5.1.1 is used. The project consists of the construction of an island off the coast of Bahrain, a satellite image of the area is given in Figure 7.3. The sand borrow area is located 5 to 10 kilometers off the coastline. The dredged material will be pumped ashore from a central point which lies about 1200 meters away from the location of the island. Because of the shallow water close to the construction site, a temporary work channel and basin are needed. The water depth at the location of the basin is 3.3 meters. A work channel connecting the re-handling basin with the deep waters near the sand borrow area will be designed with the before mentioned design tool.

Figure 7.3 - Satellite image of the Bahrain project

The depth contour-lines found on a detailed chart are inserted into the SHIPMA bottom-file, the contours of the coastline and the island are described in the layout-file. The environmental conditions in the project area are provided by the workability desk of Boskalis. The following normative situation is found:

- Currents: 0.5 knots, originating from 150 degrees
- Wind: 15 m/s, originating from 150 degrees
- Waves: height 1.3 m, period 6.0 s, originating from 150 degrees

Each condition is described in a separate file which is loaded into the SHIPMA model. This way it is easy to switch every environmental condition on or off to see its influence on the track of the TSHD. It is also possible to decrease or increase an environmental influence by using a scale factor which is included in all of these files. The situation where all conditions are at their maximum simultaneously will be used as the normative situation for assessing the design.

7.2.1 Design ship

The last input that is needed to start the design of the work channel is the design ship. As mentioned before, a ship in SHIPMA is described by a set of hydrodynamic derivatives. Most of the ships are made at MARIN by the requirements of their clients. Some of these ships are available at Deltares for simulation purposes, however none of these ships is a trailing suction hopper dredger. This is a problem which can be solved in two ways. The first options is to let MARIN make a digital model of one of the TSHD's of Boskalis to use in SHIPMA. This means MARIN has to make a thorough inventory of the TSHD's characteristics and perform several calculations to collect the hydrodynamic derivatives. Doing this takes quite some time, which was not available within this master thesis. The other option is to search within the list of available ships for one that approaches the characteristics of a TSHD. Eventually this option will be used for the simulation runs in this thesis.

During the search for a ship in the Deltares database another problem arose. Most of the SHIPMA simulation studies carried out by Deltares concerning the entrance and/or berthing of a commercial cargo ship in a port. This leads to the fact that most of the ships in the database have much larger dimensions than the average TSHD's used by Boskalis. Eventually the search ended up at a bulk carrier which approaches the dimensions of the *Queen of the Netherlands*, which is one of the largest TSHD's in the fleet of Boskalis. Because of this large resemblance in main dimensions, given in Table 7.1, this ship will be used in the simulation runs.

Table 7.1 - Main dimensions of the design ship and TSHD

	Queen of the Netherlands	SHIPMA (BUL242g1)
Length [m]	230.71	225.00
Beam [m]	32.00	32.20
Draught [m]	13.67	12.0

Looking at the main dimensions the design ship is roughly the same as the TSHD, but the ships differ on several other points. A TSHD has some typical length-beam-draught ratio's which makes the ship very full (high block coefficient) and sluggish. This is compensated by installing high power, twin propellers, twin rudders and bow thrusters. This makes the TSHD a highly manoeuvrable ship. The design ship for SHIPMA is a bulk carrier which almost has the same dimensions as the TSHD *Queen of the Netherlands*. The requirements regarding the propulsion set-up of the *Queen of the Netherlands* are not met for this bulk carrier. This makes the bulk carrier a lot less manoeuvrable which has some consequences for the results of the simulation runs. The extra installed power and bow thrusters of the TSHD can only be used at low speeds, around 2 knots or lower. At these low speeds the difference between the bulk carrier and the TSHD is too large to reach reliable results. Therefore the SHIPMA simulations will not be used to check the manoeuvring of the TSHD at low speeds, for example entering the basin or turning. At sailing speeds used to navigate through the channel (varying between 4 and 16 knots) the installed power is of less importance and will therefore give better results.

Off course, running the simulations with a ship that comes closer to a TSHD of Boskalis would give better results. It is therefore useful to make an inventory of the TSHD's within the fleet of Boskalis.

Based on this inventory an advise can be given which ship would be ideal for other simulations in the future. As seen before, a TSHD has some typical characteristics which makes it different from other commercial ships. Looking at the ratio between some of the characteristics shows a trend which can be used to describe the general form of a TSHD. These ratios and other characteristics are investigated and published in the master thesis of M.J. Kuiper [14]. This research is based on the TSHD's constructed at IHC shipyard in the period of 1975 to 2005. In general, the following trend was found:

- Beam to loaded draught ratio between 2.7 and 3.0 (increasing over the last years)
- Length to beam ratio between 5.5 and 5.0 (decreasing over the last years)
- Propeller diameter to loaded draught ratio between 0.4 and 0.5
- Block coefficient between 0.81 and 0.87
- Power density of the propellers between 320 and 420 kN/m^2
- Recently constructed TSHD's (2001 – 2005) are equipped with twin propellers
- Recently constructed TSHD's (2001 – 2005) often are shaped with a bulbous bow

A same trend can be found by looking at the TSHD's in the fleet of Boskalis. The main characteristics of 17 TSHD's are given in an overview in Table 7.2.

Table 7.2 - Overview main characteristics TSHD's Boskalis

TSHD name	year of construction	Length (L_{oa}) [m]	beam [m]	max draught [m]	propulsion power sailing [kW]	bow thruster [kW]	bulbous bow
Gateway	2010	137	28	10	12000	1400	yes
Willem van Oranje	2010	137	28	10	12000	1400	yes
Queen of the Netherlands	2009[1]	230.71	32	13.67	23000	2650	yes
Crestway	2008	97.5	21.6	7.1	4000	450	yes
Shoreway	2008	97.5	21.6	7.1	4000	450	yes
Oranje	2004	156	28	12.02	14000	1400	yes
Prins der Nederlanden	2004	156	28	12.02	14000	1400	yes
Puerto Mexico	2003[2]	113.6	20	8.2	9482	550	no
Coastway	2002	97.7	23	6.58	4000	500	yes
Seaway	2001[3]	171.9	22	10.55	8800	1000	no
Waterway	2001	97.7	23	6.58	4000	500	yes
Stuyvesant	1994[4]	113.39	21.95	10.62	9650	2720	no
Argonaut	1990	85.86	14	6.3	1956	220	no
Coronaut	1988	85.86	14	5.25	1956	220	no
Barent Zanen	1984	133.58	23.13	8.81	9120	750	no
Cornelis Zanen	1982	132.2	23	8.85	9120	756	no
Cornelia	1981	112.76	19.6	7.45	6760	550	no

[1] *constructed in 1998, updated and lengthened in 2009*

[2] *constructed in 1980, updated and lengthened in 2003*

[3] *constructed in 1986, updated and lengthened in 2001*

[4] *constructed in 1981, updated and lengthened in 1994*

A trend in TSHD dimensions can be found by looking at the beam to draught and length to beam ratio's. Both ratio's show a decrease over the last years, as was also concluded by Kuiper. Roughly the analyzed TSHD's can be divided into two categories: TSHD's originally constructed between 1981 and 2000, and TSHD's constructed from 2001 till 2010. The results are given in Table 7.3.

Table 7.3 - Typical TSHD dimension ratio's

	Constructed 1981 – 2010		Constructed 1981 – 2000		Constructed 2001 – 2010	
	B/T	L/B	B/T	L/B	B/T	L/B
Minimum	2.07	4.25	2.07	5.17	2.33	4.25
Average	2.65	5.52	2.41	6.16	2.92	4.81
Maximum	3.50	7.81	2.67	7.81	3.50	5.57

In the future the TSHD's constructed between 1981 and 2000 will be used less and less. The ideal design TSHD should therefore have a B/T and L/B which approaches the average of the TSHD's constructed in the last 10 years. A search for that TSHD ends up at the *Gateway* and *Willem van Oranje* which both have an B/T of 2.80 and a L/B of 4.89. If Boskalis decides to invest in making a TSHD model to be used in manoeuvring simulation software, it is advised to use one of these two TSHD's.

7.2.2 Channel dimension

Now that all input values are determined, the design tool can be used to make a calculation of the channel dimensions. Two situations will be examined: a one-way channel with a constant depth and a two-way channel with a deep and a shallow part. The channel dimensions calculated by the design tool are given in Table 7.4 and Table 7.5.

Table 7.4 - Channel depth calculation Bahrain

	Static draught [m]	Maximum squat [m]	Wave response [m]	UKC allowance [m]	Total depth [m]
One-way	13.70	0.69	1.00	0.65	**16.04**
Two-way, deep part	13.70	0.64	1.00	0.65	**15.99**
Two-way, shallow part	5.00	1.61	1.00	0.65	**8.26**

Table 7.5 - Channel width calculation Bahrain

	Bank clearance [m]	Width loaded [m]	Bend width [m]	Ship clearance [m]	Width empty [m]	Bend width [m]	Bank clearance [m]	Total width [m]
One-way straight	32.0	46.3	-	-	-	-	32.0	**110.3**
Two-way straight	32.0	46.3	-	48.0	40.2	-	32.0	**198.5**
One-way bend	32.0	46.3	-	-	-	19.2	32.0	**129.5**
Two-way bend	32.0	46.3	9.6	48.0	40.2	19.2	32.0	**227.3**

The following dimensions are the output of the design tool. The one-way channel has a depth of 16.0 meters and a width at the bottom of 110.3 meters. The deep part of the two-way channel has a depth of 16.0 meters, the shallow part is 8.3 meters deep. The manoeuvring lane of the deep part is 46.3 meters wide, the other lane has a width of 40.2 meters. This results in a total width of 198.5 meters measured between the toes of the outer slopes. In all cross-sections the bank slopes are considered 1:2. The distances for bank clearance are all 32.0 meters and the ship-ship interaction marge is 48 meters.

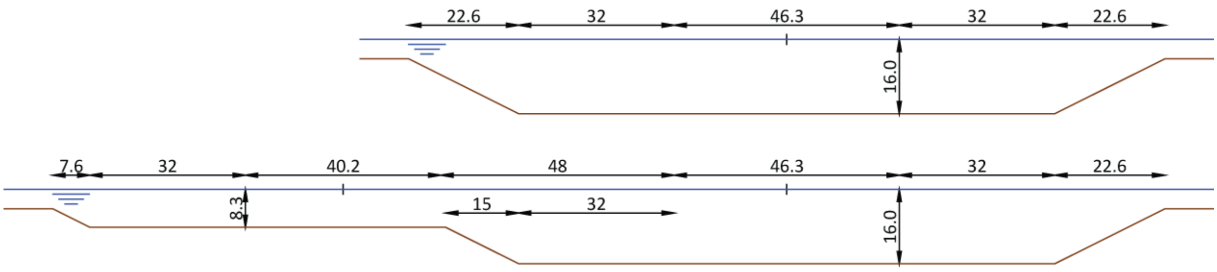


Figure 7.4 - Channel cross-sections calculated by the design tool

The channel also contains a bend of 30 degrees, with a radius of 5 times the length of the TSHD (1384 meters). This results in an extra channel width in the bends of 9.6 meters in the deep part of the channel and 19.2 meters in the shallow part.

The overview situation given by SHIPMA for these input values is given in Figure 7.5.

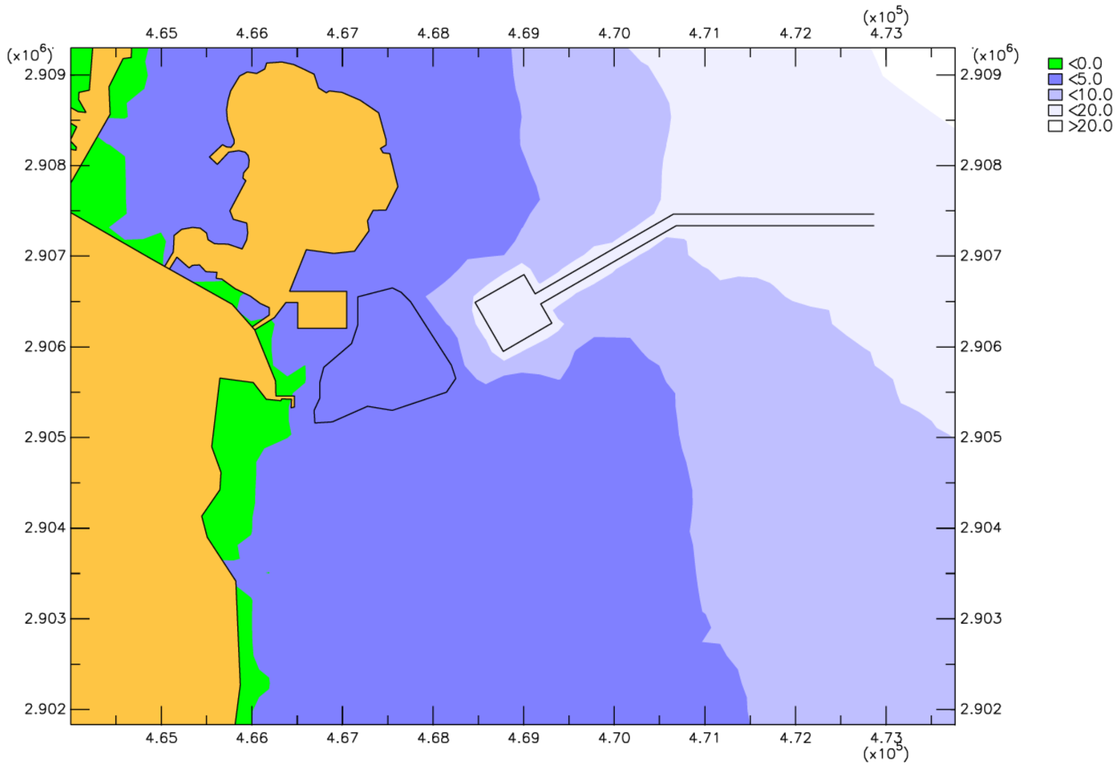


Figure 7.5 - Overview situation in SHIPMA

7.3 Simulation runs

In order to make an assessment of the design made by the design tool, several scenario's will be investigated. First of all there is the difference between a one-way and a two-way channel, which will both be simulated. Besides that both channels will be examined in a situation where no environmental conditions are applied, and in a normative situation with all environmental condition active. Also the influence of each environmental influence will be investigated by making runs with only one condition active. Based on the results some extra runs will be done with the most influencing environmental condition, where it will be varied in magnitude. An overview of all cases is given in Table 7.6.

Table 7.6 - Overview simulation cases

	Channel configuration	Direction	Environmental conditions	Sailing speed
Case 1	One-way	East - west	No conditions	6 to 8 knots
Case 2	One-way	West - east	No conditions	14 to 16 knots
Case 3	Two-way	East - west	No conditions	6 to 8 knots
Case 4	Two-way	West - east	No conditions	14 to 16 knots
Case 5	One-way	East - west	Currents 0.5 knots (0.26 m/s)	6 to 8 knots
Case 6	One-way	West - east	Currents 0.5 knots (0.26 m/s)	14 to 16 knots
Case 7	Two-way	East - west	Currents 0.5 knots (0.26 m/s)	6 to 8 knots
Case 8	Two-way	West - east	Currents 0.5 knots (0.26 m/s)	14 to 16 knots
Case 9	One-way	East - west	Wind 15 m/s	6 to 8 knots
Case 10	One-way	West - east	Wind 15 m/s	14 to 16 knots
Case 11	Two-way	East - west	Wind 15 m/s	6 to 8 knots
Case 12	Two-way	West - east	Wind 15 m/s	14 to 16 knots
Case 13	One-way	East - west	Waves 1.3 m, 6.0 sec	6 to 8 knots
Case 14	One-way	West - east	Waves 1.3 m, 6.0 sec	14 to 16 knots
Case 15	Two-way	East - west	Waves 1.3 m, 6.0 sec	6 to 8 knots
Case 16	Two-way	West - east	Waves 1.3 m, 6.0 sec	14 to 16 knots
Case 17	One-way	East - west	All conditions	6 to 8 knots
Case 18	One-way	West - east	All conditions	14 to 16 knots
Case 19	Two-way	East - west	All conditions	6 to 8 knots
Case 20	Two-way	West - east	All conditions	14 to 16 knots
Case 21	Two-way	East - west	Currents 1.0 knots (0.51 m/s)	6 to 8 knots
Case 22	Two-way	East - west	Currents 1.5 knots (0.77 m/s)	6 to 8 knots
Case 23	Two-way	East - west	Currents 2.0 knots (1.03 m/s)	6 to 8 knots
Case 24	Two-way	East - west	Currents 3.0 knots (1.54 m/s)	6 to 8 knots

A total overview of all results is added to the report in appendix B. In the next paragraph the most important results are given and discussed.

7.4 Analysis of simulation results

As seen before in the description of the SHIPMA model, several output data can be given for the cases in Table 7.6. First will be determined which output data of SHIPMA will be used for assessing the design tool. After that the data can be analyzed and compared to the results of a calculation made by the design tool.

7.4.1 Available SHIPMA output data

The design tool is used to calculate the width, depth and turning basin dimensions of a temporary work channel for a TSHD. The fast-time simulation software SHIPMA is used to check the results of this design tool for a representative case. Because of the two-dimensional setup of the SHIPMA software, output data regarding the draught of the ship or the available UKC is not given. This means the depth of the channel can not be checked by means of SHIPMA data. A same problem occurs for the check of the dimensions of the turning basin. Because of the difference in manoeuvrability at low speed between the TSHD *Queen of the Netherlands* and the bulk carrier used in SHIPMA, a representative turning manoeuvre inside the basin could not be simulated. The SHIPMA output will therefore only be used to check the width of the channel.

To make an assessment of the channel width, data concerning the ships swept path will be used. As seen before in the design considerations of a channel, the width of the ships swept path is determined by two factors. Both definitions are shown in Figure 7.6.

- The sinusoidal movement around the desired track. This can be analyzed in SHIPMA by means of the cross-track deviation of the ship, which represents the distance (in meters) from a point on the ship perpendicular to the ships course. The cross-track deviation is given for the center of the ship and the largest distances on portside and starboard.
- The drift angle of the ship. SHIPMA gives data concerning the drift angle by means of the course deviation. This is defined as the angle between the desired course and the sailed course of the ship at a certain point on the track and is given in degrees.

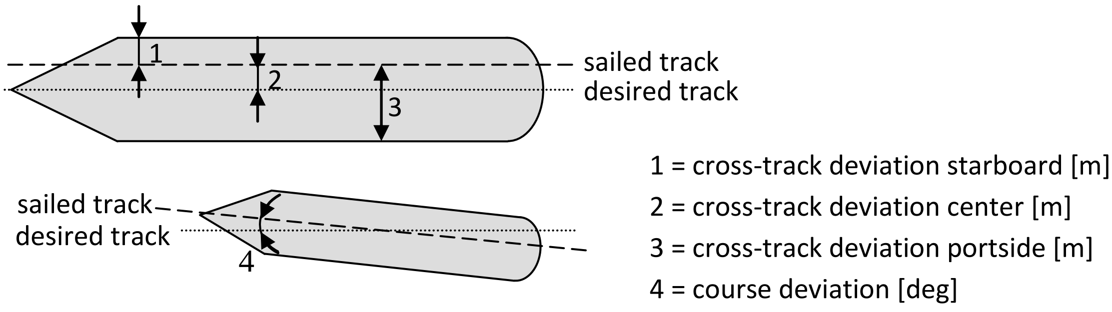


Figure 7.6 - Definition of cross-track deviation and course deviation

All the results of the SHIPMA simulations are given with respect to the pre-set ideal track of the TSHD. Before analyzing the results it is important to know more about the course and ships speed along the track. An overview of the track with distances in meters, are given in Figure 7.7 for the incoming direction and in Figure 7.8 for the outgoing direction (in these figures a two-way channel is shown). To give an indication of the sailed track, the track log of the situation when sailing under influence of the currents is also displayed in these figures.

In general the track can be divided into three parts. In the incoming direction, the first part starts at the deep water and ends at the channel entrance which corresponds to the distance along the track from 0 to 2000 meters. This is the part where the TSHD slows down from a high sailing speed (14 to 16 knots) at deep water to a speed of 8 knots at the channel entrance. The second part is between the entrance channel at 2000 meters and the bend in the channel located at about 4000 meters. In this part the TSHD sails at a speed of 8 knots and slows down to 6 knots to enter the bend. The last part of the track is located between 4000 and 6000 meters from the start, and contains the straight end between the bend and the turning basin. In this part the sailing speed remains 6 knots. All sailing speeds given above are based on interviews with TSHD captains.

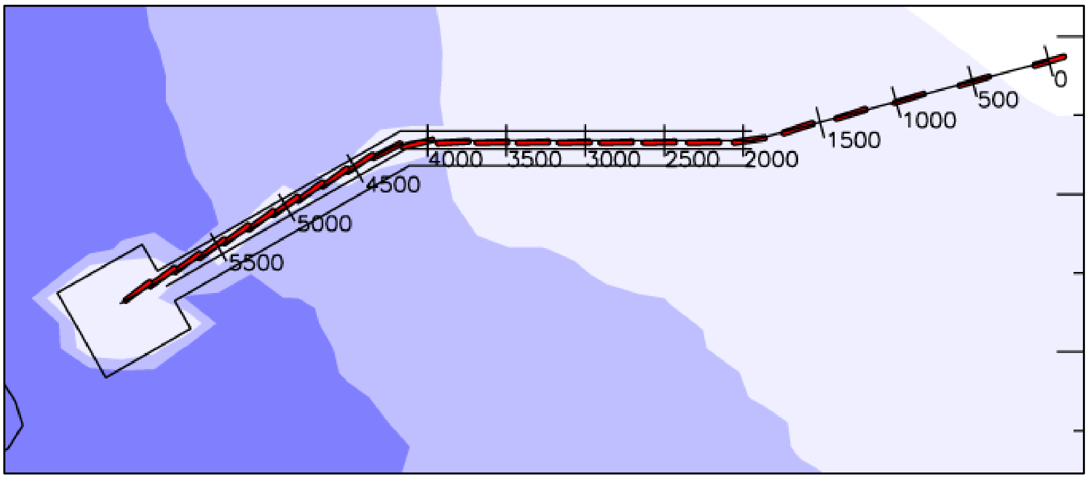


Figure 7.7 - Pre-set track for incoming direction (two-way channel)

For the cases where the ship is sailing in an outgoing direction, the three parts are the other way around. The only difference is the sailing speed. The cases with an outgoing direction represent the trip of an empty TSHD towards the sand borrow area. Because of the ballasted hopper, the sailing speed through the channel in these cases will be higher. In the first part from 0 to 2000 meters, the ship will increase its speed up to 14 knots. After the bend, in the part of the channel from 2000 to 4000 meters and further, the sailing speed increases till 16 knots. For all cases simulated by SHIPMA, the maximum cross-track and course deviations are determined for the two parts inside the channel.

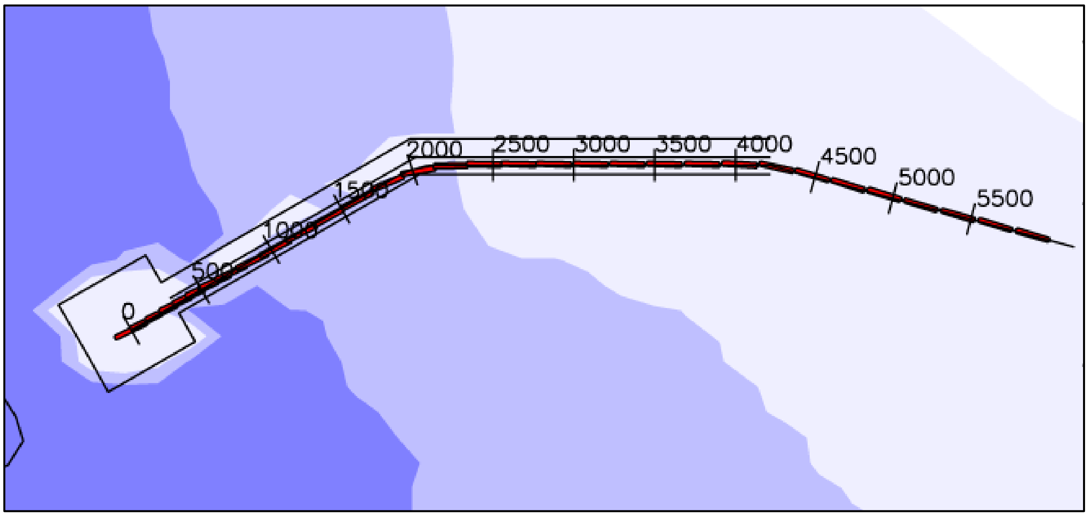


Figure 7.8 - Pre-set track for outgoing direction (two-way channel)

7.4.2 Assessment of channel width

To make an assessment of the channel dimensions calculated by the design tool, three output parameters are used to make a comparison. For each simulation case the following three parameters will be determined or calculated:

- Drift angle: the drift angle calculated by the design tool will be compared with the drift angle given by the course deviation in SHIPMA.
- Maximum swept path: the width of the channel calculated by the design tool will be compared with the maximum distance between the cross-track deviation on starboard and portside in SHIPMA. (see Figure 7.9)
- Maximum channel width: the width of the channel calculated by the design tool will be compared with the maximum required channel width according to SHIPMA. SHIPMA determines the maximum drift angle and maximum cross-track deviation of the center of the ship. Based on this drift angle, the width of the swept path can be calculated. The maximum channel width according to SHIPMA is found by adding the maximum cross-track deviation of the center of the ship to both sides of the maximum swept path. (see Figure 7.9)

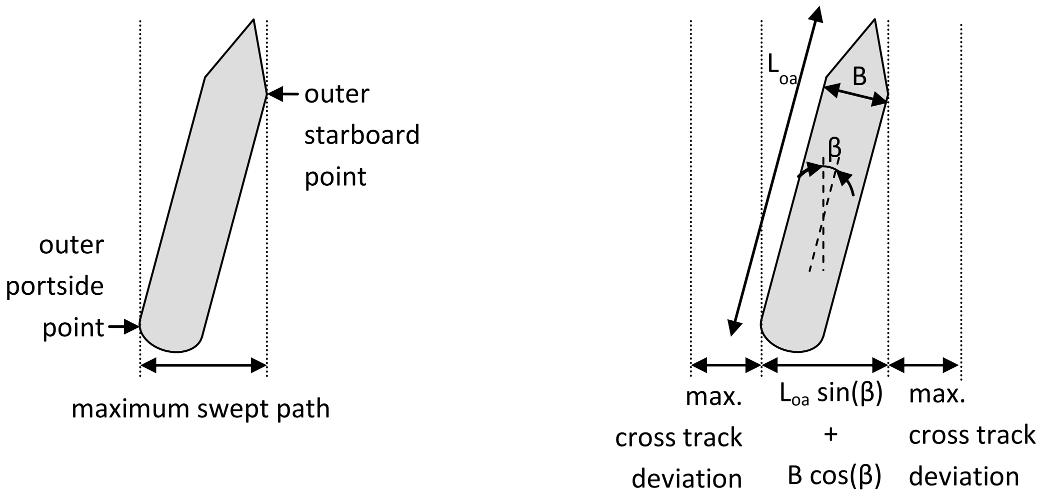


Figure 7.9 - SHIPMA parameters maximum swept path (left) and maximum channel width (right)

Besides checking the width of the channel, the simulations will also be used to check the assumptions made in the design tool regarding the environmental influences. Based on the interviews with the TSHD captain, only the influence of currents is taken into account in the calculation of the channel width by the design tool. In SHIPMA cases are simulated without environmental influence and cases with the influence of wind, waves, currents and a combination of those. The results of the SHIPMA simulations will be used to check if the influence of wind and waves are negligible.

