T.W. Braaksma

Assessing the accessibility of ports

Where the characteristics of the muddy bed material allows for innovative dredging strategies, and where deep-draughted ships sail through the muddy bed material

TU Delft

Harwich Haven Authority

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Where the characteristics of the muddy bed material allows for innovative dredging strategies, and where deep-draughted ships sail through the muddy bed material

By

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to obtain the degree of Master of Science

at the Delft University of Technology

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Preface

This thesis represents the conclusion of my academic journey at Delft University of Technology, where I have been focusing on Hydrodynamic Engineering and specifically on the topic of Ports and Waterways. Completing this research required a lot of effort, and I couldn't have done it without the support of many people.

I want to thank my supervisors from the TU Delft, Alex Kirichek, Claire Chassagne and Floor Bakker, for their consistent guidance and support. Their advice helped shape this thesis and made the research process much clearer. Furthermore, I would like to thank Jim Warner from Harwich Haven Authority for the opportunity to work on this project, to visit the port of Harwich and for sharing their knowledge on this subject.

Special thanks are due to my family and friends for their ongoing support during this challenging time. Their encouragement kept me going.

Finally, I want to acknowledge the resources and opportunities provided by TU Delft and Harwich Haven Authority, which played a key role in allowing me to pursue this research.

As I present this thesis, I hope this thesis adds to the knowledge within the Ports and Waterways section of the Hydraulic Engineering department and provides a useful foundation for future work.

Thijs Braaksma

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Abstract

For seaports to be economically viable, they must be accessible for vessels. Due to the trend of increasing ship size and draught, the ports often must deal with high costs in maintenance dredging to ensure their maintained bed level (MBL). To reduce these costs, the definition of MBL has been subject to discussion in ports with muddy bed material. The Nautical Bottom Approach (NBA) was introduced for these ports. Instead of a static design MBL, the NBA defines the MBL as the level at which the density or yield stress of the bed material reaches a critical level (e.g., 1200 kg/m³ and 50 Pa). This creates the possibility to significantly reduce the dredging costs, while maintaining accessibility for incoming seagoing vessels.

To apply the NBA, new monitoring methods and dredging techniques are applied. Particularly, Rheotune and SILAS system were used to detect 1200 kg/m³ level before, during and after dredging with the Tiamat system. An optimal application of these methods requires proper knowledge of the bed properties and sediment behaviour in time and space. The density and yield stress measured by Rheotune should be properly calibrated before applying the measurement for the NBA.

In addition, there is a knowledge gap in the conversion from the measurements of the bed level properties to an actual applicable NBA. Several ports are using the density or yield stress critical limits to define their NBA