Finally the continuity of the design tool will be examined by analyzing the channel width for increasing environmental conditions. Four cases are simulated, every case with a higher current speed. The channel widths for these increasing current speeds are also calculated with the design tool. An assessment of the maximum channel width is done to check if the design tool holds.

7.4.3 Results of SHIPMA simulations

As stated above, the channel width will be assessed by analyzing the drift angle, swept path and the combination of the two. The drift angle is a consequence of the environmental conditions working on the ship. Therefore the comparison of the environmental conditions will be made after the analysis of the drift angle. SHIPMA refers to the drift angle with the term course deviation. From here on, the term “drift angle” will be used for both design tool and SHIPMA results.

Drift angle

First a comparison is made between the calculated drift angle according to the design tool and the drift angle following from the SHIPMA simulations. For each case the maximum occurring drift angle is determined from the SHIPMA results. SHIPMA computes the drift angle of the ship on each point along the sailed track. The drift angle therefore varies due to a changing sailing speed and a changing angle of income. The magnitude of the wind, waves and currents is assumed to be constant. In all cases the maximum drift angle was found in the part of the channel between the bend and the basin. This is explained by the fact that this is the part where the sailing speed is lowest. A low sailing speed results in a low resistance to the environmental influences and a large drift angle. The maximum drift angles according to SHIPMA for all cases are given in Figure 7.10. The blue and green bars represent the drift angle for a one-way and a two-way channel, both in the incoming direction and therefore in loaded condition. The red and purple bars represent the drift angle in the outgoing direction which means the TSHD is in unloaded condition.

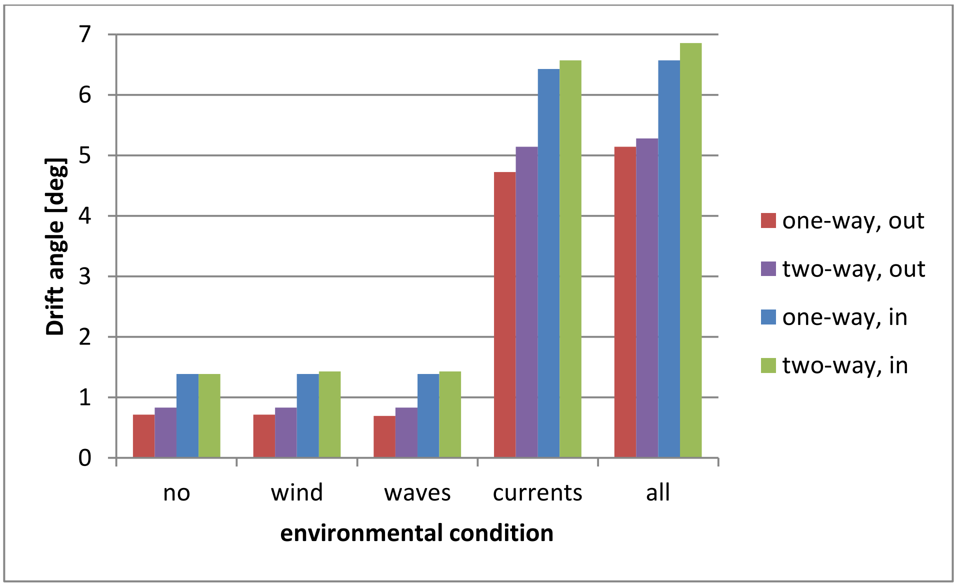


Figure 7.10 - Maximum drift angle according to SHIPMA

Figure 7.10 shows some clear trends in the drift angle resulting from the simulation results:

- Even without any environmental conditions, SHIPMA still computes a maximum drift angle of approximately 1.0 degrees.
- No significant difference in drift angle is shown between a case without any environmental conditions and a case including wind or waves.
- No significant difference in drift angle is shown between a case including currents and a case including a combination of wind, waves and currents.
- A large increase of drift angle is shown when currents are taken into account.
- For all cases, the incoming sailing direction always results in a larger drift angle compared to the outgoing direction. A two-way channel results in a slightly higher drift angle compared to a one-way channel.

The drift angle in the cases without environmental conditions can be explained by the sinusoidal movement of the ship around the pre-set course. Even without environmental conditions the ship deviates from the pre-set course now and then. When the ship returns to the ideal course, SHIPMA interprets this as a drift angle. The design tool does not take this movement into account by means of a drift angle but uses a buffer zone on each side of the manoeuvring lane. This will be analyzed further on in this chapter.

Comparing the cases with no environmental conditions with the cases with wind and waves show no significant increase in drift angle. This same result is also found by comparing the cases including currents with the cases including a combination of wind, waves and currents. However, there is a large difference between the cases without currents and the cases including currents. From these results the conclusion can be drawn that the influence of wind and waves on the drift angle can be neglected and that the drift angle is mainly based on the influence of currents. The same fact was also stated by the TSHD captains and adopted in the design tool. Based on the SHIPMA results this seems to be a good assumption.

Another clear difference can be seen between the drift angle in outgoing and incoming direction. Sailing from the borrow area to the turning basin results in a higher drift angle than the other way around. This difference is assigned to the higher sailing speed in the outgoing direction. The higher sailing speed is a result of the lower draught because of the empty hopper. In the outgoing direction the ship keeps increasing its sailing speed up to a speed of 14 knots, where in the other direction a constant speed of 6 knots is used. As seen before, a lower sailing speed leads to a higher drift angle. The design tool calculates the maximum channel width and therefore calculates the drift angle for a normative situation. Only the drift angles at the inserted sailing speeds are calculated, which often correspond with a speed of 6 knots in loaded conditions and 14 knots in unloaded conditions.

Table 7.7 and Table 7.8 show the maximum values of the drift angle for the cases with and without environmental conditions. The values calculated by the design tool are also given. All values are divided into results of a low sailing speed of 6 knots (Table 7.7) or a high sailing speed of 14 knots (Table 7.8). In Table 7.8 the cases with an incoming direction are not taken into account as the sailing speed of 14 knots is not reached in those cases.

Table 7.7 - Simulated and calculated drift angle (in degrees) at a sailing speed of 6 knots

Case	No conditions (SHIPMA)	All conditions (SHIPMA)	Calculated (design tool)
One-way, outgoing	0.7	5.1	4.8
Two-way, outgoing	0.8	5.3	4.8
One-way, incoming	1.4	6.6	4.8
Two-way, incoming	1.4	6.9	4.8

Table 7.8 - Simulated and calculated drift angle (in degrees) at a sailing speed of 14 knots

Case	No conditions (SHIPMA)	All conditions (SHIPMA)	Calculated (design tool)
One-way, outgoing	0.3	2.2	2.0
Two-way, outgoing	0.3	2.5	2.0

To make an assessment of the channel width, a normative situation is needed. In case of the drift angle a comparison is made based on the maxima. It is clear that the drift angle is highest for cases with a slow sailing speed. This is also found for both the simulation and calculation results. Within these cases, the highest drift angle is obtained in the situation with a two-way channel and an incoming sailing direction. The maximum drift angle due to currents is 6.9 degrees according to SHIPMA, while the design tool calculates a value of 4.8 degrees. This means the design tool underestimates the drift angle with 2.1 degrees for the maximum case. This does not immediately mean it leads to an underestimation of the channel width, as the channel width is not purely based on the drift angle but also on other allowances. An assessment of the complete channel width is made further on in this chapter. The underestimation of the drift angle can be explained by the fact that the drift angle in the design tool is only based on the influence of currents. The result of the SHIPMA simulation also includes the sinusoidal movement of the ship and the extra drift angle due to sailing through a bend. These influences are taken into account by means of an extra width allowance in the design tool. Looking only at the drift angle due to currents shows a better correlation between the design tool and the SHIPMA simulations. The maximum difference in that case is only 6.9 – 1.4 – 4.8 = 0.7 degrees.

Maximum swept path

Now that the drift angle is analyzed, it is time to look at the swept path. First of all, the channel width calculated by the design tool is compared to the maximum swept path given by SHIPMA. As can be seen in Figure 7.9, the maximum swept path is determined by the SHIPMA output regarding the cross-track deviation of the ship. The cross-track deviation is given for the center of the ship and for the farthest starboard or portside point (Figure 7.6). The maximum swept path is the distance between the outer starboard and outer portside point, measured in the direction perpendicular to the ships pre-set course. The maximum swept path according to the design tool is equal to the half of the width of the lane. It can be calculated by dividing the channel width at the bottom by two. The maximum allowable swept path is given in Table 7.9.

Table 7.9 - Maximum allowable swept path

Channel	Straight section [m]	Bend [m]
One-way	0.5 · (32 + 46.3 + 32) = 55.2	0.5 · (32 + 46.3 + 19.2 + 32) = 64.8
Two-way (deep part)	0.5 · (32 + 46.3 + 32) = 55.2	0.5 · (32 + 46.3 + 9.6 + 32) = 60.0
Two-way (shallow part)	0.5 · (32 + 40.2) = 36.1	0.5 · (32 + 40.2 + 19.2) = 45.7

The cases with the largest cross-track deviation following from the analysis of the SHIPMA results are:

- case 17 (one-way channel, incoming direction, all environmental conditions)
- case 19 (two-way channel, incoming direction, all environmental conditions)
- case 20 (two-way channel, outgoing direction, all environmental conditions)

The result of case 17, 19 and 20 are shown in Figure 7.11, Figure 7.12 and Figure 7.13. An overview of all cases was given in Table 7.6.

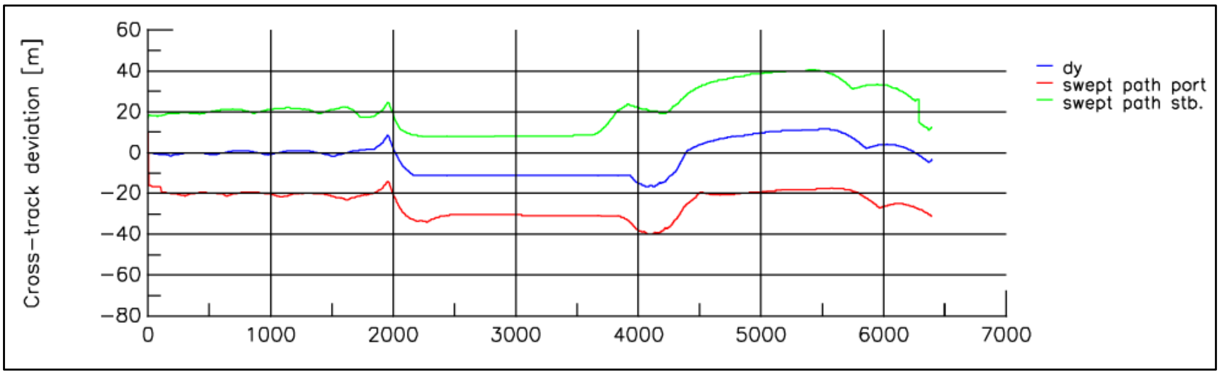


Figure 7.11 - Cross-track deviation according to SHIPMA for case 17

Case 17 is used to assess the maximum swept path for a one-way channel. The maximum cross-track deviation in the straight part of the channel according to SHIPMA is 40.8 meters at starboard. This means a buffer of 55.2 – 40.8 = 14.4 meters is left between the ship and the channel bank. In the bend (at 4100 meters along the track) the maximum cross-track deviation is found at portside and is 39.8 meters. At that point a buffer of 64.8 – 39.8 = 25.0 meters is left.

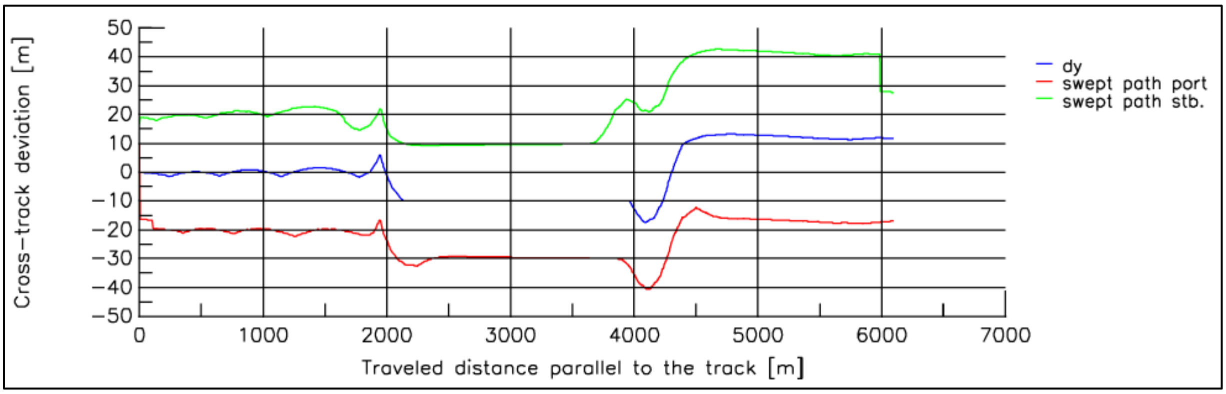


Figure 7.12 - Cross-track deviation according to SHIPMA for case 19

For the assessment of the channel width of the deep part of two-way channel case 19 is analyzed. The maximum occurring cross-track deviation in the straight part is 42.9 meters, measured at portside. In the bend this value is 40.5 meters, measured at starboard side. This leads to a buffer of 55.2 – 42.9 = 12.3 meters in the straight part and a buffer of 60.0 – 40.5 = 19.5 meters in the bend.

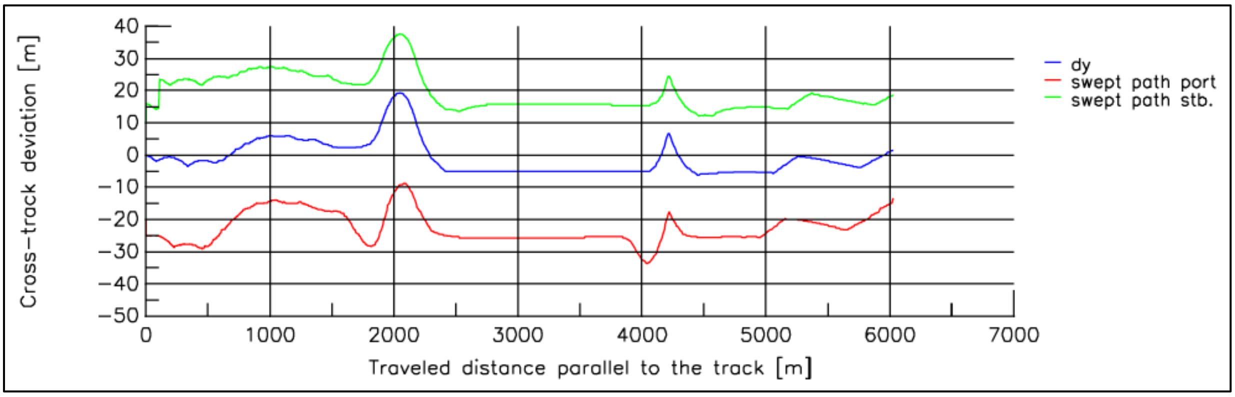


Figure 7.13 - Cross-track deviation according to SHIPMA for case 20

An analysis of the shallow part of the two-way channel is based on case 20. The maximum cross-track deviation in the bend (at 2000 meters) is a distance of 38.5 meters at starboard. This means a distance of 45.7 – 38.5 = 7.2 meters is left between the ship and the bank. In the straight part the maximum cross-track deviation is 34.3 meters at portside. This results in a remaining distance of 36.1 – 34.3 = 1.8 meters.

Maximum channel width

In this assessment, the maximum channel width is analyzed. The maximum drift angle and cross-track deviation given by SHIPMA will now be used to calculate the maximum channel width. The TSHD captains will always try to sail on the center of the channel. Therefore a symmetrical channel cross-section is required. To calculate the dimensions of the maximum (symmetrical) channel cross-section based on the SHIPMA results, the following calculation is made. The width of the swept path is calculated based on the maximum drift angle. After that, the maximum cross-track deviation of the center of the ship is added to both sides of this swept path. Figure 7.9 shows a schematization of this calculation. The resulting width will be compared to the calculated value of the design tool.

All results can be divided into eight parts. This is based on the differences between one-way and two-way traffic, incoming and outgoing direction, straight sections and bends. The values calculated by the design tool are given in Table 7.10. A schematization of the cross-sections was given in Figure 7.4.

Table 7.10 - Channel width calculated by design tool

Channel	Straight section [m]	Bend [m]
One-way, in	32 + 46.3 + 32 = 110.3	32 + 46.3 + 19.2 + 32 = 129.5
One-way, out	32 + 46.3 + 32 = 110.3	32 + 46.3 + 19.2 + 32 = 129.5
Two-way, in (deep part)	32 + 46.3 + 32 = 110.3	32 + 46.3 + 9.6 + 32 = 119.9
Two-way, out (shallow part)	32 + 40.2 = 72.2	32 + 40.2 + 19.2 = 91.4

The maximum channel widths following from the SHIPMA simulations are given in Figure 7.14. Again the results are divided into eight parts. To give a clear overview, the results are given for varying environmental conditions. The SHIPMA results are shown by bars, the values calculated by the design tool are given by an orange line.

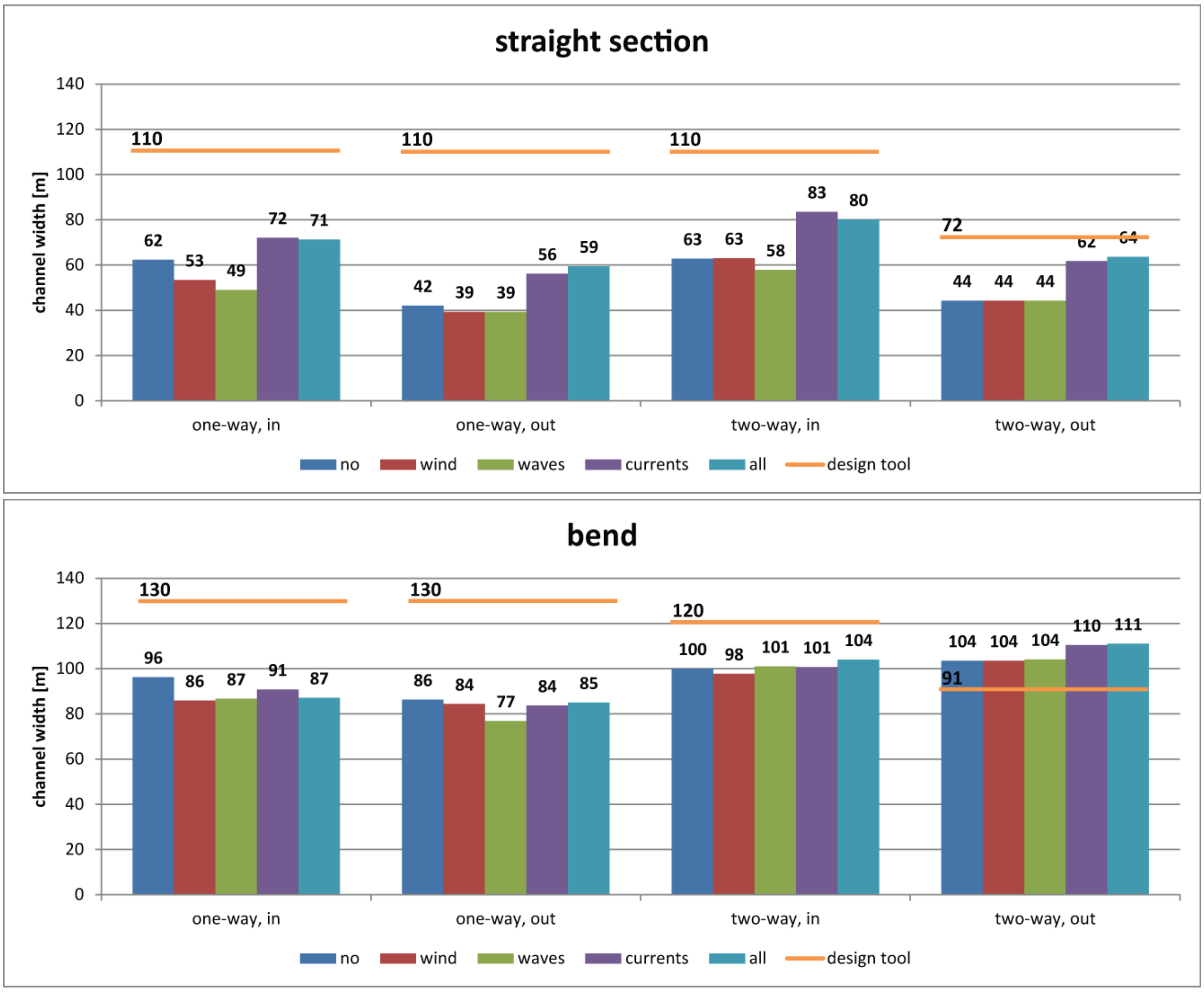


Figure 7.14 - Overview maximum channel width according to SHIPMA

From Figure 7.14 follows that, for a one-way channel, the design tool gives an overestimation of the channel width for all cross-sections and all environmental conditions. For a two-way channel, the design tool only gives an underestimation of the channel width in the bend of the shallow (outgoing) lane. For all other cross-sections of the two-way channel the design tool gives an overestimation.

To make an assessment of the channel width calculated by the design tool, the maximum values must be analyzed. The results of the design tool are computed for three lanes : a lane for one-way traffic, a lane for loaded TSHD's in two-way traffic and a lane for unloaded TSHD's in two-way traffic. The maximum values following from the SHIPMA simulations and the calculations of the design tool are shown in Table 7.11. Also the under- or overestimation by the design tool is given in this table.

Table 7.11 - Under- of overestimation of maximum channel width by design tool calculation

	Straight section			Bend		
	SHIPMA [m]	design tool [m]	under/over estimation	SHIPMA [m]	design tool [m]	under/over estimation
One-way	72	110	53 %	96	130	35 %
Two-way deep part	83	110	32 %	104	120	15 %
Two-way shallow part	64	72	13 %	111	91	-18 %

Table 7.11 shows that the design tool gives an overestimation of the channel width for a one-way channel and the deep part of a two-way channel. For the bend of the shallow part of the two-way channel a slight underestimation is made by the design tool. For that case the SHIPMA simulation results in a maximum channel width of 111 meters, where the design tool calculates a width of 91 meters. This underestimation does not immediately result in a collision of the TSHD against the outer channel banks. The fact that this happens in the bend of the shallow part of a two-way channel means the TSHD can always use the part of the channel above the slope between the shallow and the deep part. In a one-way channel or the deep part of a two-way channel this would not be possible, as those shipping lanes are bounded by a channel bank on both sides. Also, the behavior of a captain while encountering another TSHD in a bend is not taken into account by SHIPMA. In this situation, both captains will adapt their speed and course to avoid a collision.

The overestimation of the channel width could be assigned to the influences of bank suction effects. The differences between the ship used in the SHIPMA simulations and a the TSHD used in the design tool also results in different bank suction effects. The shape of the hull of a TSHD is more blocked compared to the hull of the bulk carrier. This means the TSHD occupies a larger part of the channels cross-section compared to the bulk carrier, resulting in larger bank suction forces. The overestimation of the channel width could be used to take this difference into account. The resulting buffer for bank suction differences is larger in a one-way channel compared to the cases with a two-way channel. This could be explained by the fact that a two-way channel has a larger cross-sectional area which results in lower bank suction forces. However, a quantitative analysis of the bank suction effects on a TSHD can not be given as there has not been any research for that particular case.

It can be concluded that, in general, the design tool computes channel dimensions that slightly overestimate the required channel width in practice. Looking at all of the six analyzed channel widths an average overestimation of approximately 20% is found. This percentage can be seen as a safety margin to take the uncertainties in the simulation (other design ship, bank suction, etc) into account. Eventually, the engineer can also choose to optimize the channel by not taking this margin into account. In that case, the width of the channel can be determined at 80% of the value computed by the design tool. However, this means the captain(s) of the TSHD('s) must be very alert while sailing through the channel. The sailing speed of the TSHD must be adjusted while sailing through the bend and during the encountering of another TSHD.

Increasing current speed

Finally an analysis will be made to see if the results of the design tool still hold for increasing environmental conditions. As seen before, the currents can be seen as the most influencing environmental condition. Therefore simulation cases 21 to 24 (Table 7.6) are made with current speeds of 1.0, 1.5, 2.0 and 3.0 knots. With these current speeds also the dimensions of four new channels were made with the design tool. Again, the course deviation and cross-track deviation were used to calculate the maximum channel width according to SHIPMA. The results of the design tool and SHIPMA calculations are shown in Figure 7.15. The differences between the width following from the drift angle and the width following from a course offset or extra allowance are also given.

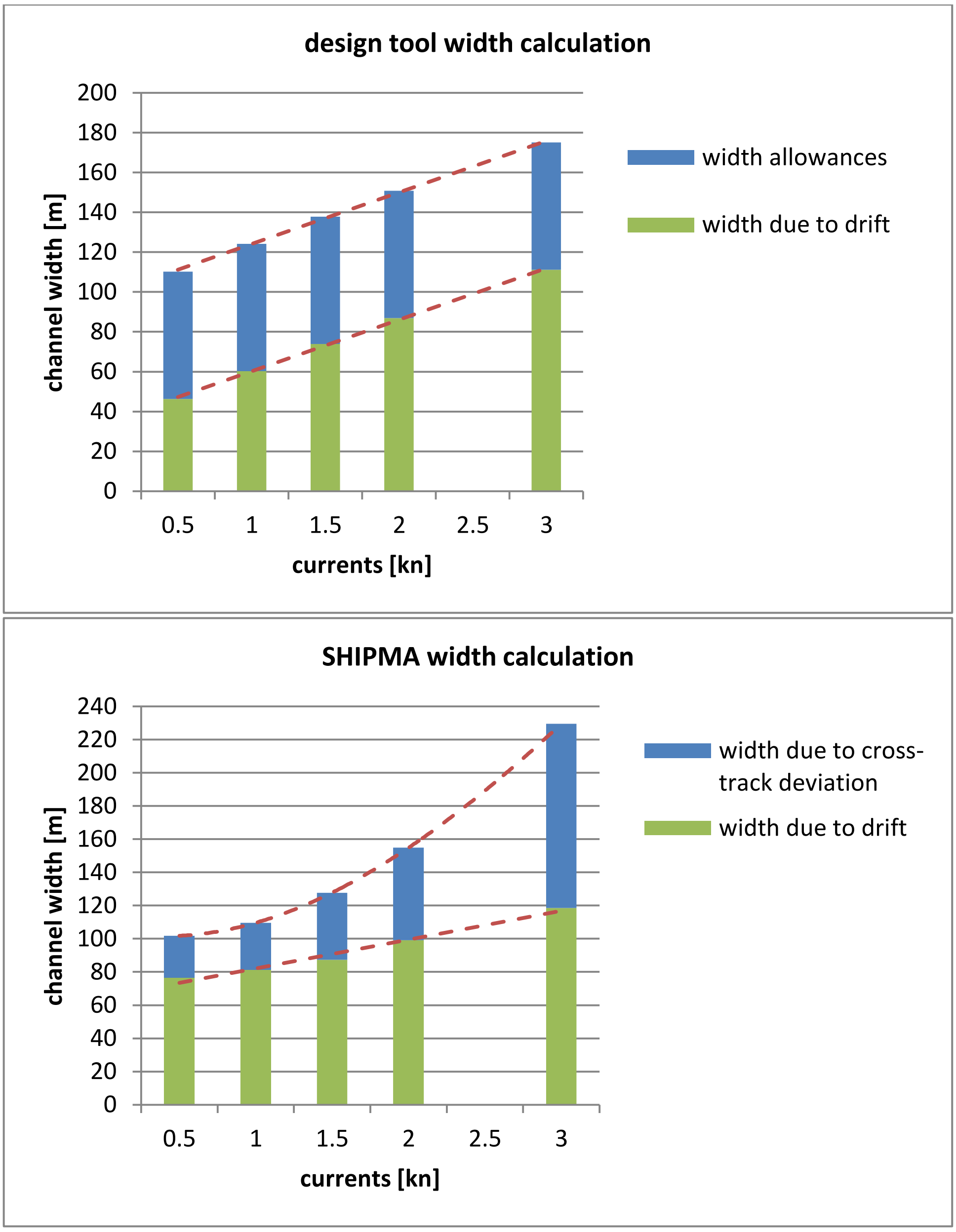


Figure 7.15 - Set-up channel width calculation for increasing currents

The results from the design tool calculation show a linear increase for increasing current speed. This is explained by the linear increase of drift angle for an increasing current speed. The extra allowances in width have the same values for all current speeds. A completely different set-up is shown in the calculation following from the SHIPMA results. The cross-track deviation increases rapidly as the current speed increases. Especially the situation with a current speed of 3 knots shows some extreme values. In that case a drift angle of 22.7 degrees was found. The TSHD captains stated that a drift angle of 20 degrees can be seen as a maximum value and in those cases measures will be taken to decrease the drift angle. The value of the cross-track deviation is even more extreme, and seems to be unrealistic. On the last straight end of the channel the simulation resulted in a cross-track deviation of 27.8 meters at a current speed of 2 knots and 55.5 meters at 3 knots. This means the center of the ship is at a distance of 27.8 to 55.5 meters parallel to the pre-set course. In these cases the captain would have already taken some measures to get back on the track. This must be taken into account when the SHIPMA results are compared to the design tool calculations. The fact that the bulk carrier used in SHIPMA does not return to the pre-set course can be assigned to the lower installed propulsion power compared to a TSHD.

To make a comparison, an overview of the calculation results are shown in Figure 7.16. For the situations with a current speed of 1.0 and 1.5 knots, the channel width resulting from the design tool satisfies the required width from the SHIPMA simulations. In the case with a current speed of 2 knots the channel width is exceeded by only 2.5 percent, which is acceptable. In the cases with a current speed 3.0 knots, the calculated channel width does not hold for the results of the simulation. This is a result of the extremely high values of drift angle and cross-track deviation, which will not be found in a practical situation. It must be noted that the assessment for increasing current speeds is only based on a case including a two-way channel with incoming sailing directions. Based on the analysis of cases 1 to 20, this can be seen as the normative case.

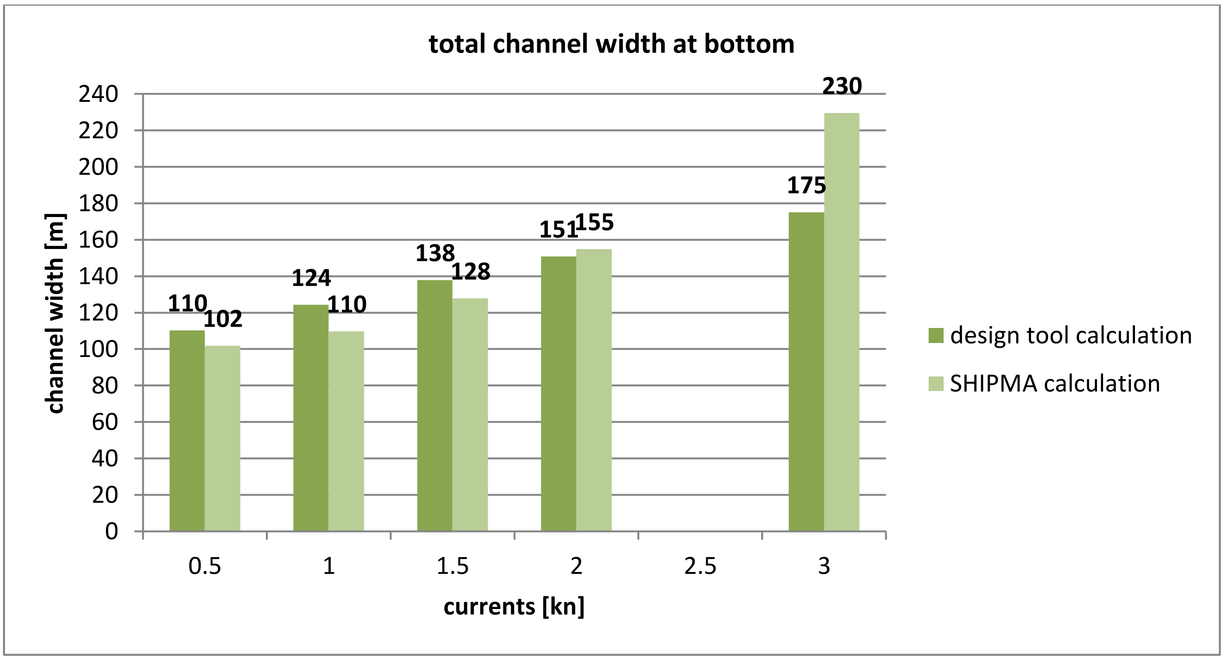


Figure 7.16 - Channel width for increasing currents

7.5 Conclusions

Based on the results of the SHIPMA simulations, an assessment is made of the channel dimensions calculated by the design tool. The simulation software SHIPMA is set up as 2-dimensional manoeuvring simulator. This means the channel depth is not taken into account and only the width of the channel could be analyzed. Some general conclusions can be drawn:

- The largest drift angle occurs in the cases with a two-way channel and incoming sailing direction. A general trend that is found is that the incoming sailing direction results in a larger drift angle compared to the outgoing sailing direction and a two-way channel results in a larger drift angle compared to a one-way channel. This can be explained by the differences in sailing speed and the area of the channel cross-section. The influence of wind and waves on the drift angle can be neglected, currents have a large influence on the drift angle.
- The drift angle calculated by the design tool shows an underestimation of the results from SHIPMA. This difference can be explained by the fact that the drift angle calculated by the design tool is only based on the influence of currents. SHIPMA also includes the sinusoidal movement of the ship and the behavior in bends in the drift angle.
- Based on the output data of SHIPMA regarding the cross-track deviation, an analysis of the maximum swept path was made. It concluded that there is still a small buffer left, between the outer point of the swept path and the channel bank.
- Eventually, an analysis of the maximum channel width is made. A maximum width is calculated based on the drift angle and maximum course deviation resulting from SHIPMA. Comparing this width with the calculated values of the design tool again shows an overestimation for all channel cross-sections, except for the bend in the shallow lane of the two-way channel. In this case a slight underestimation by the design tool is found.
- In general, the design tool overestimates the channel width by 20% compared to the required channel width in practice. This can be seen as a safety margin to take the assumptions in the simulation into account. However, if an engineer wants to take higher risks, the channel width can be decreased until 80% of the value computed by the design tool. In this situation the TSHD captains must be fully alert while sailing through the channel.
- Increasing the current speed from 0.5 knots to 3.0 knots gave insight in the results of the design tool for increasing environmental conditions. Up to 2.0 knots the results of the design tool shows a good correlation with the SHIPMA results. For higher current speeds the SHIPMA results show an extraordinary high value for the cross-track deviation, which makes the results seem unrealistic. For these cases, the design tool gives a large underestimation.

While analyzing the SHIPMA results, the following must be kept in mind:

- The SHIPMA simulations are made with a bulk carrier instead of a TSHD. Although this is a good approximation, it still leads to some uncertainties in the results. For example, the influence of bank suction effects can differ largely between a bulk carrier and a TSHD.
- The design tool is based on general input parameters regarding the characteristics of the TSHD. Taking much more parameters, like detailed hull shape or propulsion power, into account could lead to better results. However, the design tool must be fast and easy to use. This goal can not be achieved when the design tool is based on extensive input data.

8 Analysis of costs

In the previous chapters the design method for a temporary work channel is discussed. The design of the channel is based on the input values for the TSHD, the project location and environmental influences. As a result, the design tool computes the dimensions of a one-way and a two-way channel cross-section. Hence, the choice of the eventual channel dimensions depends on the choice for a one-way or two-way channel and on the choice of the input parameters.

This choice can be made based on an analysis of costs. An optimum must be found between the costs of the temporary work channel and the benefits this channel leads to during the execution of the project. In this chapter the costs of a reclamation project will be calculated and analyzed to find a relation between the input parameters of the design calculation and the resulting costs. The analysis of costs will be made for the same project that is used for the manoeuvring simulation. This project includes the reclamation of an island in front of the coast of Bahrain.

8.1 Calculation method

In general the analysis of costs can be reduced to one assessment. When do the benefits from using a larger TSHD or two TSHD's on a project weigh up to the extra costs of a larger work channel? The answer to this question leads to an optimum for the used input values of the project. Varying the input parameters gives insight in when a one-way or two-way channel should be used, and when a large TSHD or a small TSHD should be used.

To make this assessment, the costs of a reclamation work and the costs of a temporary work channel must be calculated. The calculation is based on the method given by van der Schrieck [24] and the VBKO [23]. An overview of the total calculation is given in Figure 8.1 on the next page.

Costs reclamation

The costs of a reclamation project can be divided into a fixed part and a part that depends on the execution time of the project.

costs reclamation [€] = fixed costs [€] + (production costs TSHD [€/wk] * execution time [wk])

The fixed part of the costs contains the mobilization and demobilization of the project equipment. The TSHD('s) must be transported to the project location and several facilities and discharge pipelines must be installed. Most of the fixed costs are made by the transport of the TSHD('s). Therefore, in this calculation the fixed costs will be based on the weekly production costs of a TSHD. For mobilization one week is assumed, for demobilization a half week is used.

fixed costs [€] = mobilization [€] + demobilization [€]

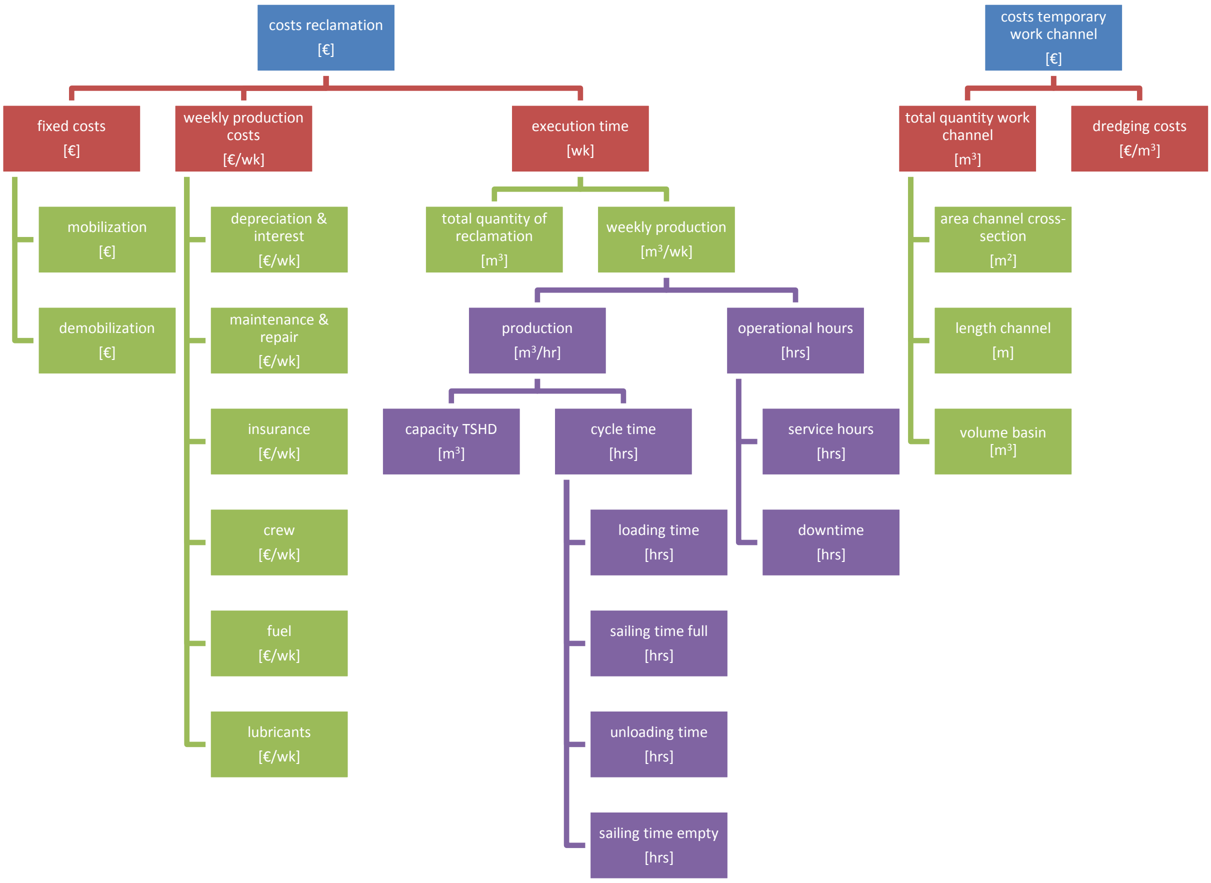


Figure 8.1 - Overview calculation method

The weekly production costs of a TSHD in this calculation are based on the standard method set up by the CIRIA (Construction Industry Research and Information Association) in 2005 [25]. The method divides the weekly costs of a TSHD into six parts:

production costs TSHD [€/wk] = depreciation and interest + maintenance and repair + insurance + crew + fuel + lubricants

Most of these parts are based on the Computation of Value (waardenorm in Dutch) of the TSHD. This can be seen as a measure for the value of the TSHD. It is calculated according to the lightweight of the TSHD, the power of the dredgepumps and jetpumps, the free sailing power and the service hours per week. The lightweight of the TSHD is the actual weight of the ship, without fuel, crew, cargo, water, etc. on board. From this "value of the TSHD", the production costs can be calculated. The following factors are taken into account:

- Depreciation and interest is computed based on annuity. An interest rate, service life, utilization and residual value are used as input for the calculation.
- Maintenance and repair is a percentage of the value of the TSHD and can be found in a table. It is divided into a variable part based on the workable hours per week and a fixed part.
- Insurance costs are assumed as a percentage of 0.03% of the value of the TSHD.
- Crew costs are calculated based on the size of the TSHD.
- Fuel consumption is calculated based on the propulsion power of the TSHD.
- An extra 10% of the fuel costs is taken as costs for lubricants.

A detailed explanation of the calculation method is given in appendix C.

The total execution time of the reclamation is based on the total quantity of the reclamation and the weekly production of the TSHD. The weekly production is depending on the capacity of the TSHD, the total cycle time and the amount of operational hours per week.

execution time [wk] = total quantity of reclamation [m³] / weekly production TSHD [m³/wk]

weekly production TSHD [m³/wk] = production [m³/hr] * operational hours [hr/wk]

production [m³/hr] = capacity TSHD [m³] / cycle time [hrs]

The amount of operational hours is calculated by subtracting the hours of downtime from the total service hours. The service hours are based on the number of shifts, in this calculation 168 service hours per week are assumed. The downtime is calculated as a percentage of the service hours. In the calculation mechanical (3%), operational (5%) and tides and waves (10%) are taken into account.

operational hours [hr/wk] = service hours – downtime

The total cycle time is the sum of the loading time, loaded sailing time, unloading time and empty sailing time. This calculation includes characteristics of the TSHD, the length of the work channel and the distance to the borrow area.

cycle time [hr] = loading time + sailing time full + unloading time + sailing time empty

loading time [hr] = capacity TSHD [m³] / loading production TSHD [m³/hr]

sailing time full [hr] = (distance 1 [km] / speed 1 [km/hr]) + (distance 2 / speed 2)

where: distance 1 = distance from the borrow area to the entrance of the channel
speed 1 = sailing speed with a loaded hopper in unrestricted water
distance 2 = distance from the entrance of the channel to the basin
speed 2 = sailing speed with a loaded hopper through a channel

unloading time [hr] = capacity TSHD [m³] / unloading production TSHD [m³/hr]

sailing time empty [hr] = (distance 2 [km] / speed 3 [km/hr]) + (distance 1 / speed 4)

where: speed 3 = sailing speed with an unloaded hopper through a channel
speed 4 = sailing speed with an unloaded hopper in unrestricted water

Costs temporary work channel

All the above calculations sum up to the costs of the reclamation. This must be weighed up to the costs of the temporary work channel. These costs are based on the total dredged quantity of the work channel and basin and a fixed value of the dredging costs per cubic meter of the work channel.

costs temporary work channel [€] = total quantity work channel [m³] * dredging costs [€/m³]

The total quantity of the dredged material for the work channel results from the design made by the design tool. For the dredging costs a fixed value per cubic meter is used. For a channel a value of 4,00 €/m^3 is used.

Total costs reclamation

The above given calculations lead to the total costs of the reclamation.

total costs reclamation = costs reclamation [€] + costs temporary work channel [€]

This calculation can be made for the situation with one or two TSHD's. This will lead to a difference in reclamation costs on the one hand because of the variation in construction method. On the other hand it leads to a difference in the costs of the work channel because of the difference between a one-way and a two-way channel. These differences are expressed in the difference in total reclamation costs.

Occupation TSHD('s)

The total reclamation costs is not the only factor that needs to be taken into account. Also the total time needed to construct the project has a large influence. The aspect of time is first included in the calculation of the costs of the reclamation. It also plays a role when the project is finished, as the TSHD('s) can be used on another project. This difference in occupation of the TSHD('s) must also be taken into account. The influence of time on the occupation of the TSHD('s) is shown in Figure 8.2.

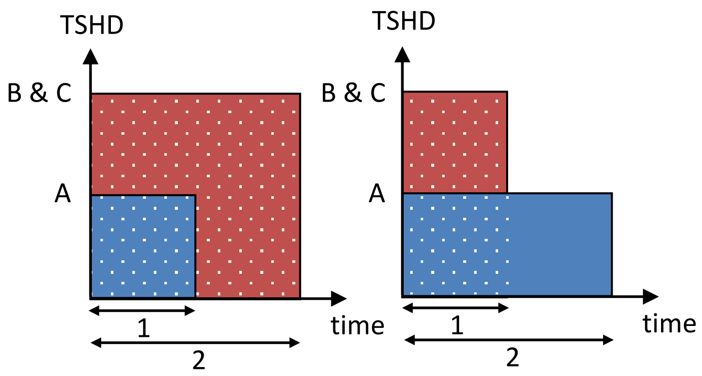


Figure 8.2 - Occupation TSHD('s) on the project

The left graph shows the situation where one TSHD needs less time to construct the whole project than two TSHD's. This could be the case when the difference between a large TSHD and two small TSHD's is examined. In the calculation, the occupation of the TSHD's is calculated with respect to the longest time of the two scenario's (time period 2). The following income can be generated by using the TSHD's in another project:

- Choosing for one TSHD (A) on the reclamation project, leads to income from:
  - TSHD's B and C during period 2 on another project
  - TSHD A during the difference between period 1 and 2 on another project
- Choosing for two TSHD's (B & C) on the reclamation project, leads to income from:
  - TSHD A during period 2 on another project

The same calculation can be made for the scenario in the right graph, where two TSHD's need the shortest time to construct the reclamation. In this case the following income can be generated:

- Choosing for one TSHD (A) on the reclamation project, leads to income from:
  - TSHD's B and C during period 2 on another project

- Choosing for two TSHD's (B & C) on the reclamation project, leads to income from:
    - TSHD A during period 2 on another project
    - TSHD's B and C during the difference between period 1 and 2 on another project

The income generated from the TSHD's on other projects is calculated by multiplying the weekly production costs of the TSHD('s) with the time. This income will be subtracted from the total costs of the reclamation. The first week of a TSHD on another project will be seen as mobilization and will therefore be calculated as costs, not as income. The resulting values can be compared to find the most cost-efficient work channel for a reclamation project.

8.2 Cases

As can be seen in Figure 8.1, the calculation of the total costs is depending on a lot of input parameters regarding the project and the TSHD's. To give insight in the costs, three cases are calculated. With respect to the project input, the parameters will be based on the Dilmunia project. The input parameters of the TSHD's will be determined for three TSHD's: *Prins der Nederlanden*, *Cornelis Zanen* and *Coastway / Waterway*. The TSHD's have a hopper capacity of 15961 m^3, 8530 m^3 and 4906 m^3. The *Coastway* and the *Waterway* are two TSHD's with exactly the same specifications.

The costs of a reclamation project and a work channel depend on a great variety of parameters. Some of these parameters also influence each other because there are linked. For example, the channel length is used to calculate the costs of the channel but it also has an influence on cycle times. The most important parameters are:

- Total volume of the reclamation
- Length of the work channel
- Set-up of the work channel, one-way or two-way
- Sailing distance between the sand borrow area and the channel basin
- Capacity of the TSHD('s)
- Sailing speed of the TSHD('s)

To examine the influence of these parameters, 3 cases are set up.

Case 1: vary the reclamation volume and the length of the work channel, keep the sailing distance between the borrow area and the work channel fixed at 10 kilometers, use a sailing speed of 6 knots in the channel for a loaded TSHD.

Case 2: vary the reclamation volume and the sailing distance between the borrow area and the work channel, keep the length of the work channel fixed at 1650 meters, use a sailing speed of 6 knots in the channel for a loaded TSHD

Case 3: vary the reclamation volume and the length of the work channel, keep the sailing distance between the borrow area and the work channel fixed at 10 kilometers, use the maximum sailing speed of a loaded TSHD in the channel.

Within these cases, the capacity of the TSHD('s) and the area of the channel cross-section will be varied by choosing a combination of TSHD's. This way the difference in costs between a one-way and a two-way channel can be found. The following combinations will be used (in case of a two-way channel, the capacity is the sum of the two TSHD's):

Table 8.1 - Combination of TSHD's and their capacity

Combination	One-way channel TSHD	Capacity [m^3]	Two-way channel TSHD	Capacity [m^3]
A	Prins der Nederlanden	15961	Coastway & Waterway	9812
B	Cornelis Zanen	8530	Coastway & Waterway	9812
C	Prins der Nederlanden	15961	Cornelis Zanen & Coastway	13436
D	Coastway	4606	Cornelis Zanen & Coastway	13436

The situation of the *Coastway* in a one-way channel versus the *Coastway* and the *Waterway* in a two-way channel is not examined. Calculations with this combination of TSHD's turned out that the costs and income for the reclamation are the same for one and two TSHD's. When using two TSHD's the costs were twice as high as using one TSHD, but the construction time was exactly the half. Taking the income from using the TSHD on another project into account, results in the same costs. The only difference is found in the costs of the work channel which are higher for a two-way channel. This leads to the fact that for varying input parameters, the difference in costs is always the same and no optimal point can be found. In practice this is not completely the same. Some of the equipment, like pipelines, workshops and spare parts, can be used on both TSHD's and should therefore be taken into account once in the case of two TSHD's. However, these costs are small compared to the dredging costs resulting from the work channels.

For each combination of TSHD's from Table 8.1, the total costs of the project are calculated for the situation with a one-way channel and a two-way channel. In case 1, this calculation is made for varying reclamation volume and channel length. In case 2 the reclamation volume and sailing distance are varied. For all cases described above, the point will be calculated where the final costs (including the income gained by using the TSHD on another project) of the situation with a one-way channel is equal to the situation with a two-way channel. Calculating these points for the varying input parameters gives insight in when to use a one-way or two-way channel.

In the first two cases, the sailing speed in the channel is restricted at 6 knots. This value is used in the design tool and is based on experiences of TSHD captains. But what happens when the TSHD sails through the work channel at its maximum speed? A higher speed leads to a larger cross-section of the work channel, but also to a shorter construction time. A speed of 6 to 8 knots is always assumed to be the optimal speed. It is now interesting to examine the differences in costs when sailing at full speed compared to a speed of 6 knots. This will be done in case 3.

8.3 Results

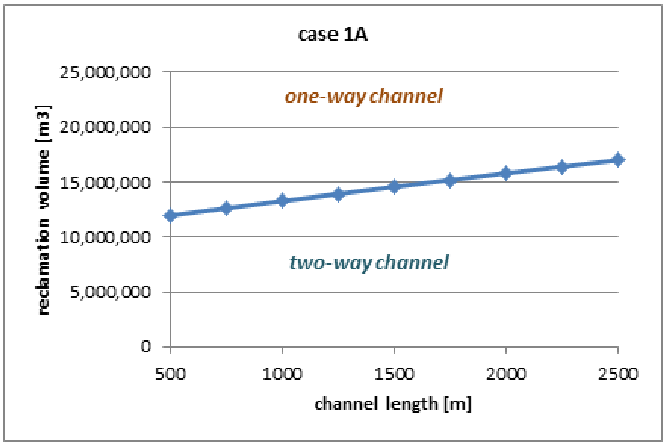
All cases and the results of the calculations will be discussed below.

8.3.1 Case 1: volume reclamation vs channel length

Case 1 shows the influence of the dredged volume of the reclamation and the channel length on the choice for a one-way channel or a two-way channel. The sailing distance between the sand borrow area and the work channel is assumed at 10 kilometers. The results of the calculation of costs for this case are given in this paragraph. The line in each graph represents the point where the costs for a one-way channel are equal to the costs of a two-way channel. The texts above and under the line show which channel should be used in that area of the graph. The influence of channel type and TSHD characteristcs on the costs are large. It is therefore important to know the cross-sectional area of the channel and the capacity and production costs of the TSHD while analyzing the results of the cost calculations.

Case 1A: Prins der Nederlanden vs Coastway & Waterway

Case 1A represents the choice between one large TSHD (*Prins der Nederlanden*) and two small TSHD's (*Coastway and Waterway*). The large TSHD has a large capacity but also requires a large channel cross-section. At a certain reclamation volume, the benefits of the higher capacity counter the extra costs of the work channel. The required reclamation volume to counter the extra costs of the work channel increases for increasing channel length. This is explained by the fact that a larger channel also leads to higher costs of the work channel.



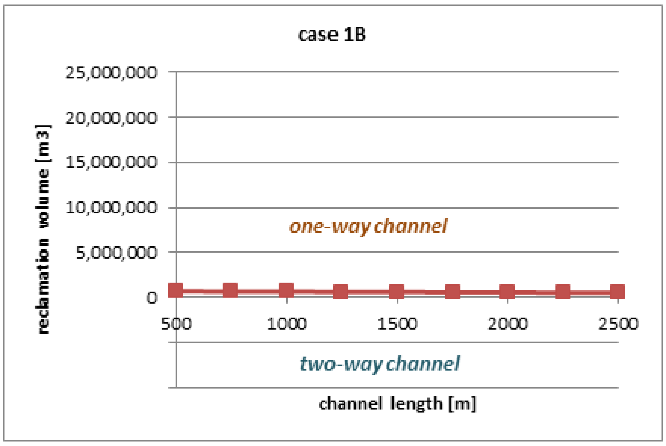
One-way channel	
TSHD	Prins der Nederlanden
Capacity	15961 m^3
Channel area	1055 m^2
Production costs	565000 €/wk

Two-way channel	
TSHD	Coastway & Waterway
Capacity	9812 m^3
Channel area	467 m^2
Production costs	520000 €/wk

Figure 8.3 - Results cost calculation case 1A

Case 1B: Cornelis Zanen vs Coastway & Waterway

In this case the choice between one and two TSHD's is examined, where the total capacity approaches each other closely. Also the cross-sectional area of the work channel is in both situations of the same order of magnitude. However, weekly production costs of two TSHD's is much larger than the costs of one TSHD. This results in the fact that even at a small reclamation volume (approximately 700 m^3) the one-way situation with the larger TSHD is most profitable. The fact that the line does not increase or decrease for increasing channel length is explained by the small difference in cross-section area. The channel length therefore has a very small influence on the total difference in costs.



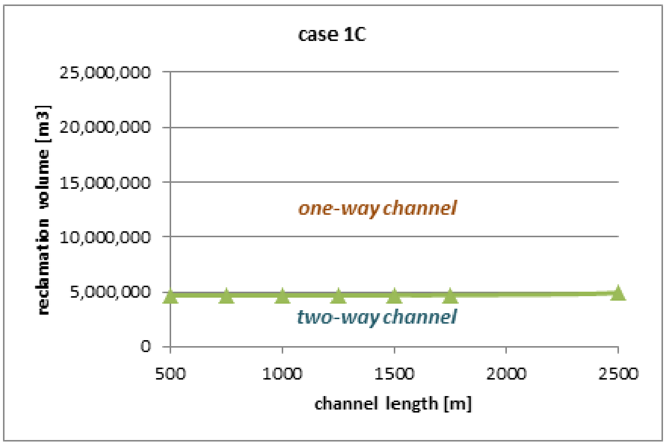
One-way channel	
TSHD	Cornelis Zanen
Capacity	8530 m^3
Channel area	556 m^2
Production costs	370000 €/wk

Two-way channel	
TSHD	Coastway & Waterway
Capacity	9812 m^3
Channel area	467 m^2
Production costs	520000 €/wk

Figure 8.4 - Results cost calculation case 1B

Case 1C: Prins der Nederlanden vs Cornelis Zanen & Coastway

This case again compares two situations with almost similar capacities. Only this time the differences in channel cross-sectional area are somewhat larger and the difference in production costs is smaller compared to case 1B. The calculation shows the same trend as seen in case 1B. Again the influence of the channel length on the difference in costs is negligible. Due to the larger difference in production costs, the TSHD with the largest capacity requires a larger reclamation volume to become profitable than seen in case 1B.



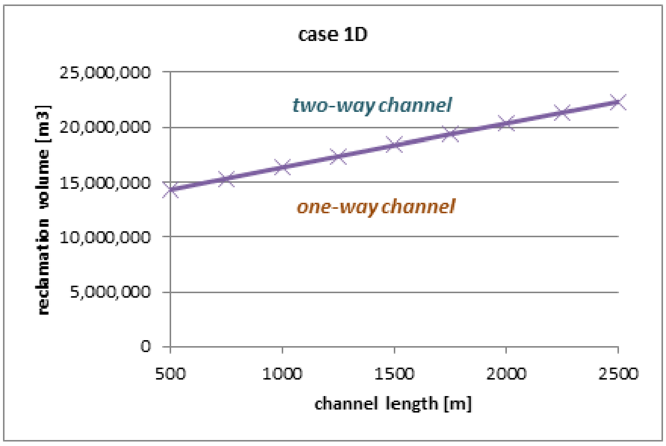
One-way channel	
TSHD	Prins der Nederlanden
Capacity	15961 m^3
Channel area	1055 m^2
Production costs	565000 €/wk

Two-way channel	
TSHD	Cornelis Zanen & Coastway
Capacity	13436 m^3
Channel area	723 m^2
roduction costs	630000 €/wk

Figure 8.5 - Results cost calculation case 1C

Case 1D: Coastway vs Cornelis Zanen & Coastway

In this case the capacity of the two TSHD's together is much higher than the capacity of the single TSHD. This results in a similar trend as seen in case 1A, but this time the two-way channel results in lower costs for higher reclamation volumes. This is explained by the much higher capacity of the two TSHD's which counters the extra costs of the work channel at large reclamation volumes. Again the required reclamation volume increases for increasing channel length.



One-way channel	
TSHD	Coastway
Capacity	4606 m^3
Channel area	346 m^2
Production costs	260000 €/wk

Two-way channel	
TSHD	Cornelis Zanen & Coastway
Capacity	13436 m^3
Channel area	723 m^2
Production costs	630000 €/wk

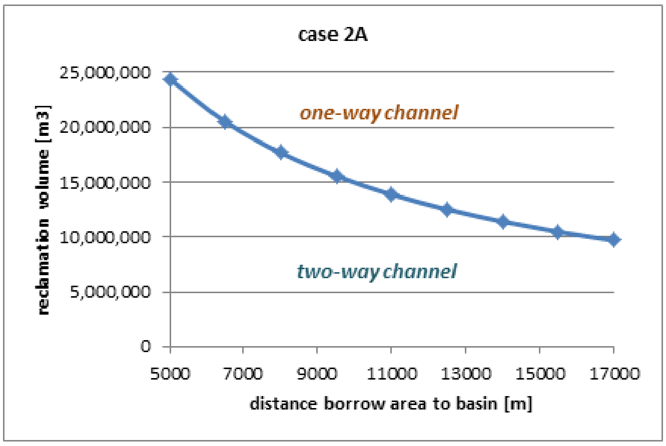
Figure 8.6 - Results costs calculation case 1D

8.3.2 Case 2: volume reclamation vs sailing distance

Case 2 shows the influence of the dredged volume of the reclamation and the sailing distance between the sand borrow area and the work channel on the choice for a one-way channel or a two-way channel. This time the length of the work channel is assumed to be 1650 meters. The results are given below.

Case 2A: Prins der Nederlanden vs Coastway & Waterway

As in case 1A, again a certain reclamation volume is required to counter the extra costs of the work channel. In this case the influence of the sailing distance is examined. The figure shows that the required reclamation volume for a two-way channel decreases for increasing sailing distance. This is explained by the fact that the benefits in time by using a higher capacity, get higher for a larger sailing distance.



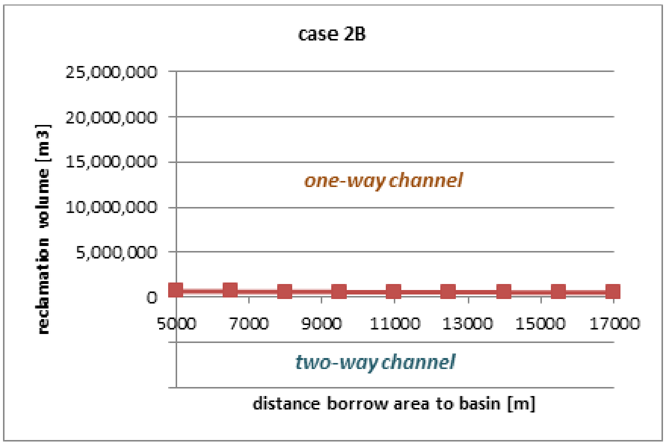
One-way channel	
TSHD	Prins der Nederlanden
Capacity	15961 m^3
Channel area	1055 m^2
Production costs	565000 €/wk

Two-way channel	
TSHD	Coastway & Waterway
Capacity	9812 m^3
Channel area	467 m^2
Production costs	520000 €/wk

Figure 8.7 - Results costs calculation case 2A

Case 2B: Cornelis Zanen vs Coastway & Waterway

This case shows the same trend as seen in case 1B. For capacities and channel cross-sections in the same order of magnitude, a one-way channel is already profitable at low reclamation volumes. This case shows that also a varying sailing distance does not lead to an increase or decrease of the required reclamation volume.



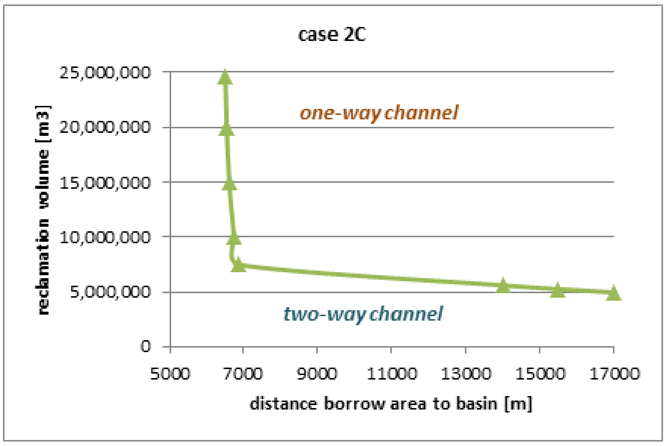
One-way channel	
TSHD	Cornelis Zanen
Capacity	8530 m^3
Channel area	556 m^2
Production costs	370000 €/wk

Two-way channel	
TSHD	Coastway & Waterway
Capacity	9812 m^3
Channel area	467 m^2
Production costs	520000 €/wk

Figure 8.8 - Results costs calculation case 2B

Case 2C: Prins der Nederlanden vs Cornelis Zanen & Coastway

From a sailing distance larger than 7 kilometers, this case shows a similar trend as seen in case 1C. A relatively small reclamation volume is needed to make the one-way channel profitable. The influence of the sailing distance is larger than the influence of the channel length, but still does not lead to a significant increase or decrease of the line. However, for a sailing distance smaller than 7 kilometer, the line shows a rapid increase. It can be stated that for a sailing distance smaller than approximately 7 kilometers, the one-way channel leads to extremely high costs compared to the two-way channel. At distances smaller than 7000 meters, the distance is too small to obtain benefits in time (and costs) by using a larger capacity. This way the costs of the reclamation are almost equal, but the costs of the work channel are larger for the one-way channel compared to the two-way channel.



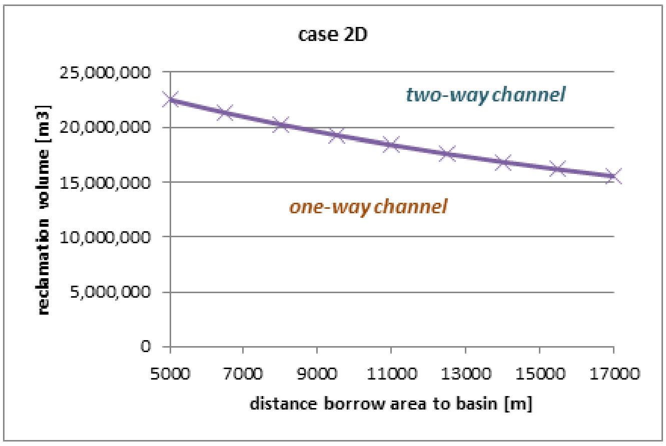
One-way channel	
TSHD	Prins der Nederlanden
Capacity	15961 m^3
Channel area	1055 m^2
Production costs	565000 €/wk

Two-way channel	
TSHD	Cornelis Zanen & Coastway
Capacity	13436 m^3
Channel area	723 m^2
Production costs	630000 €/wk

Figure 8.9 - Results costs calculation case 2C

Case 2D: Coastway vs Cornelis Zanen & Coastway

The same situation as seen in case 1D occurs in case 2D. This time the influence of the sailing distance can be examined. It again shows that increasing sailing distance leads to a lower required reclamation volume to make the choice with the highest capacity profitable.



One-way channel	
TSHD	Coastway
Capacity	4606 m^3
Channel area	346 m^2
Production costs	260000 €/wk

Two-way channel	
TSHD	Cornelis Zanen & Coastway
Capacity	13436 m^3
Channel area	723 m^2
Production costs	630000 €/wk

Figure 8.10 - Results costs calculation case 2D

8.3.3 Case 3: maximum sailing speed

In this case a sailing distance of 10 kilometers between the borrow area and the work channel is assumed. The reclamation volume and channel length are again variable. For all of the three TSHD's, a calculation of the costs is made for a sailing speed (with a loaded hopper) in the work channel of 6 knots and a the maximum sailing speed. The maximum sailing speed varies among the TSHD's:

- Prins der Nederlanden: 16.2 knots
- Cornelis Zanen: 13.5 knots
- Coastway: 12.5 knots

The result of these calculations are shown in Figure 8.11. The area above each line represents the area where the costs are lower when sailing at full speed. At the area under the line, sailing at 6 knots leads to lower costs.

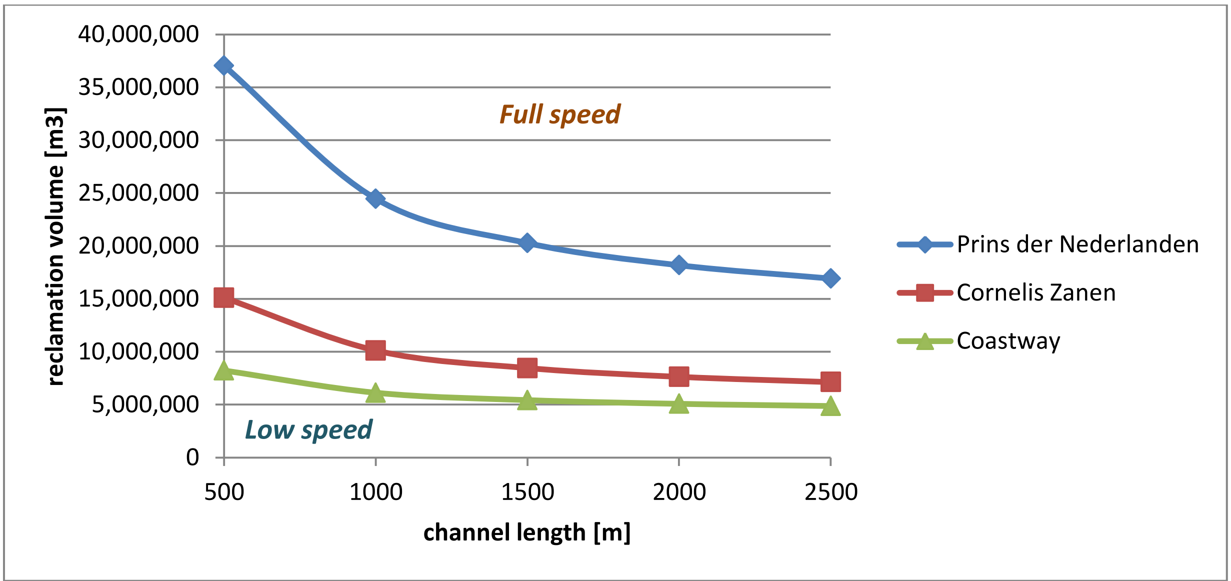


Figure 8.11 - Results cost calculation case 3

This calculation shows that for large reclamation volumes and channel lengths of approximately 1500 meters or longer, the maximum sailing speed leads to lower costs. However, the difference in costs increases very slowly for increasing reclamation volume. From that point of view, the benefits of sailing at full speed are not significant. Because of the rough calculation method, there are some points that need to be taken into account:

- The calculation uses a constant speed through the full channel and does not take the TSHD slowing down near the end of the channel into account. This leads to a longer construction time and shifts the lines in Figure 8.11 upwards.
- The difference in fuel consumption between sailing at 6 knots and sailing at maximum, is not taken into account. The calculation is based on an assumed fuel consumption depending on the engine power of the TSHD.
- A higher sailing speed in a restricted channel could lead to a higher risk of damage. The risk of damage is not taken into account in this calculation.

- Due to the limiting speed of the TSHD in a restricted channel, it is not always possible to sail at the maximum speed in a channel. This fully depends on the dimensions of the channels cross-section and the surrounding water depth.

It is recommended to do more research on the increase of the sailing speed through a work channel. By taking all influences into account, an optimal sailing speed could be determined in the future.

8.4 Conclusions

The analysis of the calculation above showed that it is very hard to give a general view on when to use a one-way channel or a two-way channel. The costs are influenced by a great variety of factors following from the choice of the TSHD, work channel and project location.

Some general conclusion followed from the analysis:

- The main parameters determining the choice between a one-way channel and a two-way channel are:
    - Total volume of the reclamation
    - Length of the work channel
    - Set-up of the work channel, one-way or two-way, and resulting area of the cross-section
    - Sailing distance between the sand borrow area and the channel basin
    - Capacity of the TSHD('s)
    - Sailing speed of the TSHD('s)
- There are situations where there is a large difference in capacity between one TSHD and the combination of two TSHD's. When in this situation the volume of the reclamation increases, the choice for the highest capacity gets more profitable. The volume of reclamation where the highest capacity gets profitable increases with increasing channel length and decreases with increasing sailing distance.
- There are situations where there is a small difference in capacity between one TSHD and the combination of two TSHD's. In these situations, the influence of the channel length and sailing distance are negligible.
- At large reclamation volumes and relatively large channel lengths, sailing at the maximum speed through the work channel could lead to lower costs. However, this is based on several assumptions. It is recommended to do more research on this subject.

9 Conclusions and recommendations

In this chapter an overview of the final conclusions is given. The conclusions can be formulated as an answer to the research questions given in chapter one. After that, recommendations for further development of the investigated subject are given.

9.1 Conclusions

The central research question of the thesis was formulated as follows:

What is the optimal design of a work channel for TSHD's in an arbitrary situation?

To answer that question, a set of sub-questions were made. These sub-questions also formed the structure of the research. For every sub-question some general conclusions were drawn which are discussed below.

Which factors determine the movements of a ship in a channel and are therefore of influence on the design of a channel?

- From the literature review followed that the movements of a ship is a result of the interaction between the ship and the channel. The following factors have a contribution to the determination of the channel width and depth.
    - The dimensions and shape of the ship and the channel
    - The ships movement through the channel (manoeuvrability, ship speed, squat)
    - The interaction between environmental conditions (wind, waves, currents) and the ship
    - The interaction between the ship and the channel (shallow water effects, restricted water effects, bank suction effects)
    - The interaction between two ships (encountering or overtaking)
    - The presence and quality of aids to navigation
- All these influences combined will lead to the design of the channel dimensions. However, not all influences have to be taken into account in case of a TSHD in a temporary work channel.

What are the current design guidelines, where are they based upon and what are the differences between them?

- The most commonly used guidelines nowadays are given by the PIANC, USACE, Japan Institute of Navigation, Spanish Port Authority and the Canadian Coast Guard.
- A comparison of the guidelines is made based on a case-study. In all guidelines the channel depth is calculated by rules of thumb which results in a channel depth varying between 1.10 and 1.15 times the draught of the design ship.
- For the channel width calculation more differences between the guidelines are found. Some guidelines are based on empirical relations, others are based on analytical calculations. Based on the case-study the values for the channel width vary between 3 and 5 times the ships beam for one-way channels and 5 to 10 times for two-way channels.

- The guidelines by USACE and Japan Institute of Navigation show an underestimation of the eventually constructed width of 15 to 20%. The Canadian Coast Guard and PIANC guidelines give a slight overestimation of 15 to 25%. The Spanish guideline overestimates the channel width with almost 60%.
- A large problem of the empirical methods is that they do not give a continuous result for increasing environmental conditions. Therefore, the channel width is often not exactly calculated for the prevailing conditions.
- All guidelines are developed to be used for all ships and all conditions and a long lifetime. Therefore the results often show an overestimation when used for a temporary work channel.

Where is the design of a work channel within Boskalis currently based upon and how does the design relate to the theory and practice?

- Currently the channel dimensions are calculated according to the PIANC guidelines.
- An inventory of the differences between the various interpretations of the PIANC guidelines and the differences between the design and the construction is made based on five projects executed by Boskalis.
- The PIANC calculation for channel width is not continuous for varying conditions and the calculation of the channel depth only follows from rules of thumb. This results in an underestimation of the channel width by the Boskalis engineers. Often the width of the channel is adjusted after the first TSHD's have already sailed through the channel. A more conservative interpretation of the PIANC guidelines gives a value which deviates from the eventual constructed channel width by -15% to +30%.

Which factors determine the movements of a TSHD in a temporary work channel and how can these factors be quantified (either based on theories or based on experiences of TSHD captains)?

- The channel depth is calculated by a superposition of the TSHD's maximum draught (fixed value given as input), the maximum squat (calculated by method of Ankudinov), an allowance for wave response (calculated based on wave height) and an allowance for UKC (value depending on bottom material, based on the experiences of TSHD captains).
- The channel width is a combination of the TSHD's swept path (calculated by the drift angle following from the currents, the TSHD's beam and length), an allowance for bank suction forces and sinusoidal movement of the TSHD (value depending on ships beam, based on the experiences of TSHD captains) and an allowance for ship-ship interaction (value depending on ships beam, based on experiences captains).
- The dimensions of the turning basin are calculated with the ships length and is based on the experiences of TSHD captains.

What is the most optimal lay-out of a work channel?

- The combination of the influences given above lead to an optimal value for the depth, width and turning basin dimensions. All these calculations are combined in a design tool.
- An assessment of the design tool is made based on a case study. The design of a work channel is calculated by the design tool and several runs are made with the fast-time

simulation software SHIPMA. The following conclusions can be drawn from the SHIPMA simulations:
  - The calculated drift angle shows a good correlation with the average value from SHIPMA, for the maximum value the design tool gives a slight underestimation
  - An analysis based on the swept path and maximum required channel width based on SHIPMA output data was made to assess the width calculated by the design tool. For the width of the one-way channel and the deep part of the two-way channel, the design tool gave a slight overestimation resulting in a small buffer between the ship and the channel banks. This overestimation can be seen as a safety margin in the design, to take uncertainties in some of the assumptions into account. For the shallow part of the two-way channel, the design tool gave a small underestimation of the width. In general, the channel width is overestimated by approximately 20%.
- The design tool computes the dimensions of a one-way channel and a two-way channel. The choice between the two channels can be made according to an analysis of costs. When choosing for a two-way channel, the benefits of using two TSHD's must weigh up to the extra production costs and the extra costs of a larger channel. This all depends on the used TSHD('s) and the nature of the project. For the case of the reclamation in Bahrain, a larger reclamation volume leads to the choice for a one-way channel with a large TSHD. The smaller the reclamation volume gets, the more profitable a two-way channel with two small TSHD's gets.

9.2 Recommendations

The goal of this Masters thesis is to develop a tool for the calculation of the dimensions of a temporary work channel for TSHD's. The resulting tool needs to be easy in use and has to provide a fast calculation method. Most of the theories and assumptions made in the design tool are still subject to ongoing research. Therefore a list of recommendations is made that can help to keep the design tool up-to-date. The design tool is build up in a transparent way so that it is easy to make improvements in the coming years. The following recommendations are made:

- The prediction of squat is still subject to a lot of uncertainties. The method of Ankudinov used in the design tool shows good correlation with the model test results of a TSHD in shallow water. However, a validation of this method for a TSHD in shallow, restricted water could not be made. It is recommended to set up a program to investigate the squat of a TSHD in a shallow, restricted water. Test results can be used to make a validation of the method of Ankudinov for this particular situation. It is also recommended to keep up-to-date on new developments regarding other squat-prediction methods.
- Other effects following from the interaction between the ship and the channel are also still being investigated. There is a lot unknown about the ship-ship interaction forces and bank suction effects. Both have been investigated for a general case, not including a shallow, restricted water or the typical shape of a TSHD. It is recommended to keep up-to-date on these subjects. Better calculation methods could lead to a better determination of the ship-ship interaction lane and buffer used for bank suction effects.
- To gain more insight on the exact movement of a TSHD in a work channel, it is recommended to collect DGPS-data of a TSHD in that situation. This data can be used to check the results of the design tool in a real-life case.

- In the assessment of the design tool, some assumptions are made regarding the SHIPMA simulations. The use of a TSHD was approached by a bulk carrier. The simulation results will give a closer approach to the reality when a model of a TSHD is used. It is therefore recommended to have a model of a TSHD made, that can be used in SHIPMA or another fast-time simulation software.
- For a better view on the applicability of the design tool, more simulations must be made. A larger variation in projects and environmental conditions can lead to a more extensive assessment of the design tool.
- SHIPMA simulations can only be used to check the width of the channel calculated by the design tool. It is recommended to also make a check regarding the channel depth and the dimension of the turning basin. The channel depth can be checked with measurements of the net UKC on board of a TSHD. The turning manoeuvre inside a basin can be checked by making a simulation run using a TSHD instead of another ship.
- The analysis of costs concluded that the sailing speeds of the TSHD indicated by the captains, do not always lead to the lowest costs. Above a certain reclamation volume, it is more profitable to sail at a higher speed through the channel with a loaded hopper. The underlying calculation is based on several assumptions and is therefore rather rough. It is therefore recommended to do more research on the optimal sailing speed of a TSHD in a work channel.

10 References

[1] JAPAN INSTITUTE OF NAVIGATION, STANDARD COMMITTEE (2003) Design Standard for Fairway in Next Generation, *Japan Institute of Navigation (Standard committee), Ministry of Land, Infrastructure and Transport (National Institute for Land an Infrastructure Management, Port and Harbor Department)*

[2] PIANC (1997) Approach Channels - A Guide for Design, *Final report of the joint Working Group PIANC and IAPH, in cooperation with IMPA and IALA (Supplement to Bulletin no 95), Brussels*

[3] USACE (2006) Hydraulic Design of Deep-Draft Navigation Projects, *Department of the Army, US Army Corps of Engineers, Washington DC*

[4] M.J. BRIGGS, M. VANTORRE, K. ULICZKA, P. DEBAILLON (2010) Prediction of Squat for Underkeel Clearance, *Handbook of Coastal and Ocean Engineering (p723-774), Los Angeles*

[5] H.J. VERHEIJ, C. STOLKER, R. GROENVELD (2008) Inland Waterways, *Lecture notes Delft University of Technology, Delft*

[6] IALA-AISM (2006), Aids to Navigation Guide (NavGuide), *International Association of Lighthouse Authorities, France*

[7] PIANC (1985) Underkeel clearance for large ships in maritime fairways with hard bottom, *Report of a working group of the Permanent Technical Committee II (Supplement to Bulletin no 51), Brussels*

[8] Z. DEMIRBILEK, F. SARGENT (1999) Deep-Draft Coastal Navigation Entrance Channel Practice (Coastal Engineering Technical Note I-63), *Department of the Army, US Army Corps of Engineers, Washington DC*

[9] USACE (2008) Coastal engineering manual - Part V, chapter 5: Navigation projects, *Department of the Army, US Army Corps of Engineers, Washington DC*

[10] PUERTOS DEL ESTADO (2007) ROM 3.1-99, Design of the Maritime Configuration of Ports, Approach Channels and harbour basins, *Spanish National Ports & Harbours Authority, Madrid*

[11] CANADIAN COAST GUARD (1999) Canadian Waterways National Manoeuvring Guidelines – Channel Design Parameters, *Waterways development, marine navigation services, Canadian coast guard, fisheries and oceans*

[12] BRITISH STANDARDS INSTITUTE (2000) Maritime Structures – Part 1: Code of practice for general criteria, *Technical Committee B/525, Building and civil engineering structures*

[13] M.J. BRIGGS (2006) Ship Squat Predictions for Ship/Tow Simulator (Coastal and Hydraulics Engineering Technical Note I-72), *Department of the Army, US Army Corps of Engineers, Washington DC*

[14] M.J. KUIPER (2004) Invloed van ontwerpparameters op het ondiep water gedrag van de moderne sleephopperzuiger (Master thesis), *TU Delft & Royal Boskalis Westminster NV, Papendrecht*

[15] M.J. BRIGGS (2009) Ankudinov Ship Squat Predictions – Part I: Theory, Parameters and FORTRAN Programs (Coastal and Hydraulics Engineering Technical Note IX-19), *US Army Engineer Research and Development Centre, Vicksburg MS*

[16] M.J. BRIGGS, L. DAGGETT (2009) Ankudinov Ship Squat Predictions – Part II: Laboratory and Field Comparisons and Validations (Coastal and Hydraulics Engineering Technical Note IX-20), *US Army Engineer Research and Development Centre, Vicksburg MS*

[17] M. VANTORRE, G. DELEFORTRIE, K. ELOOT, E. LAFORTE (2003) Experimental investigation of ship-bank interaction forces, *proceedings of the international conference on marine simulation and ship maneuverability 2003 (MarSim '03), Kanazawa, Japan*

[18] T.P. GOURLAY (2006) A Simple Method for Predicting the Maximum Squat of a High-Speed Displacement Ship, *Marine Technology, Vol. 43, No. 3, July 2006, pp. 146-151*

[19] T.P. GOURLAY (2007) Ship Underkeel Clearance in Waves, *Proceedings Coasts and Ports, Melbourne, July 2007*

[20] Y. ABDELOUARIT (2010) Probabilistische Diepte Modellering Binnenhavengebied Haven van Rotterdam (Master thesis), *TU Delft & Port of Rotterdam, Rotterdam*

[21] H.H. DE KONING GANS, H. BOONSTRA (2007) Squat Effects of Very Large Container Ships with Drift in a Harbor Environment, *Proceedings of the international maritime-port technology and development conference, Singapore*

[22] M.H. KAARSEMAKER, O.M. WEILER, G. KANT, H.J. VERHEIJ (2010) Evaluation of Flow Fields for their Impact on Manoeuvring, *Proceedings of the PIANC MMX Congress 2010, Liverpool*

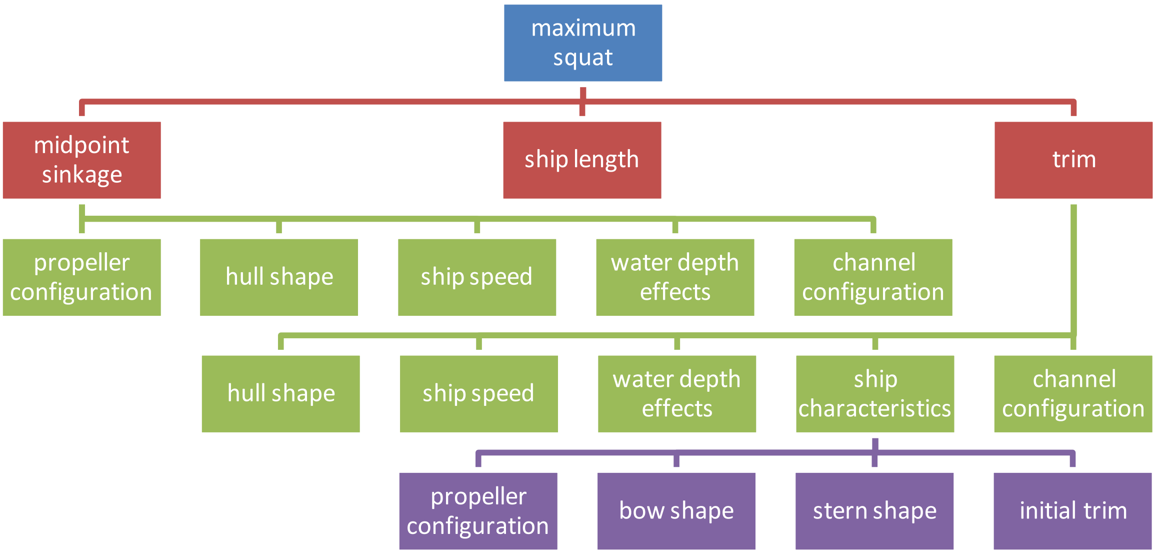
[23] THE DUTCH ASSOCIATION OF CONTRACTORS IN DREDGING, SHORE AND BANK PROTECTION (1998) Voortgezette Opleiding Uitvoering Baggerwerken: part 13 Planning & Kostenraming, *Gouda*

[24] G.L.M. VAN DER SCHRIECK (2009) Dredging Technology, *Lecture notes Delft University of Technology, Delft*

[25] C. VAN RHEE (2008) Rough Costprice Calculation of TSHD's and CSD's, *Lecture notes Delft University of Technology, Delft*

Appendix A:
Ankudinov squat prediction method

The method used to predict the ship squat in the design tool is made by Ankudinov. The method involves several factors influencing the squat of a ship, mainly based on ship characteristics and environmental conditions. The way the method is build up is shown in the following figure.



As input for the squat calculation several ship and channel characteristics are needed. These factors are shown in the table below. Besides these values some other ship characteristics, like propeller configuration and hull shape, are included in formulas.

Symbol	Unit	Description
L_{pp}	[m]	ships length between perpendiculars
B	[m]	ships beam
T	[m]	ships draught
T_{ap}	[m]	static draught at stern
T_{fp}	[m]	static draught at bow
h	[m]	channel depth
h_t	[m]	channel trench height
C_B	[-]	block coefficient
$S = A_S / A_{Ch}$	[-]	blockage factor
A_S	[m^2]	ship cross-section area
A_{Ch}	[m^2]	channel cross-section are
$F_{nh} = V/\sqrt{g \cdot h}$	[-]	Froude depth number
V	[m/s]	ship speed
g	[m/s^2]	gravitational acceleration

As seen before, the maximum squat is calculated as a combination of the midpoint sinkage, the length and the trim of the ship. Two formulas are give, one for bow squat and one for stern squat. The largest of the two is the maximum squat.

$S_b = L_{pp}(S_m - 0.5 \cdot Trim)$	[m]	Squat at bow
$S_s = L_{pp}(S_m + 0.5 \cdot Trim)$	[m]	Squat at stern

The midpoint sinkage is calculated based on the characteristics of the ship and the channel. The ships characteristics that are taken into account are the propeller configuration, the shape of the hull and the speed. The channel is included by means of a factor for shallow water effects, channel configuration and channel dimensions.

	$S_m = (1 - K_P^S) \cdot P_{Hu} \cdot P_{F_{nh}} \cdot P_{+h/T} \cdot P_{Ch1}$		[m]	Midpoint sinkage
1.1	$K_P^S = 0.15$ *Single propeller* $K_P^S = 0.15$ *Twin propellers*		[-]	Propeller parameter
1.2	$P_{Hu} = 1.7 \cdot C_B \cdot \left(\frac{B \cdot T}{L_{pp}^{\ 2}} \right) + 0.004 \cdot C_B^{\ 2}$		[-]	Ship hull parameter for shallow water
1.3	$P_{F_{nh}} = F_{nh}^{\ (1.8 + 0.4 \cdot F_{nh})}$		[-]	Ship forward speed parameter
1.4	$P_{+h/T} = 1.0 + \frac{0.35}{(h/T)^2}$		[-]	Water depth effects pararmeter
1.5	$P_{Ch1} = 1.0$ $P_{Ch1} = 1.0 + 10 \cdot S_h - 1.5(1.0 + S_h)\sqrt{S_h}$	*U* *R, C*	[-]	Channel effects parameter

U = unrestricted channel

R = restricted channel

C = canal

1.5.1	$S_h = C_B \left(\frac{S}{h/T} \right) \left(\frac{h_T}{h} \right)$		[-]	Channel depth factor

The second large contribution to the squat is given by the trim of the ship. Again the ship speed, water depth effects and channel configuration are included. Also the some other ship characteristics are involved, namely the propeller configuration, the shape of the bow and stern and the initial trim of the ship. Some of the parameter included in the calculation of the midpoint sinkage are also included in the calculation of trim.

$Trim = -1.7 \cdot P_{Hu} \cdot P_{F_{nh}} \cdot P_{h/T} \cdot K_{Tr} \cdot P_{Ch2}$		[-]	Vessel trim
2.1 $P_{h/T} = 1 - e^{\left[\frac{2.5(1-h/T)}{F_{nh}}\right]}$		[-]	Vessel trim parameter
2.2 $K_{Tr} = C_B^{\,n_{Tr}} - \left(0.15 \cdot K_P^S + K_P^T\right) - \left(K_B^T + K_{Tr}^T + K_{T1}^T\right)$		[-]	Trim coefficient
2.2.1 $n_{Tr} = 2.0 + 0.8 \frac{P_{Ch1}}{C_B}$		[-]	Trim exponent
2.2.2 $K_P^T = 0.15$	*Single propeller*	[-]	Propeller trim parameter
$K_P^T = 0.20$	*Twin propellers*		
2.2.3 $K_B^T = 0.1$	*Bulbous bow*	[-]	Bulbous bow factor
$K_B^T = 0.0$	*No bulbous bow*		
2.2.4 $K_{Tr}^T = 0.1\left(\frac{B_{Tr}}{B}\right) \approx 0.04$	*Stern transom*	[-]	Stern transom factor
$K_{Tr}^T = 0.0$	*No stern transom*		
2.2.5 $K_{T1}^T = \frac{\left(T_{ap} - T_{fp}\right)}{\left(T_{ap} + T_{fp}\right)}$		[-]	Initial trim effect factor
2.3 $P_{Ch2} = 1.0$	*U*	[-]	Channel effect trim correction parameter
$P_{Ch2} = 1.0 - 5 \cdot S_h$	*R, C*		

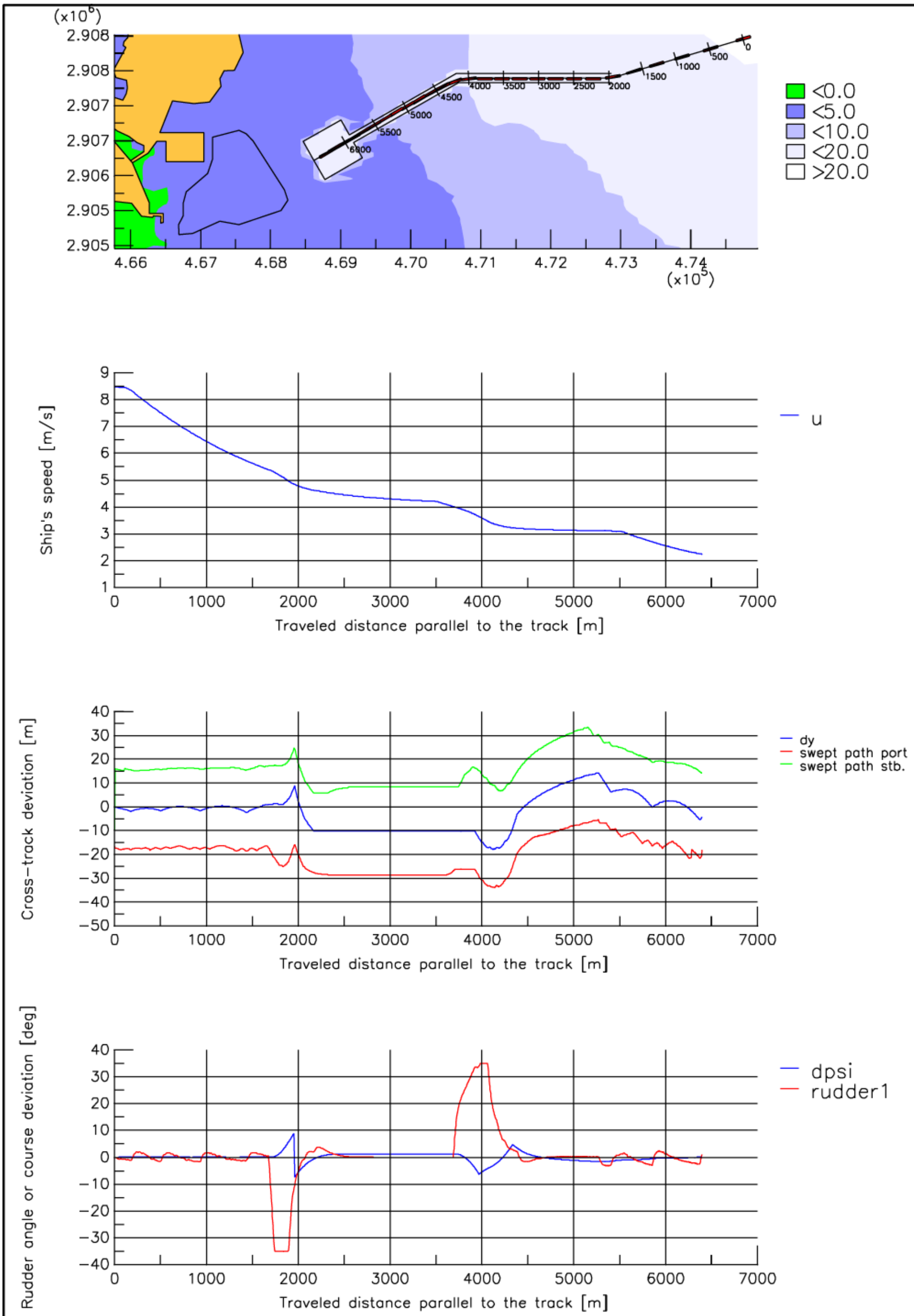
Appendix B: SHIPMA results

In this appendix all results of the SHIPMA simulations are given. The following table gives an overview of all the cases.

Case	Configuration	Direction	Wind [m/s]	Waves [m]	Currents [m/s]	Sailing speed [kn]
1	One-way	Incoming	0	0	0	6 to 8
2	One-way	Outgoing	0	0	0	14 to 16
3	Two-way	Incoming	0	0	0	6 to 8
4	Two-way	Outgoing	0	0	0	14 to 16
5	One-way	Incoming	0	0	0.26	6 to 8
6	One-way	Outgoing	0	0	0.26	14 to 16
7	Two-way	Incoming	0	0	0.26	6 to 8
8	Two-way	Outgoing	0	0	0.26	14 to 16
9	One-way	Incoming	15	0	0	6 to 8
10	One-way	Outgoing	15	0	0	14 to 16
11	Two-way	Incoming	15	0	0	6 to 8
12	Two-way	Outgoing	15	0	0	14 to 16
13	One-way	Incoming	0	1.3	0	6 to 8
14	One-way	Outgoing	0	1.3	0	14 to 16
15	Two-way	Incoming	0	1.3	0	6 to 8
16	Two-way	Outgoing	0	1.3	0	14 to 16
17	One-way	Incoming	15	1.3	0.26	6 to 8
18	One-way	Outgoing	15	1.3	0.26	14 to 16
19	Two-way	Incoming	15	1.3	0.26	6 to 8
20	Two-way	Outgoing	15	1.3	0.26	14 to 16
21	Two-way	Incoming	0	0	0.51	6 to 8
22	Two-way	Incoming	0	0	0.77	6 to 8
23	Two-way	Incoming	0	0	1.03	6 to 8
24	Two-way	Incoming	0	0	1.54	6 to 8

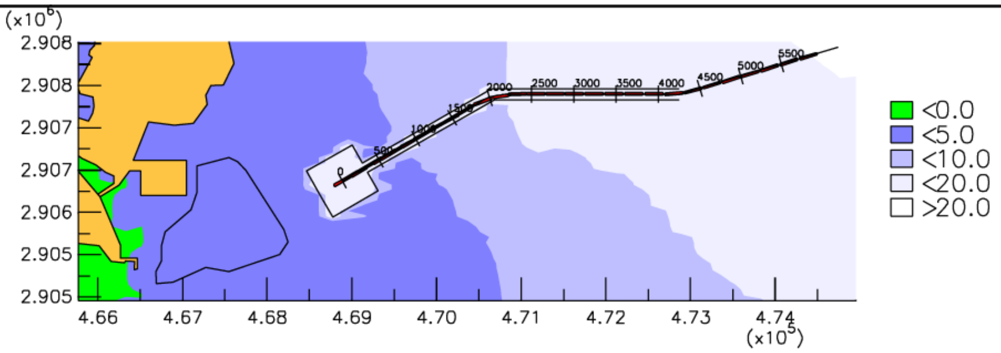
On the following pages an overview of every case is given. The results are shown in four windows:

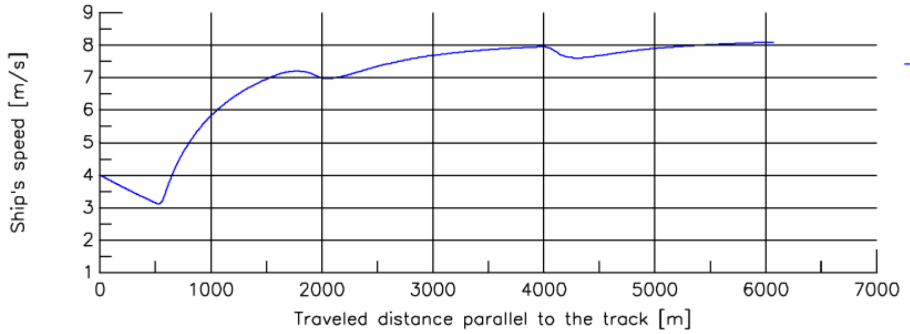
- Overview of the bathymetry and track log
- Distribution of the sailing speed (in meters per second) along the sailed track
- Distribution of the cross-track deviation (in meters) along the sailed track for:
    - the center of the ship
    - the outer starboard point of the ship
    - the outer portside point of the ship
- Distribution of the cross-track deviation and rudder angle (in degrees) along the sailed track

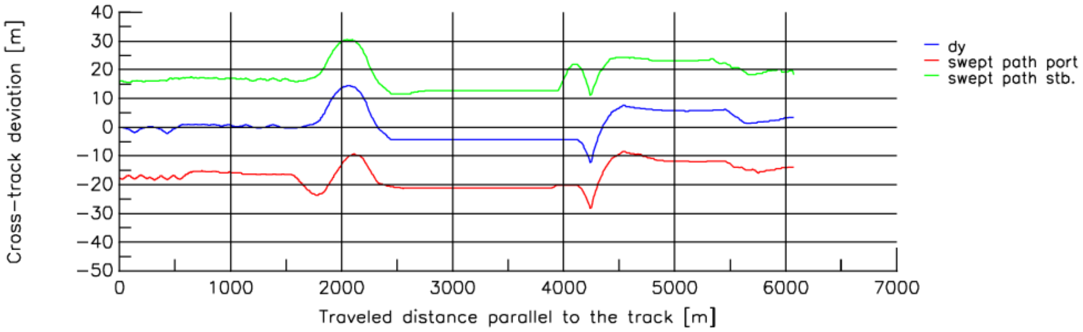


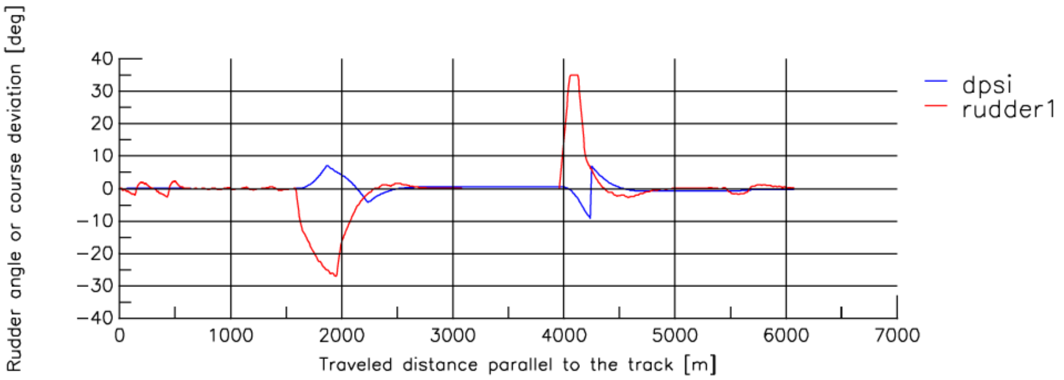
CASE 1: one-way channel, direction east-west

no environmental conditions

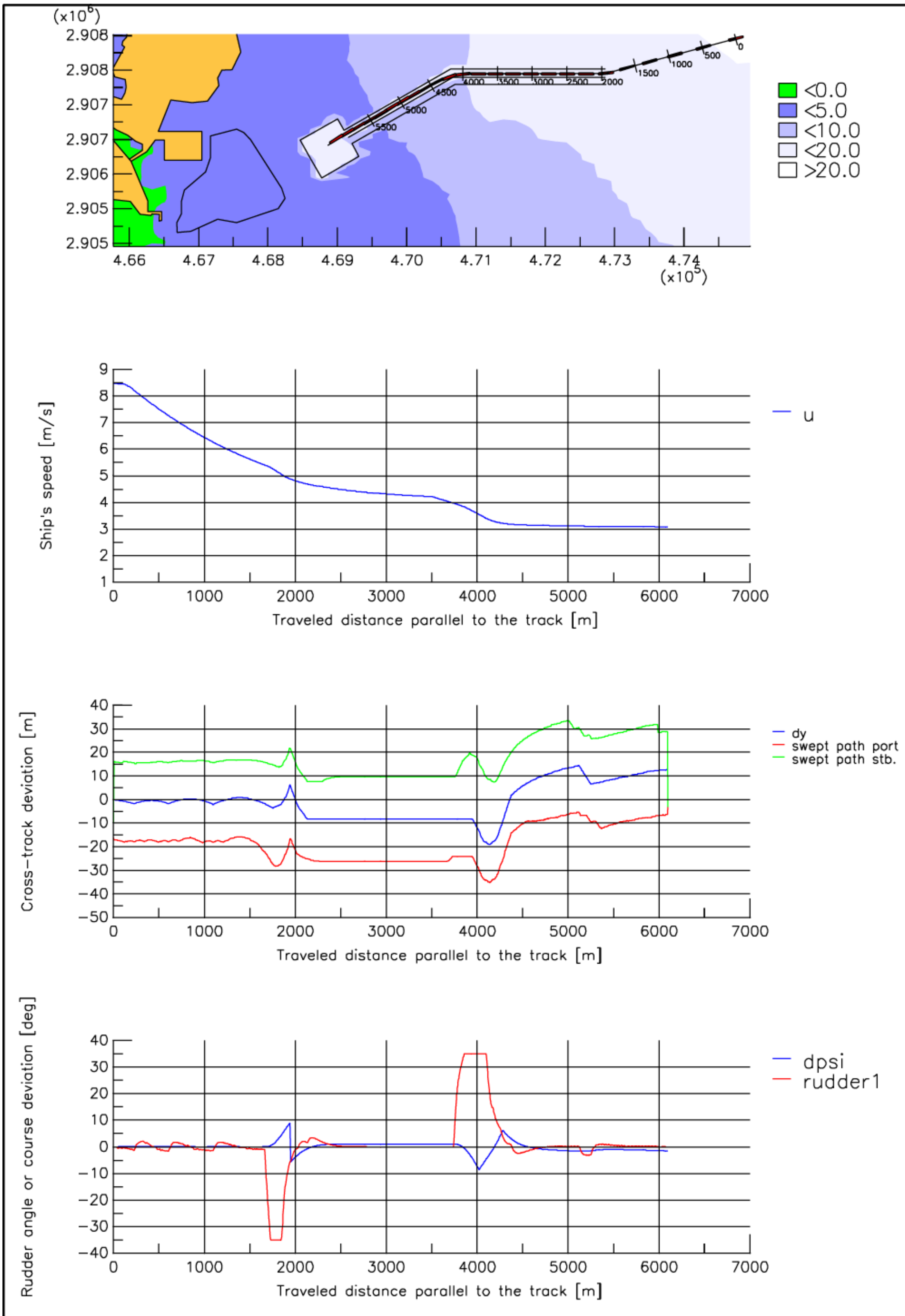




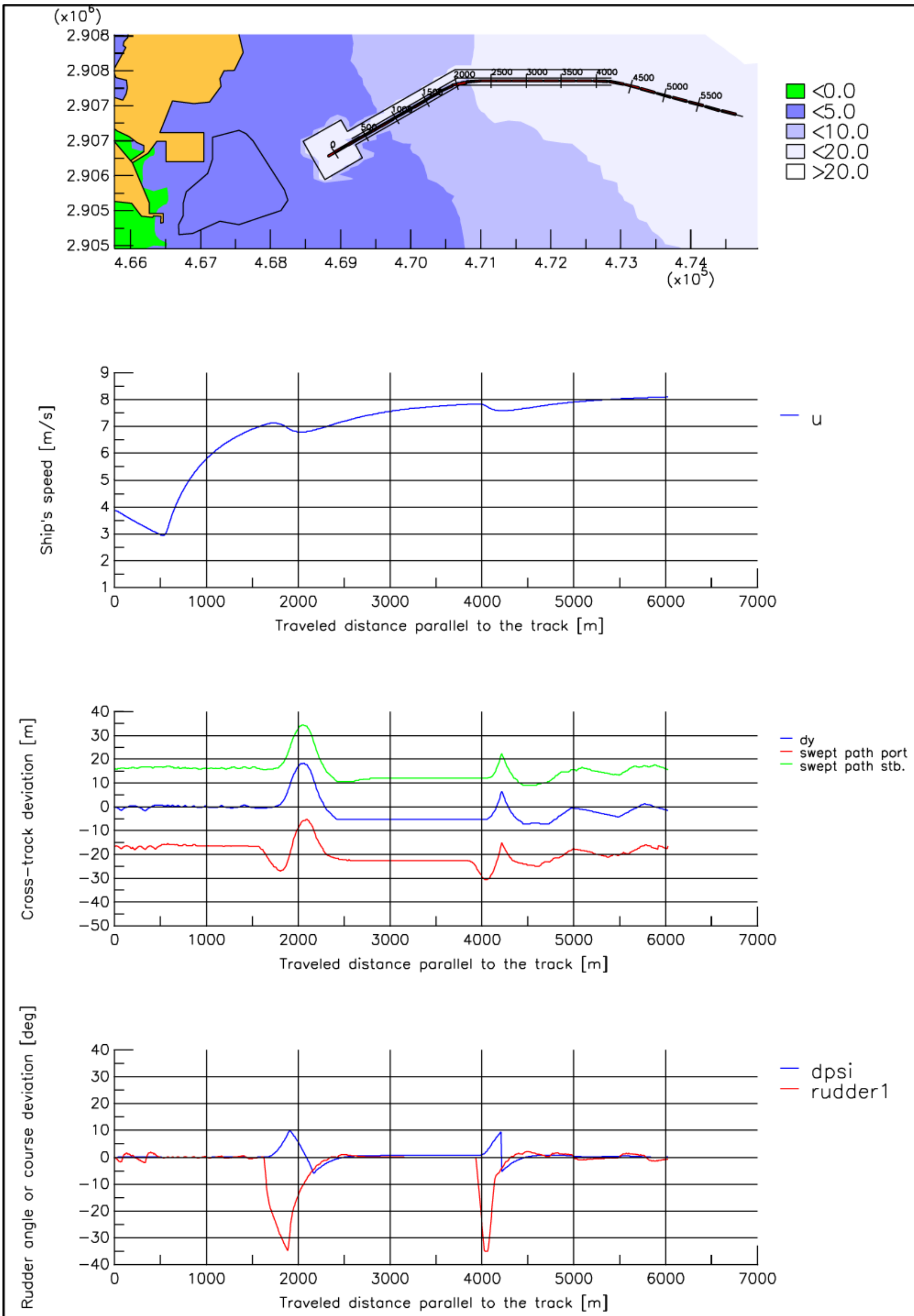




CASE 2: one-way channel, direction west-east
no environmental conditions

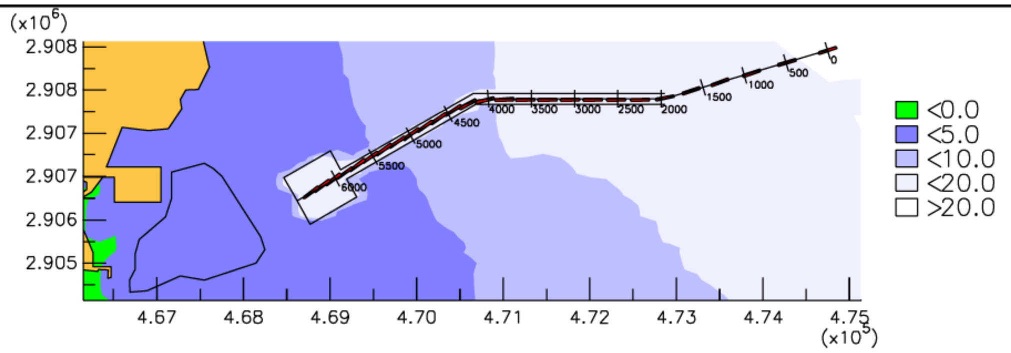


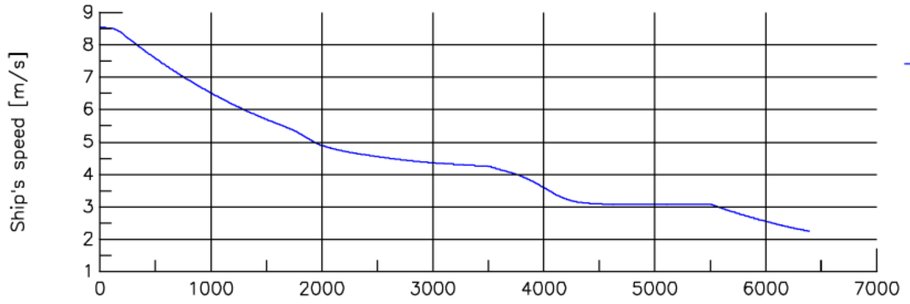
CASE 3: two-way channel, direction east-west no environmental conditions		

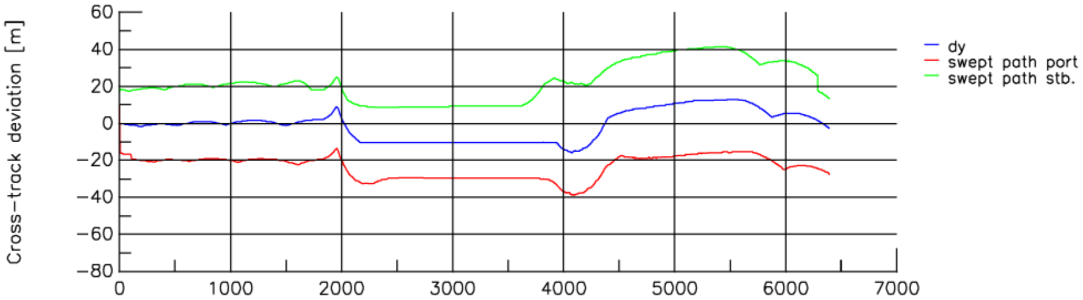


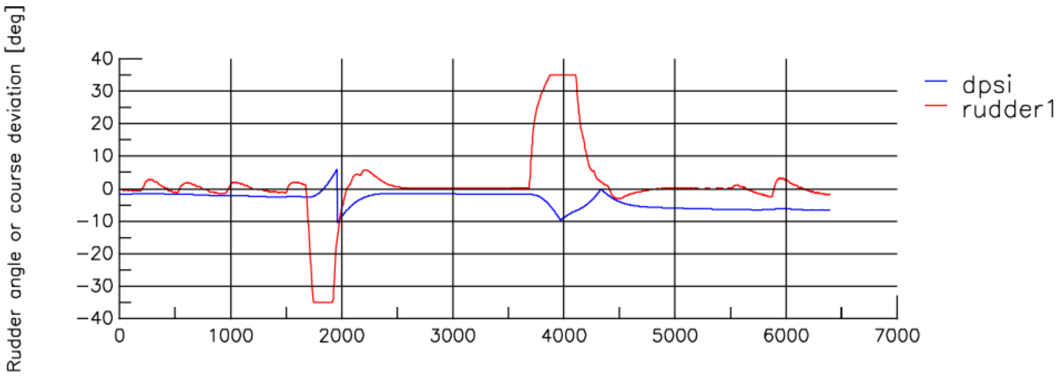
CASE 4: two-way channel, direction west-east

no environmental conditions



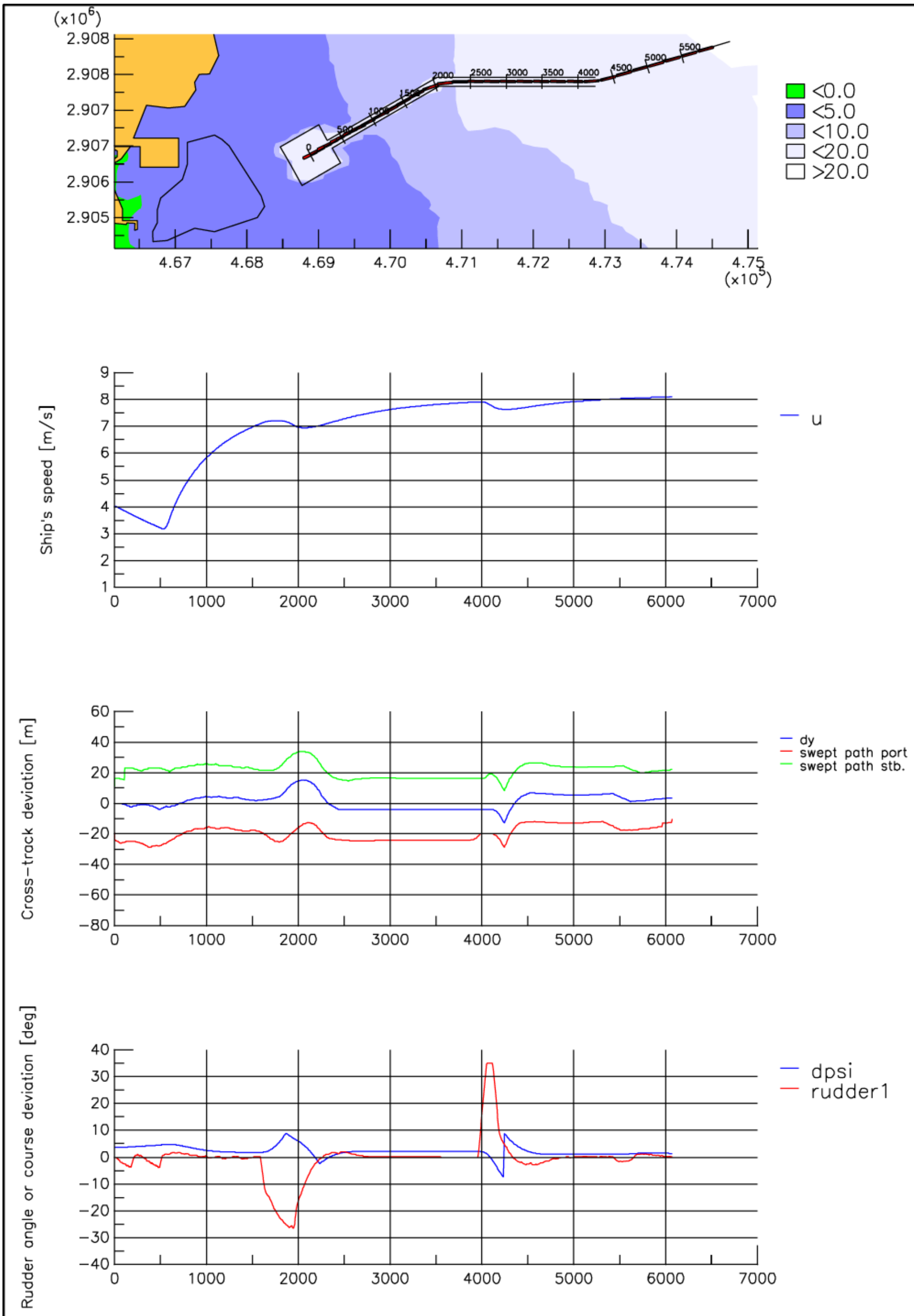




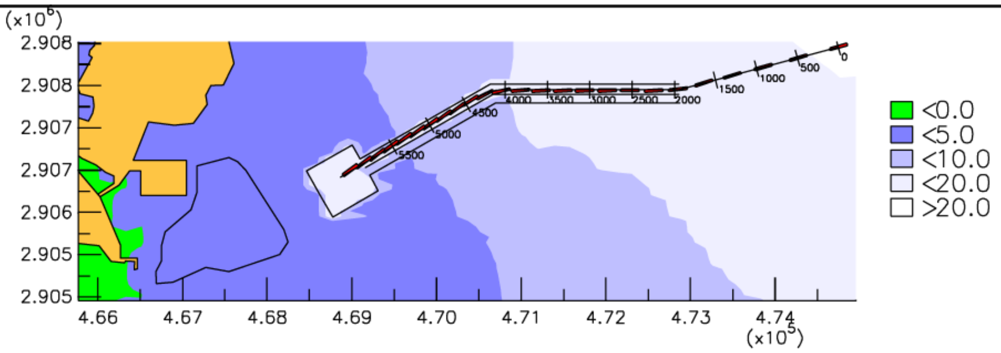


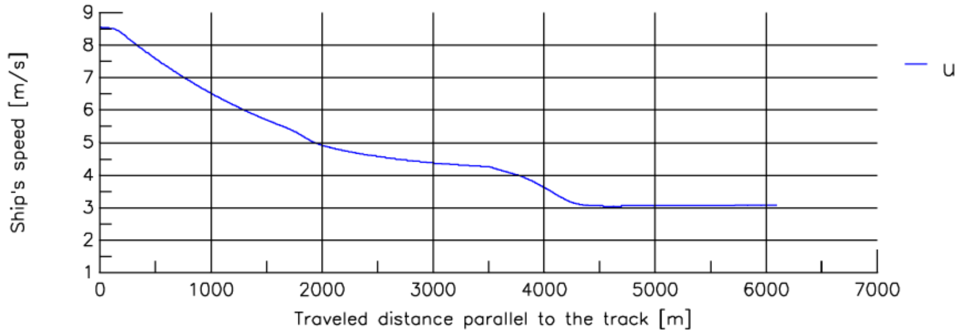
CASE 5: one-way channel, direction east-west

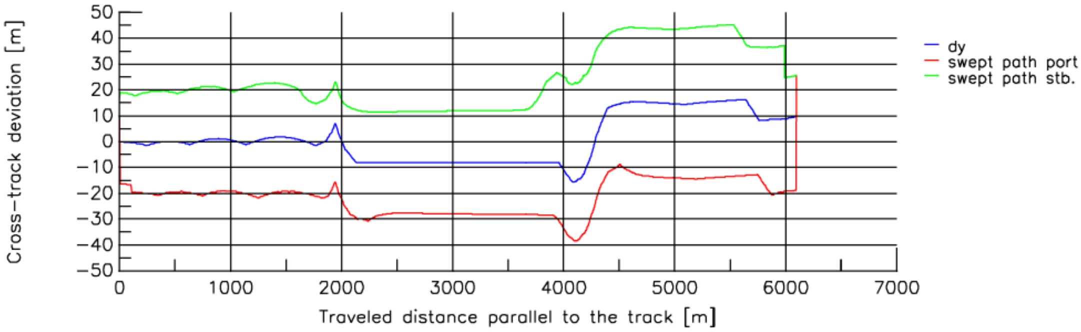
environmental condition: currents

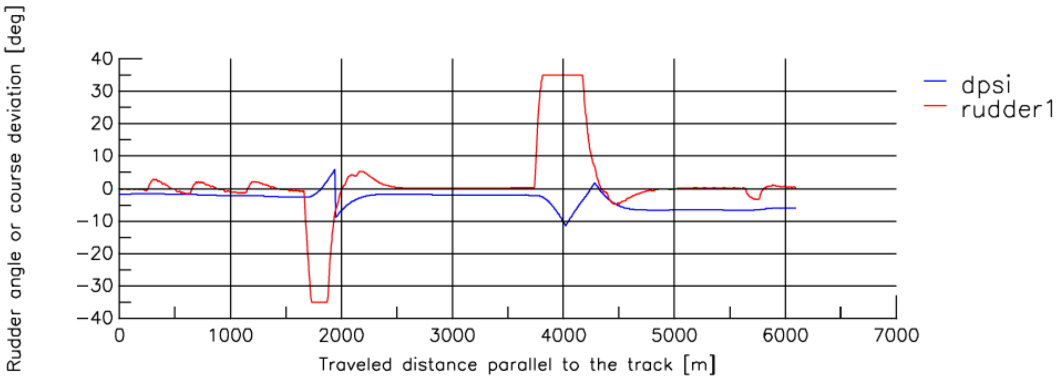


CASE 6: one-way channel, direction west-east environmental condition: currents		

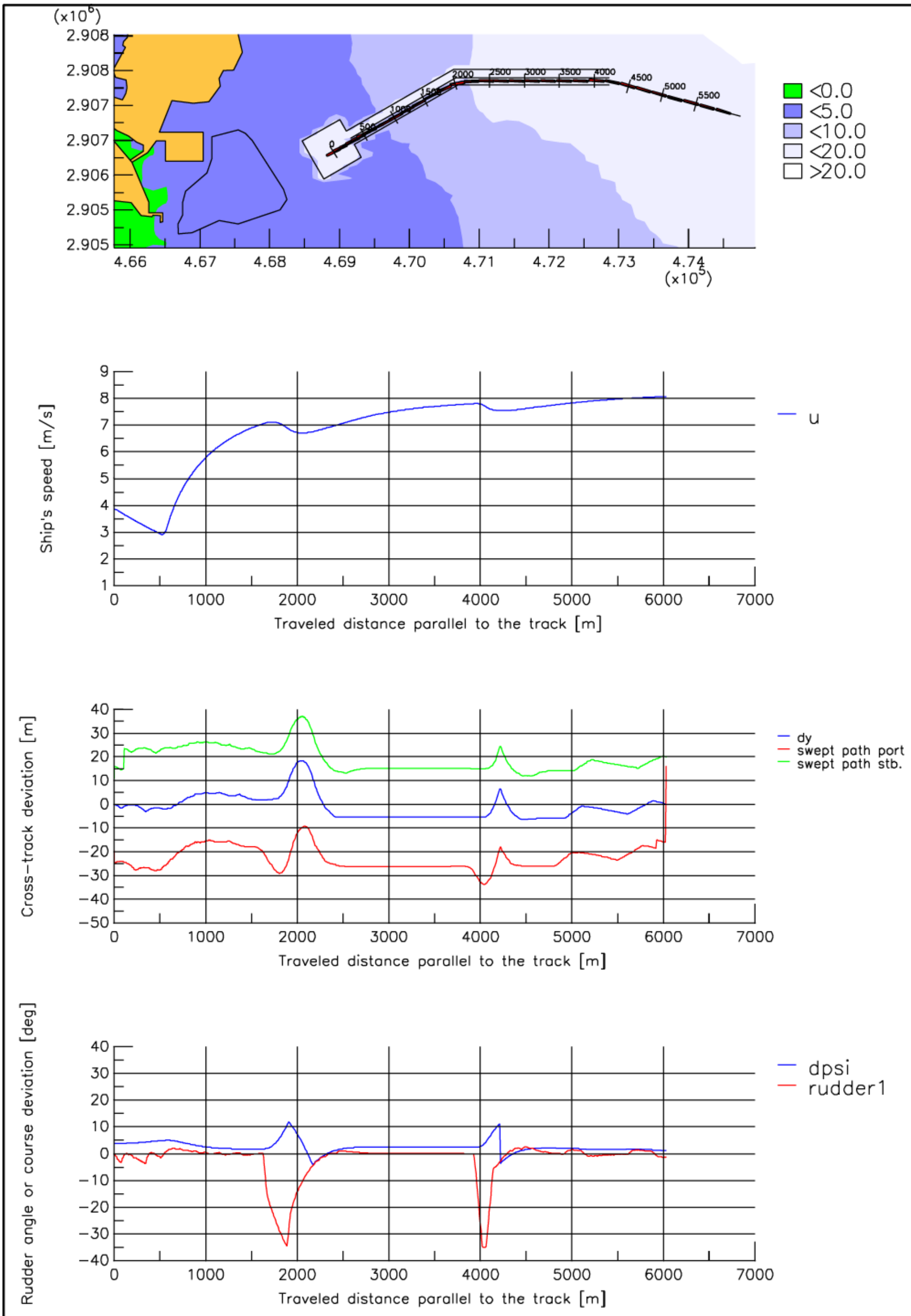




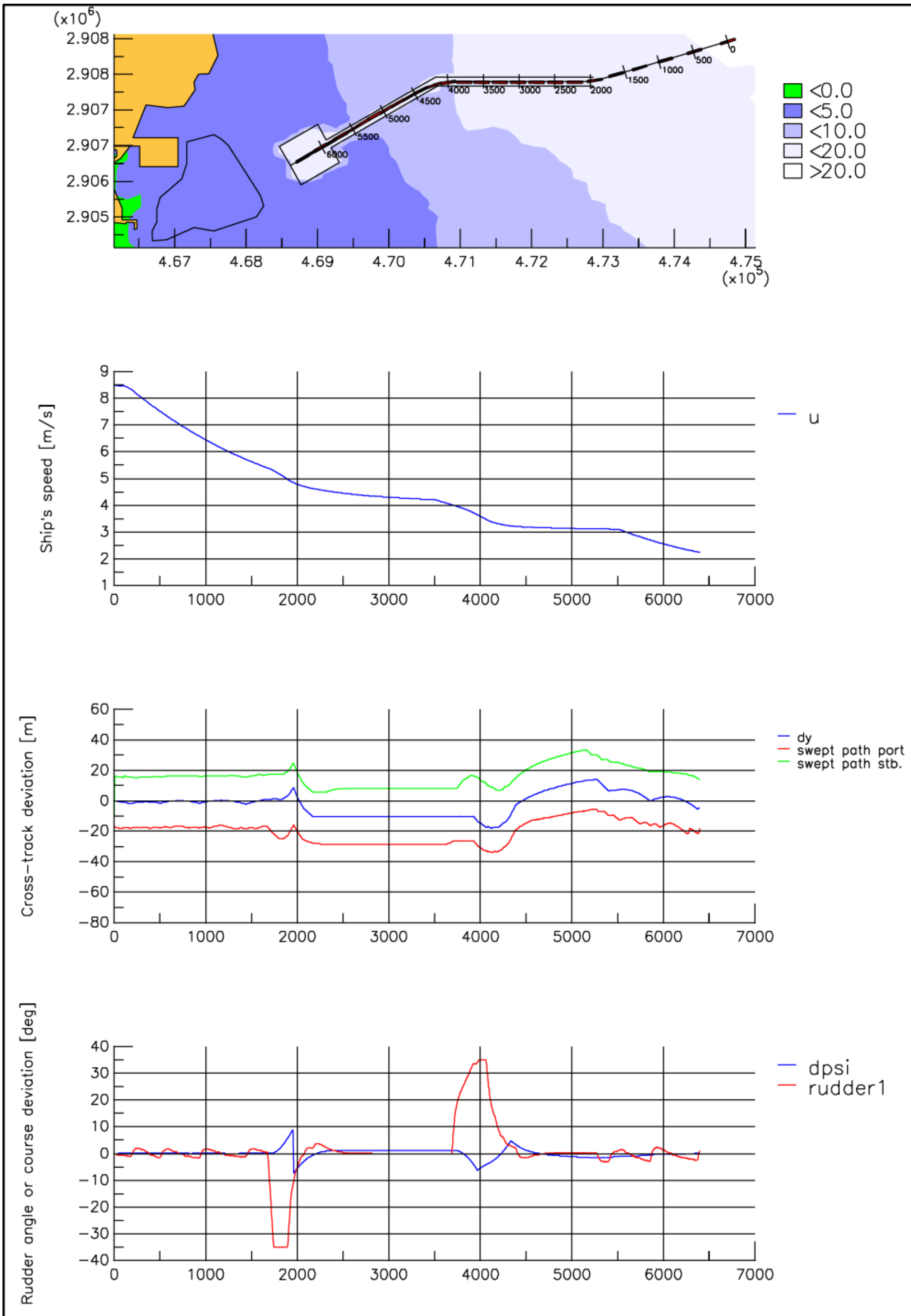




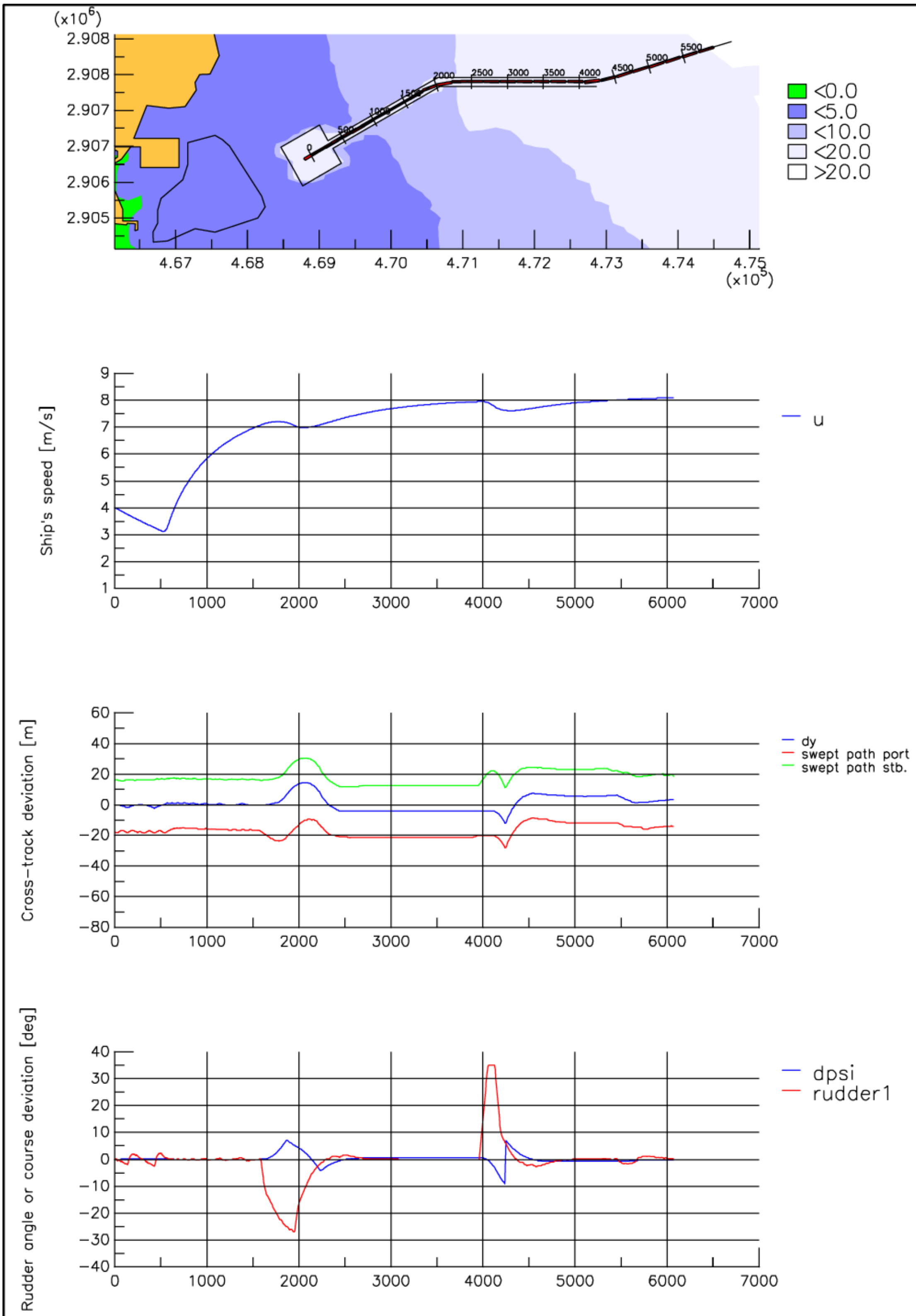
CASE 7: two-way channel, direction east-west
environmental condition: currents



CASE 8: two-way channel, direction west-east environmental condition: currents		

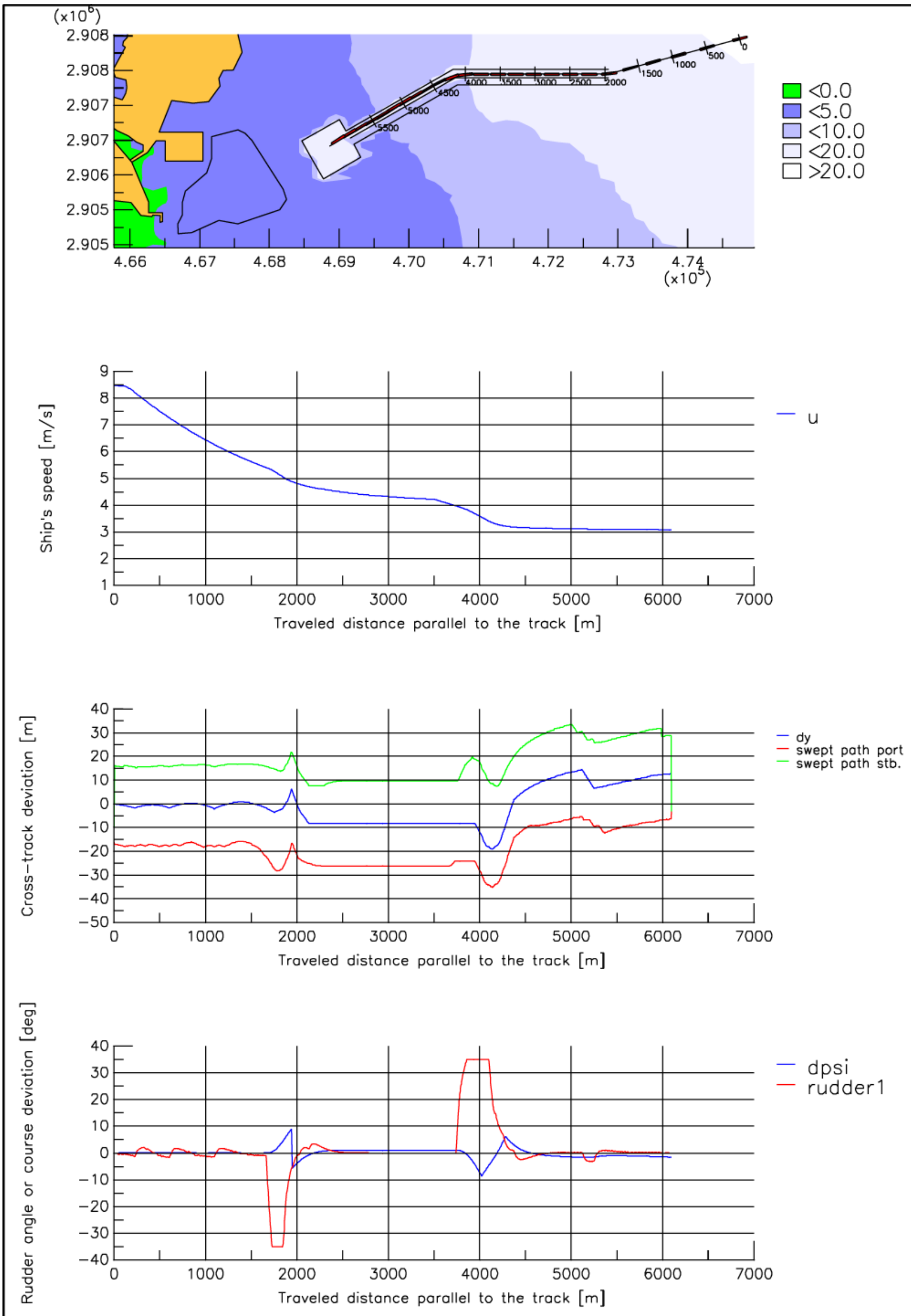


CASE 9: one-way channel, direction east-west
environmental condition: wind

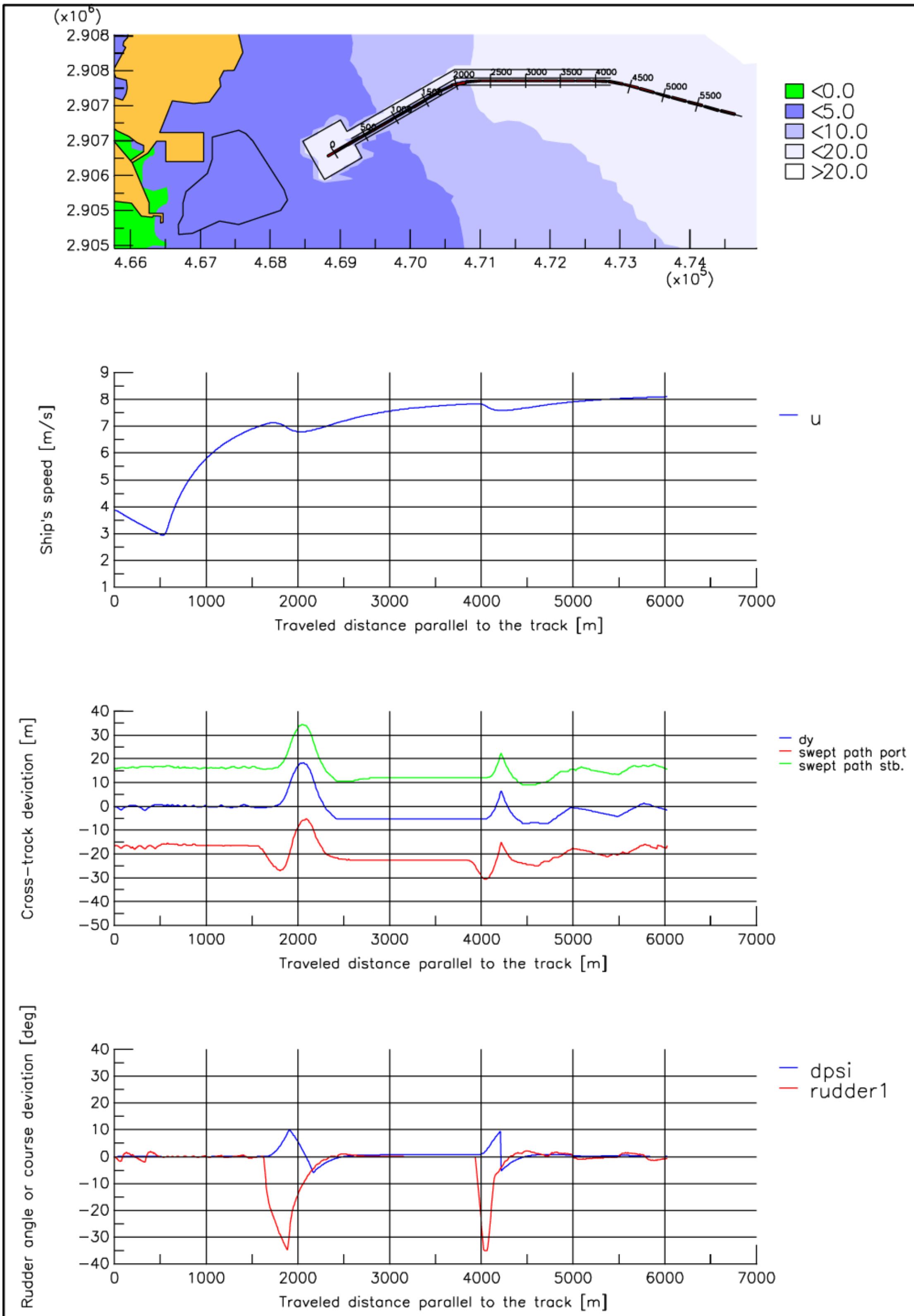


CASE 10: one-way channel, direction west-east

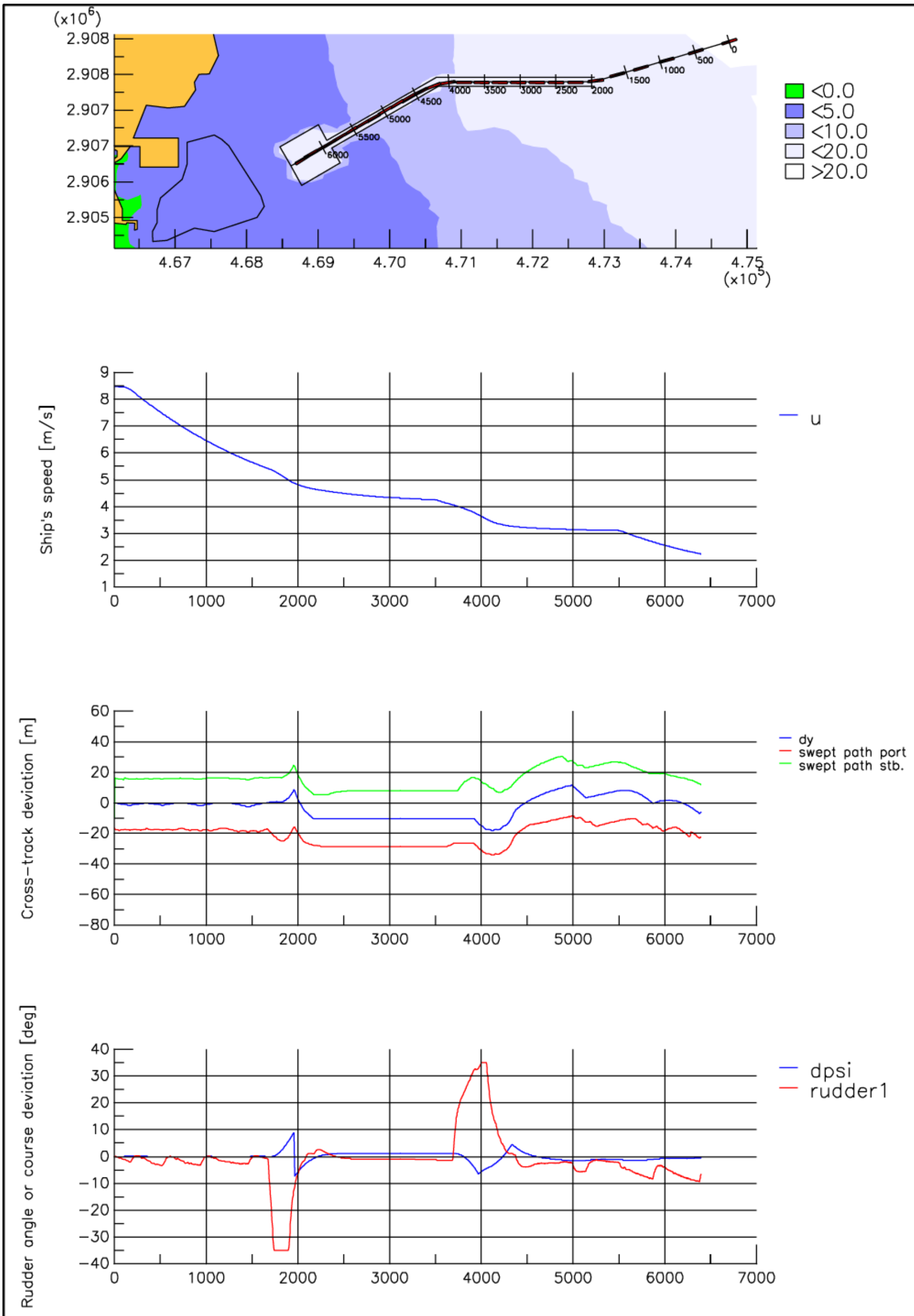
environmental condition: wind



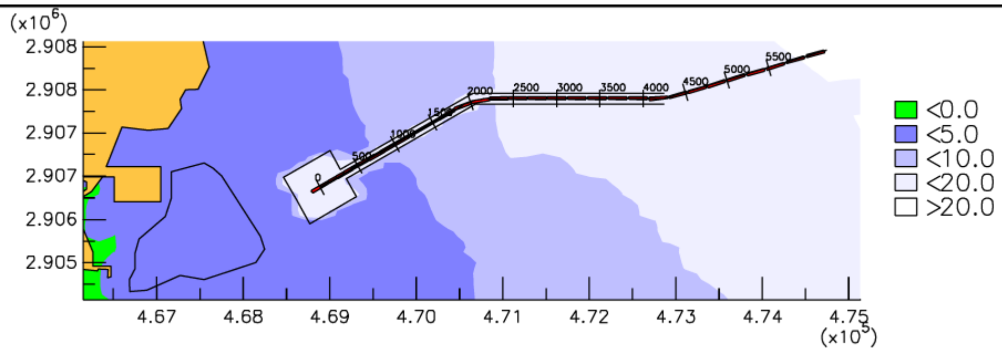
CASE 11: two-way channel, direction east-west
environmental condition: wind

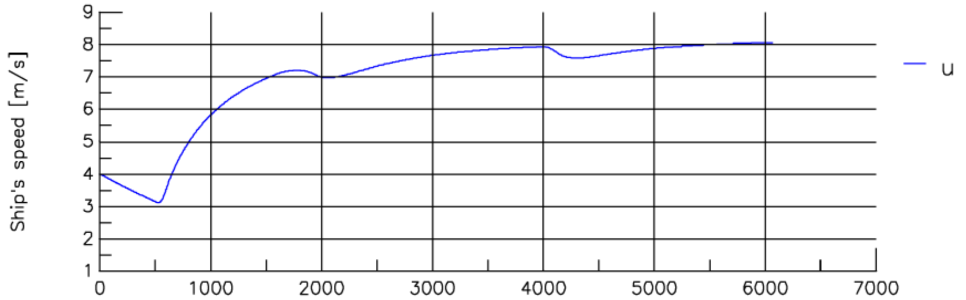


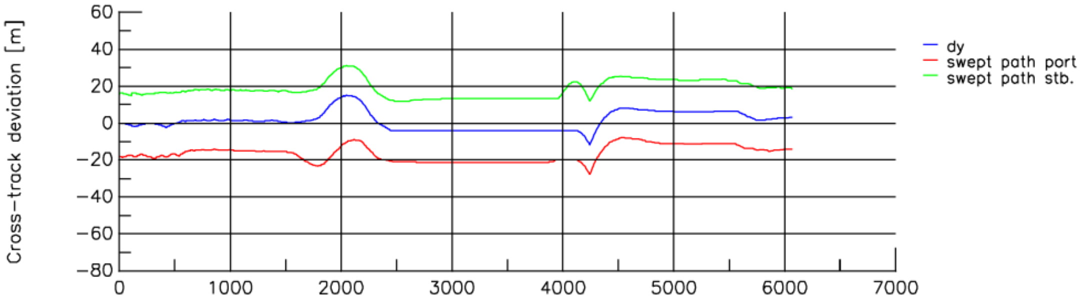
CASE 12: two-way channel, direction west-east environmental condition: wind		

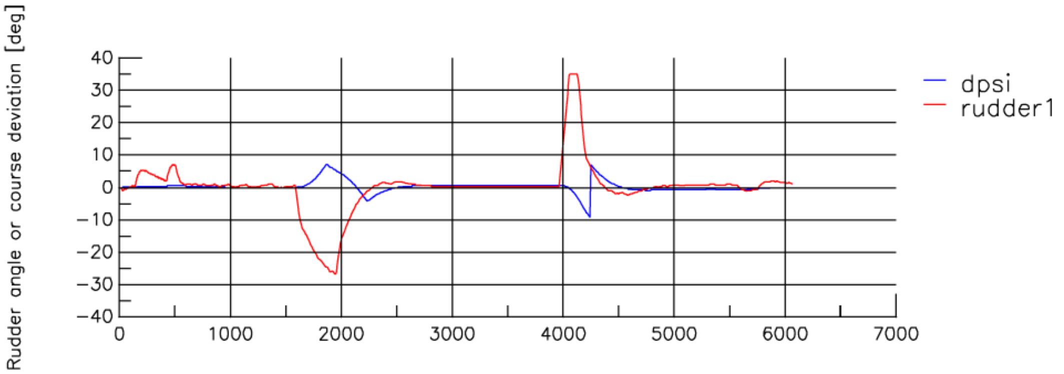


CASE 13: one-way channel, direction east-west
environmental condition: waves

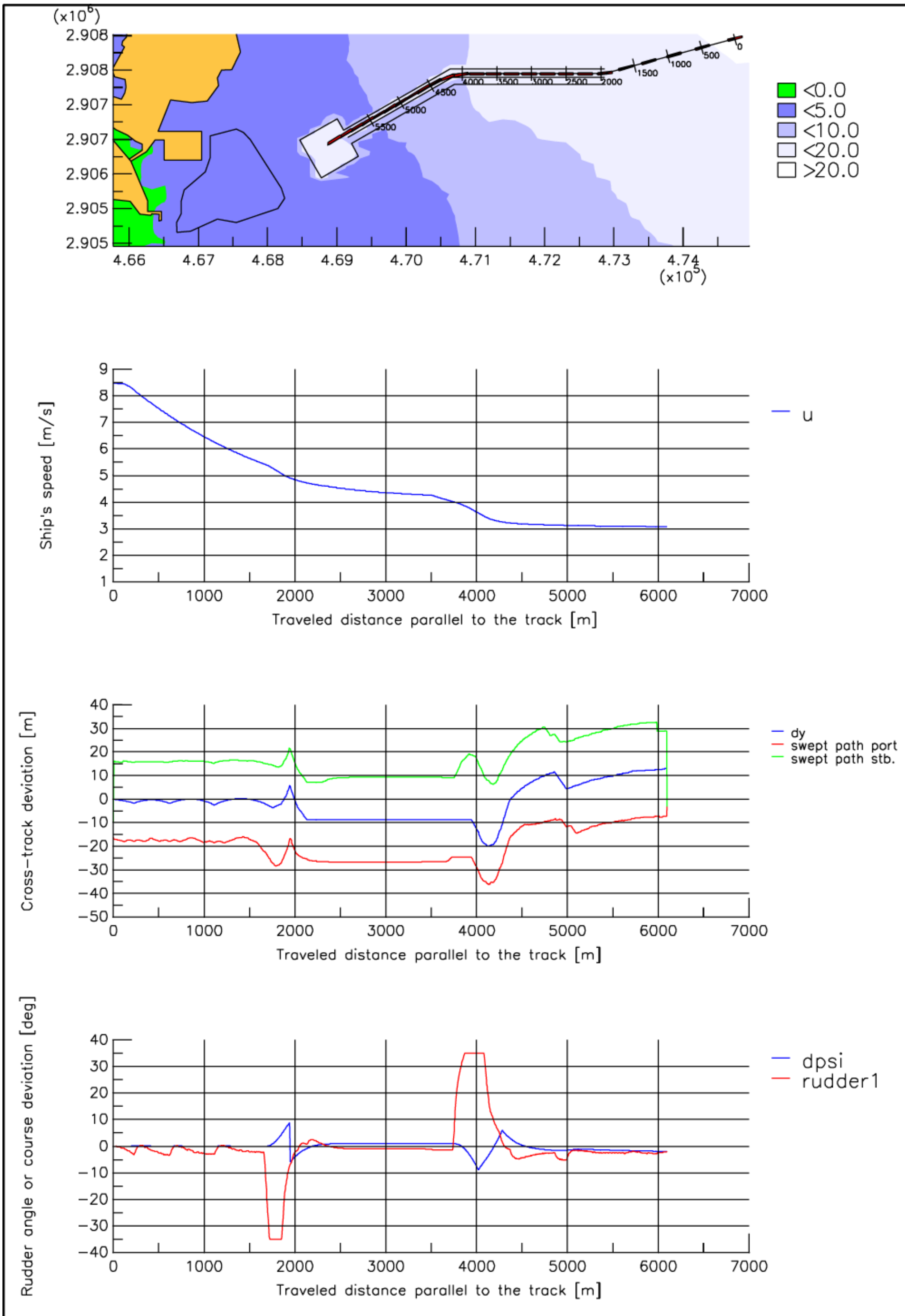






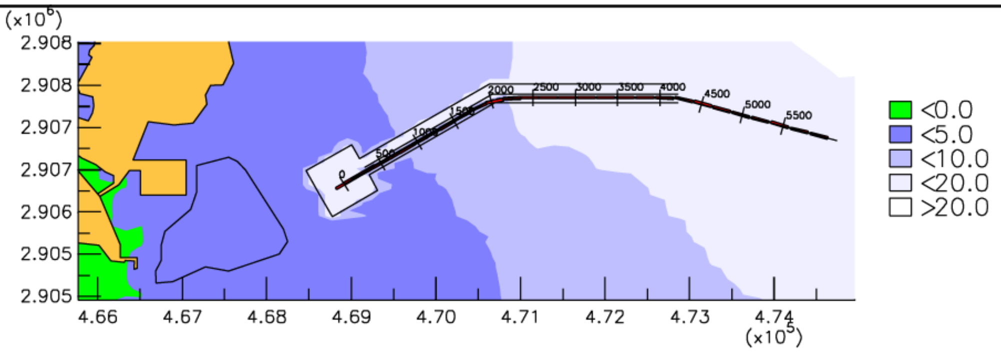


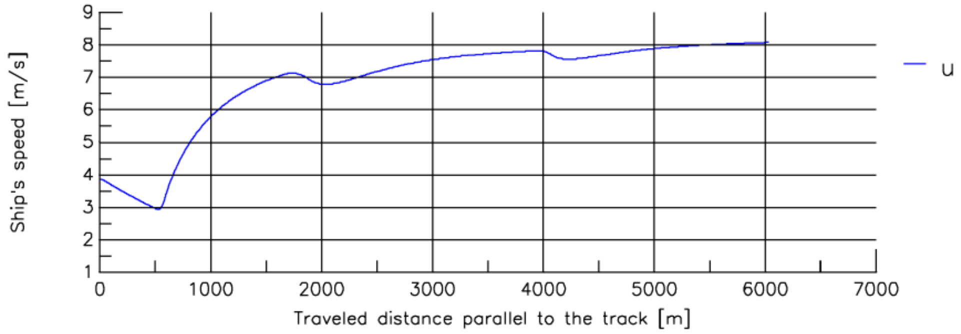
CASE 14: one-way channel, direction west-east environmental condition: waves		

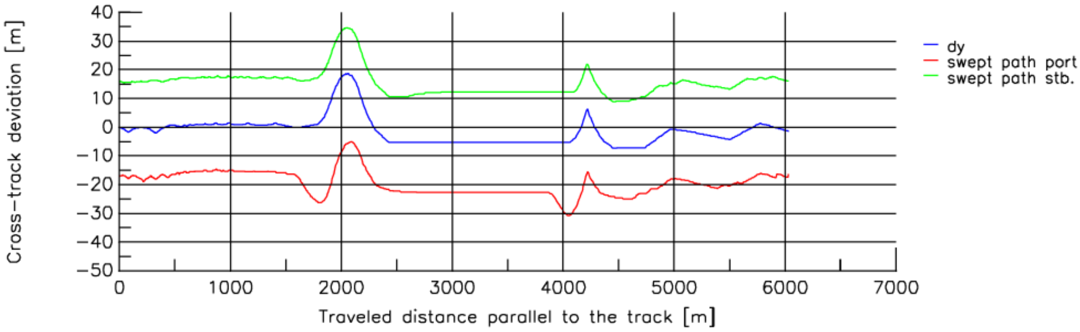


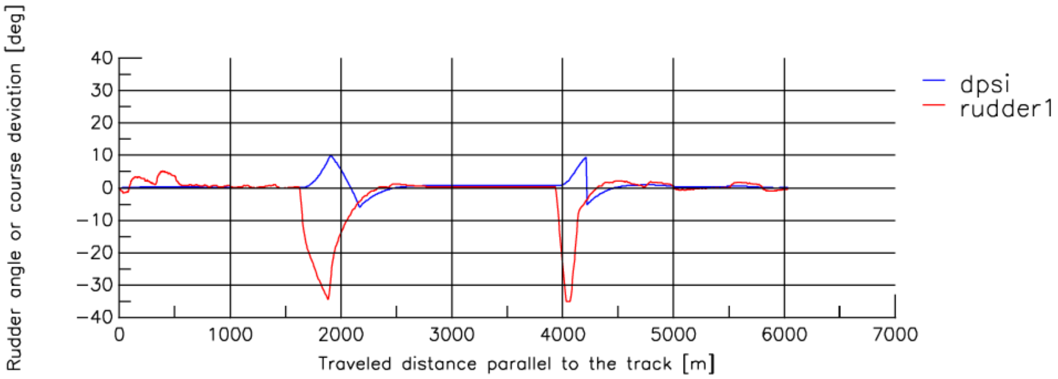
CASE 15: two-way channel, direction east-west

environmental condition: waves

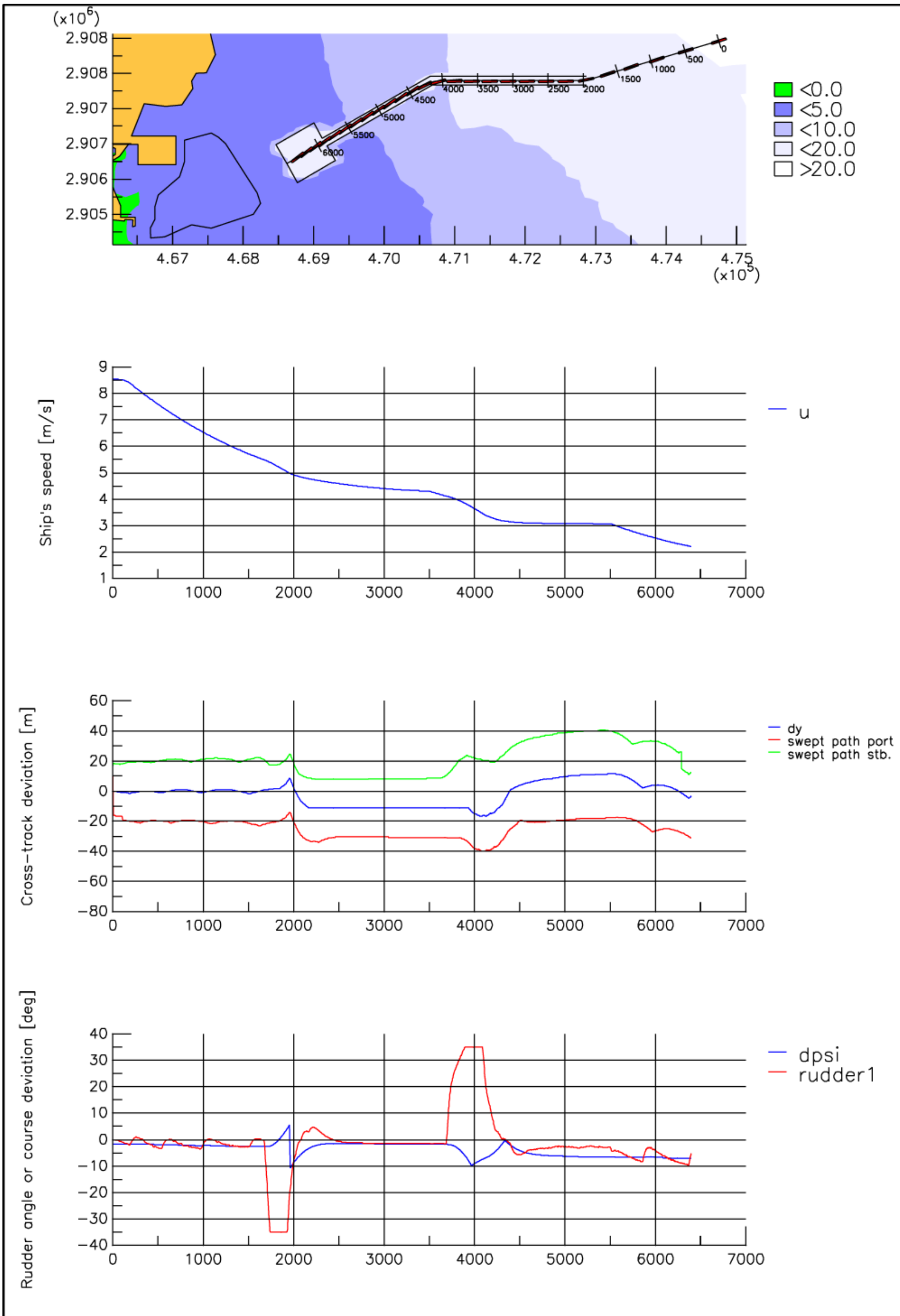






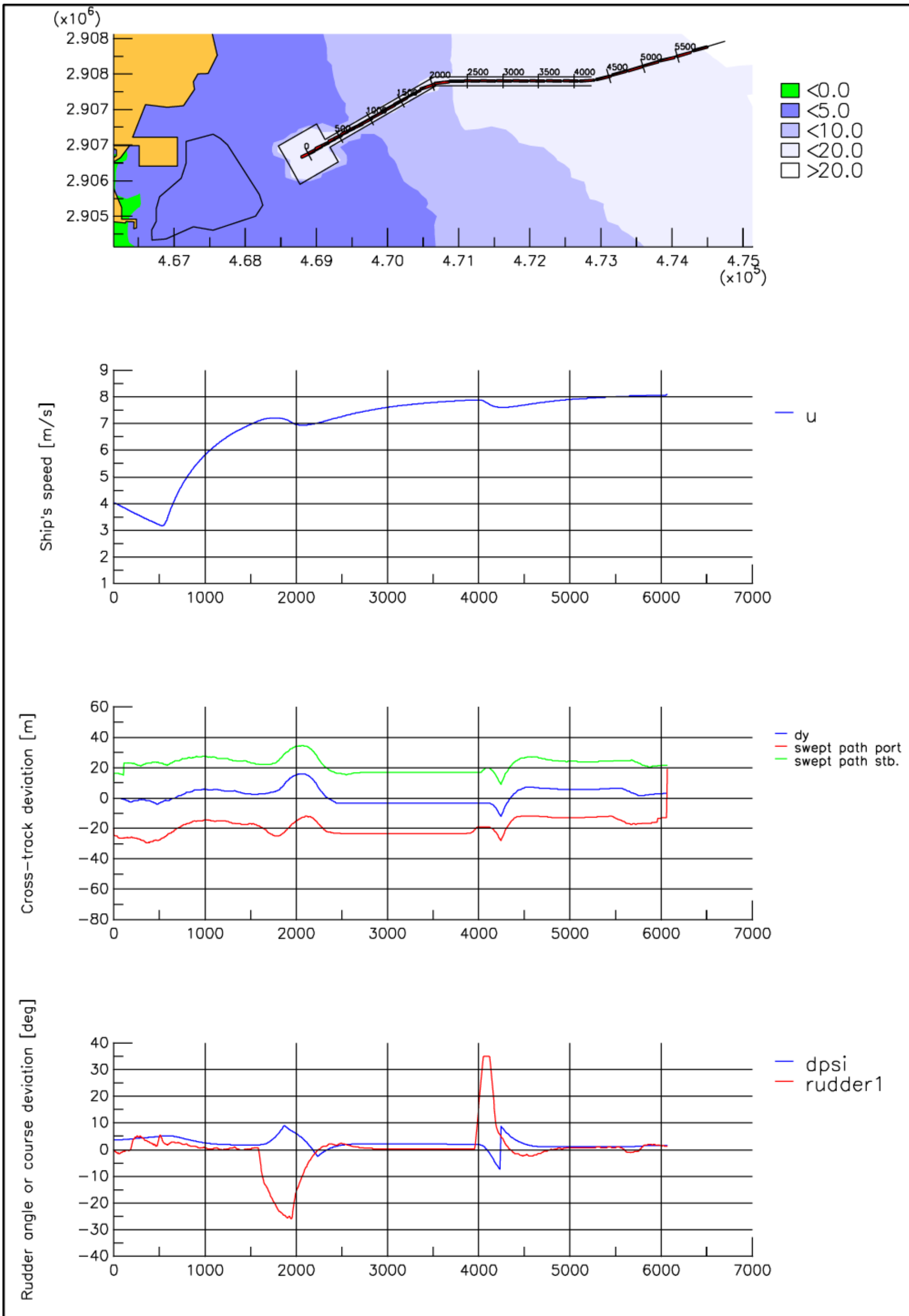


CASE 16: two-way channel, direction west-east
environmental condition: waves



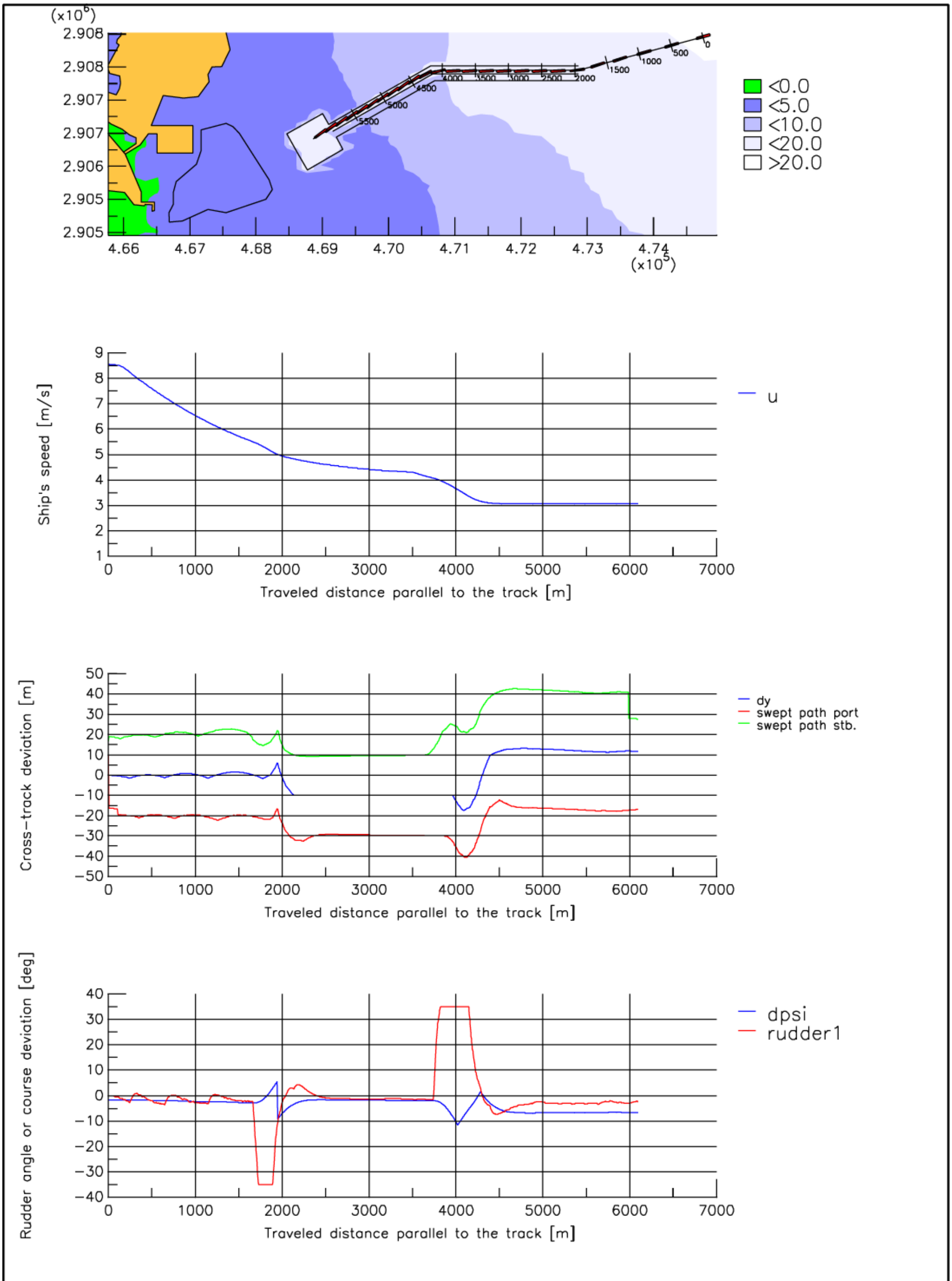
CASE 17: one-way channel, direction east-west

environmental condition: currents, wind, waves



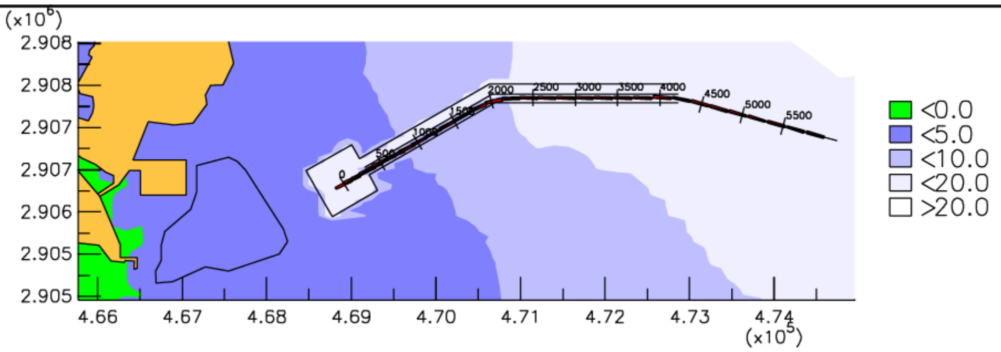
CASE 18: one-way channel, direction west-east

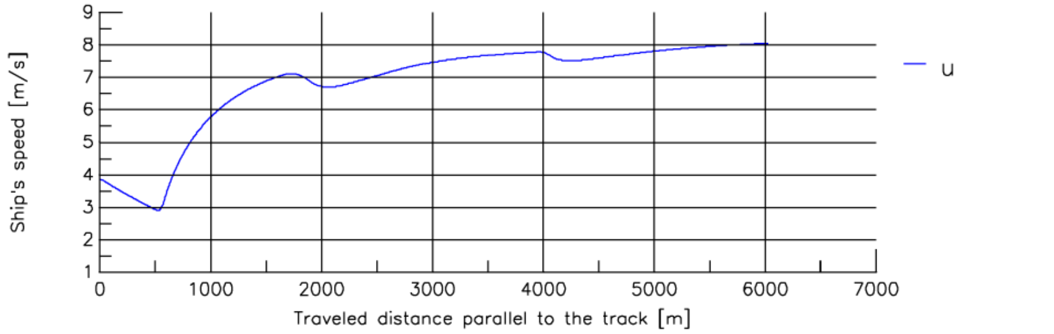
environmental condition: currents, wind, waves

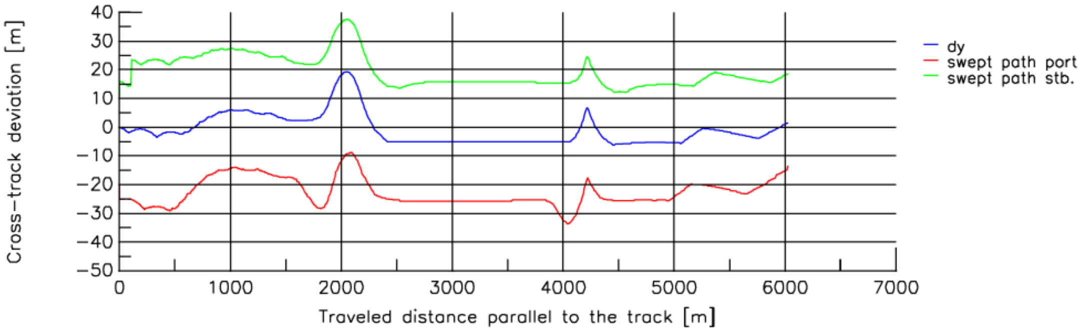


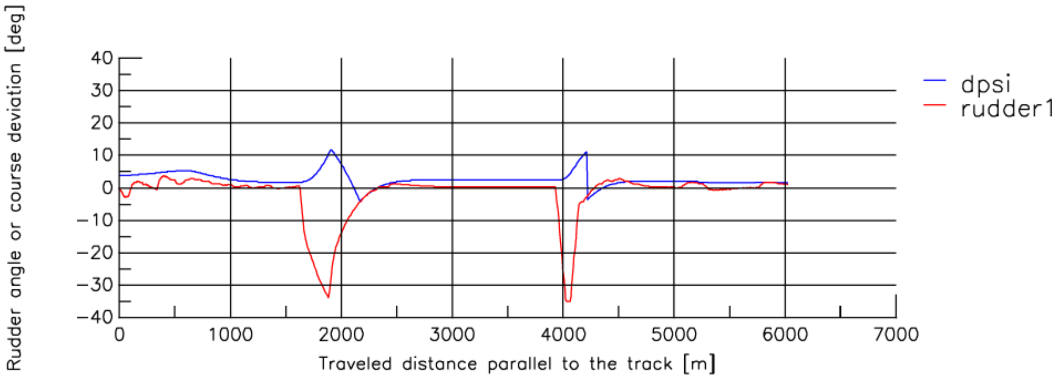
CASE 19: two-way channel, direction east-west

environmental condition: currents, wind, waves

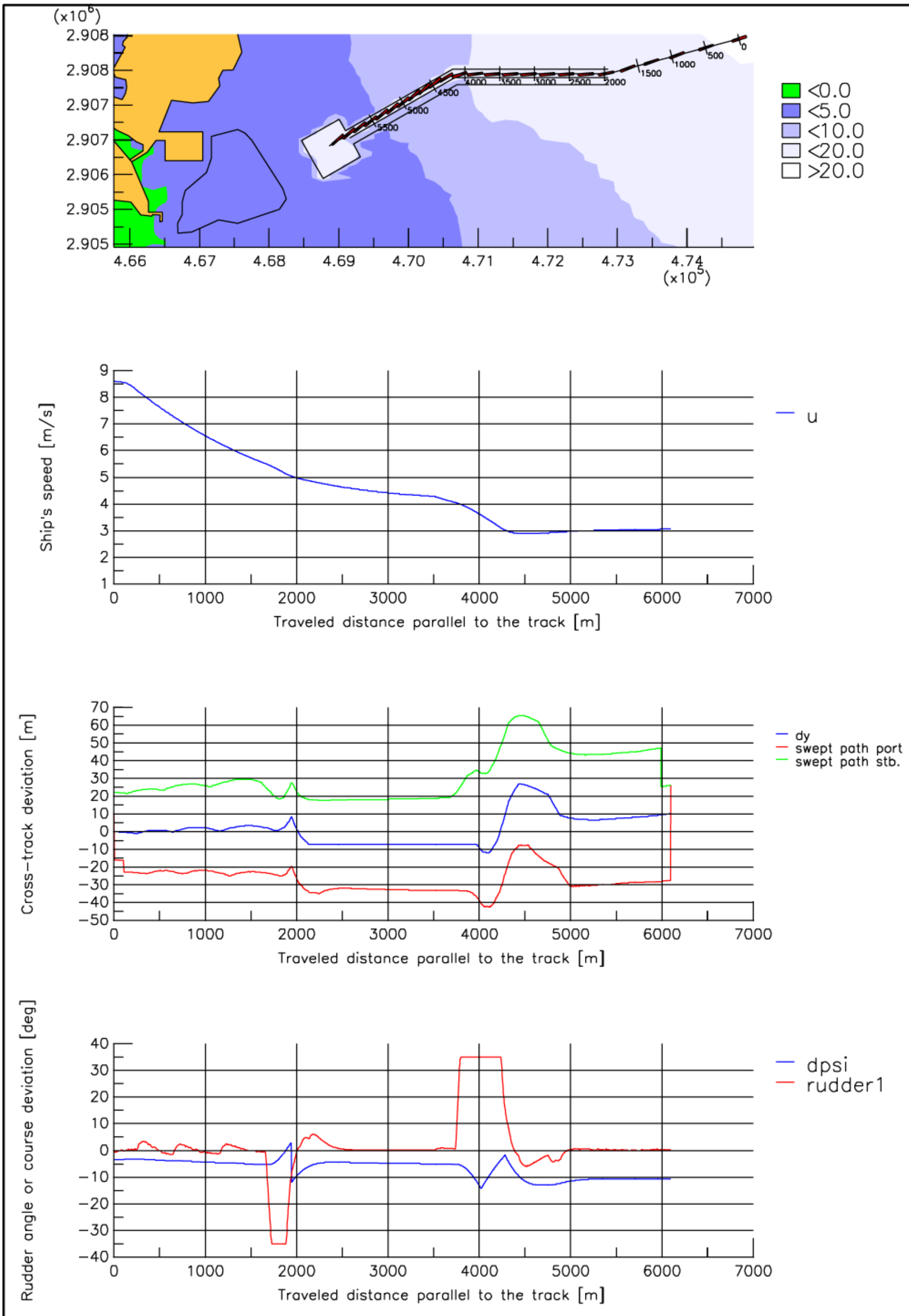




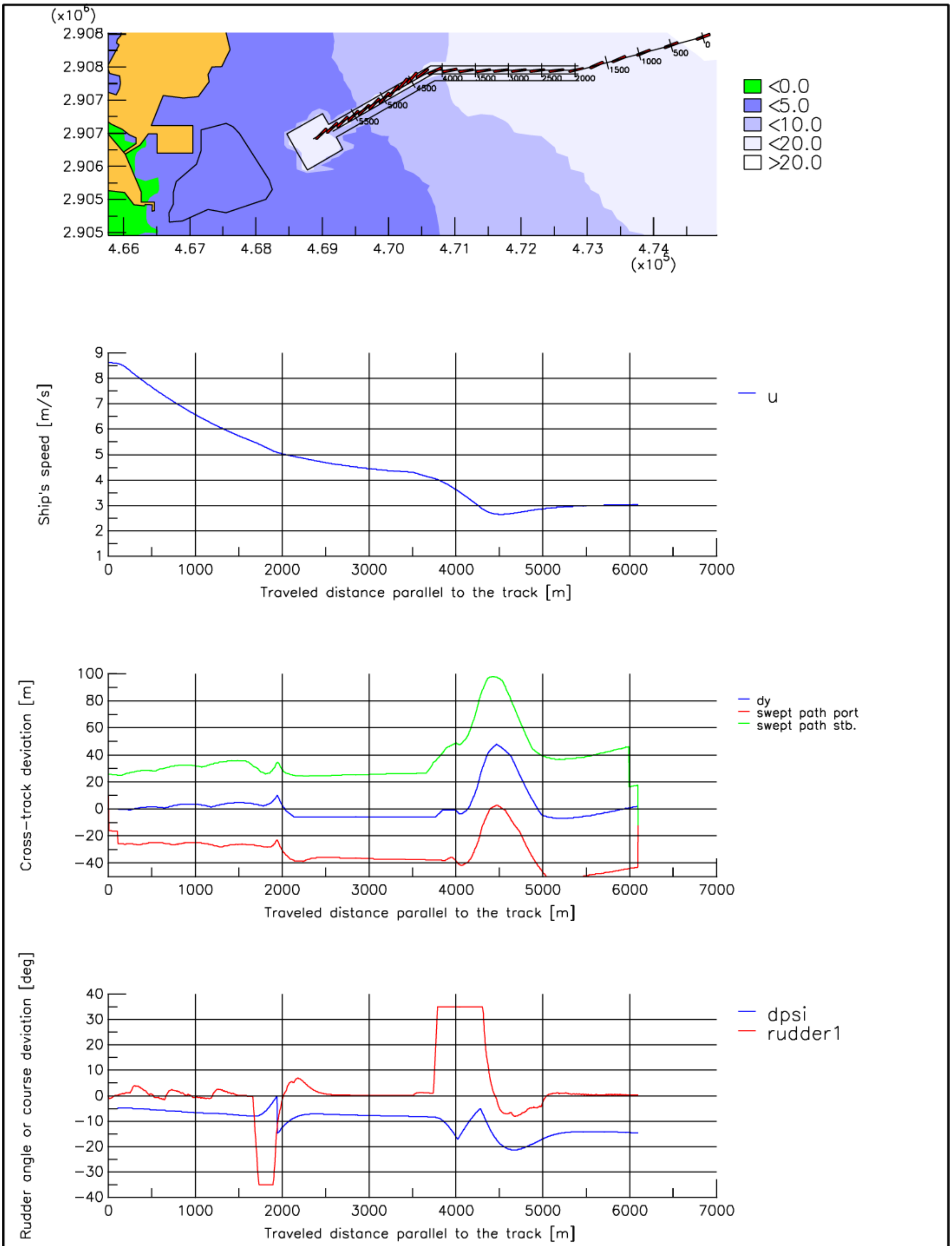




CASE 20: two-way channel, direction west-east environmental condition: currents, wind, waves		

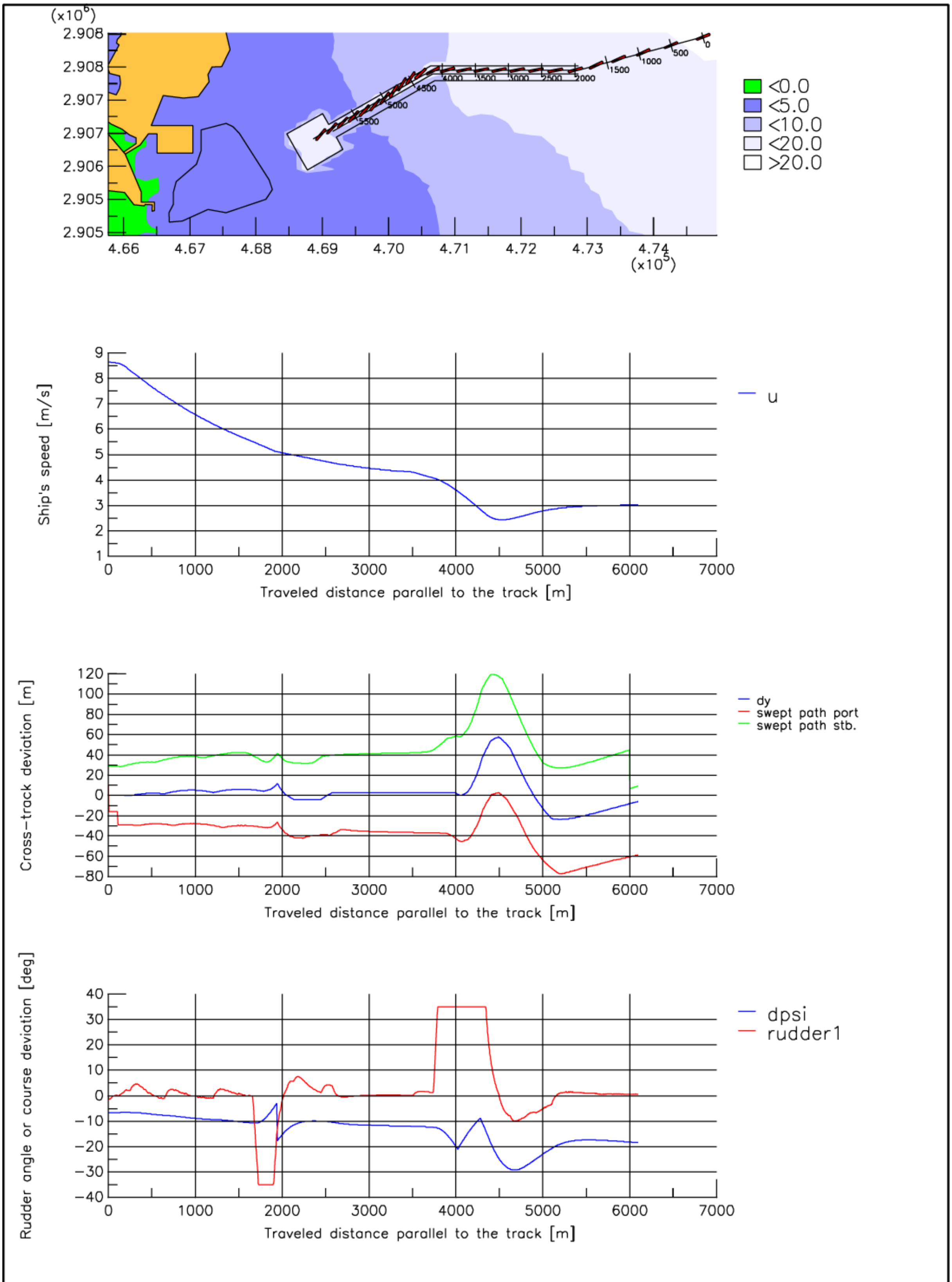


CASE 21: two-way channel, direction east-west
environmental condition: currents 1.0 knots (0.51 m/s)



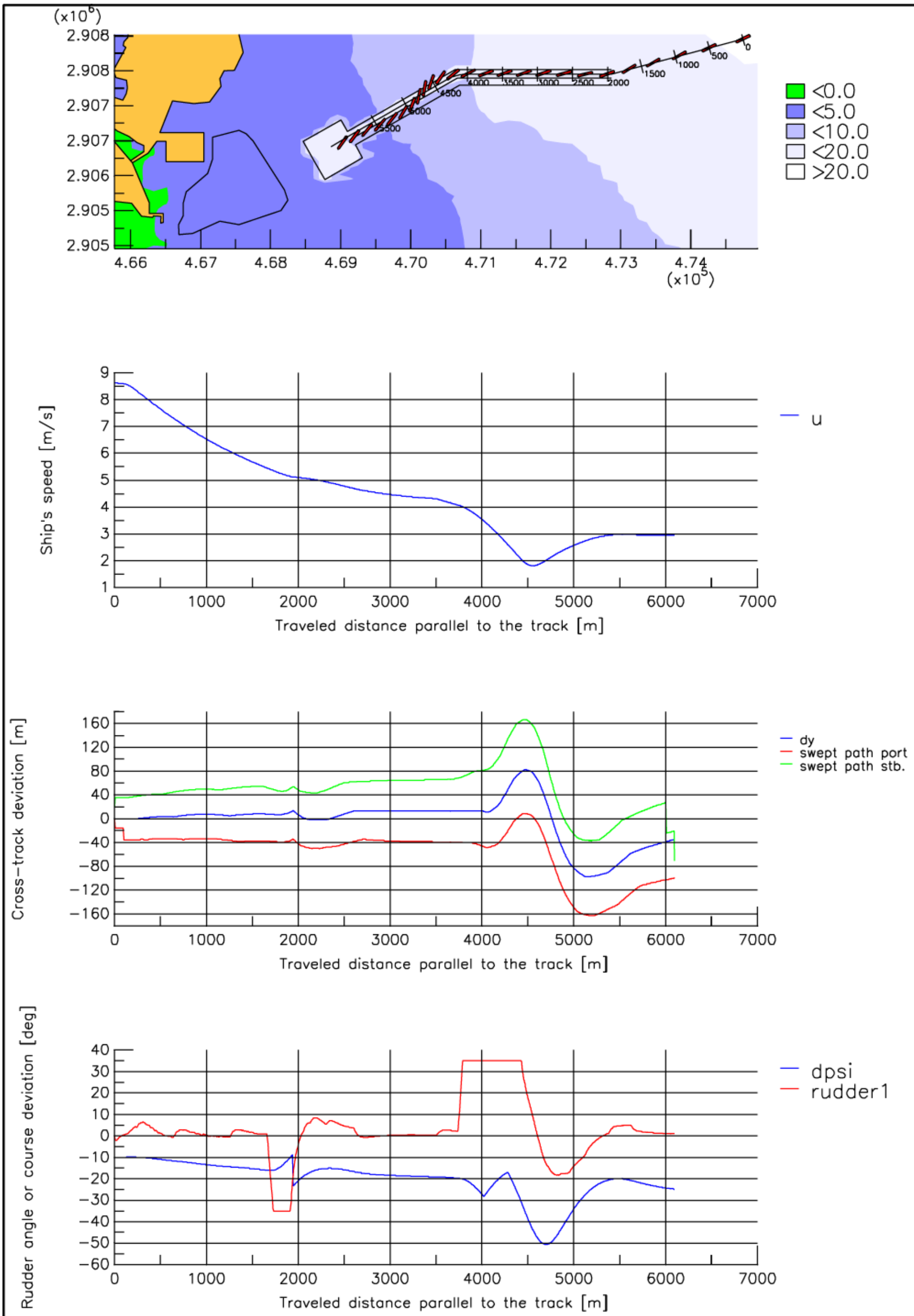
CASE 22: two-way channel, direction east-west

environmental condition: currents 1.5 knots (0.77 m/s)



CASE 23: two-way channel, direction east-west

environmental condition: currents 2.0 knots (1.03 m/s)



CASE 24: two-way channel, direction east-west

environmental condition: currents 3.0 knots (1.54 m/s)

Appendix C:
Rough Costprice Calculation of TSHD's

The weekly costs of a TSHD are build up as follows:

1. Depreciation and interest
2. Maintenance and repair
3. Insurance
4. Crew
5. Fuel and lubricants
6. Wear and tear

Computation of value

Some of the above are determined based on the computation of value, which represents the value of the TSHD.

$$V = 4400 \cdot W + 89400 \cdot W^{0.35} - 4766000 + 1400 \cdot P_t + 580 \cdot J_t + 670 \cdot S \qquad [€]$$

V	*value*	*[€]*
W	*lightweight TSHD*	*[ton]*
P_t	*power dredgepumps during suction*	*[kW]*
J_t	*power jetpumps during suction*	*[kW]*
S	*free sailing power*	*[kW]*

Depreciation and interest

There are several methods to determine the depreciation and interest. The method used here is based on annuity.

$$DI = A \cdot V \qquad [€/wk]$$

$$A = \frac{i}{p^n - 1} \frac{1}{u} \left(p^n - z\right) \qquad [-]$$

i	*interest rade*	*[-]*
n	*service life*	*[yr]*
p	*1+I*	*[-]*
u	*utilization*	*[wk/yr]*
z	*residual value at rest of service life as a fraction of V*	*[-]*

As an indication of the values, the following can be used:
i = 0.07, n = 18 years, u = 33 weeks per year, z = 0.1

Maintenance and repair

The costs for maintenance and repair is a percentage of the value V. The values can be found in the following table:

V [€]	% per week
7,840,000	0.230
9,480,000	0.225
11,300,000	0.219
13,000,000	0.213
14,600,000	0.206
17,800,000	0.185
20,000,000	0.170
24,700,000	0.151
30,100,000	0.133
36,900,000	0.123
42,800,000	0.114
50,500,000	0.107
59,100,000	0.103
66,000,000	0.101
71,900,000	0.100
94,200,000	0.099
104,000,000	0.099
116,000,000	0.098
135,000,000	0.098
156,000,000	0.098

The costs per week for maintenance and repair is given by M1, where M1 is V times the percentage from the table. When the discharge method is rainbowing or pumping ashore, the resulting value must be increased by 15%:

$$M1T = 1.15 \cdot M1 \qquad [€/wk]$$

Now, these costs must be split into a fixed part (30%) and a variable part (70%). The variable part depend on the number of service hours per week given by SH.

$$M1\mathrm{var} = 0.7 \cdot M1T \cdot \frac{SH - 84}{84 + 1} \qquad [€/wk]$$

$$M1tot = 0.7 \cdot M1T \cdot \frac{SH - 84}{84 + 1} + 0.3 \cdot M1T \qquad [€/wk]$$

Insurance

The costs for insurance are assumed to be 0.03% of the value of V per week.

Crew

The crew costs are divided into expat and local crew. For the expat crew a table with values is used, for the local crew a formula is used. Both are depending on the length of the TSHD.

Expat crew:

L [m]	Costs [€/wk]
< 65	21,000
65 – 80	24,500
80 – 90	28,000
90 – 110	42,000
110 – 135	52,500
> 135	64,750

Local crew:

$$crew = 100 \cdot L - 3660 \quad [€/wk]$$

Fuel and lubricants

The costs for fuel and lubricants depend on the installed sailing power of the TSHD. For the fuel consumption a rate of 0.19 litre per hour per kW is assumed. The diesel load during sailing is assumed to be 95% and the costs of fuel per liter is assumed to be 0.25 euro. This leads to the following formula to compute the fuel costs per hour:

$$fuel = 0.95 \cdot 0.19 \cdot 0.25 \cdot S \qquad [€/hr]$$

S   *free sailing power*   *[kW]*

For the lubricants, 10% of the fuel costs is taken into account.

Wear and tear

The wear and tear of the equipment is depending on a great variety of influences. It is therefore not possible to compute these costs by means of a rule of thumb.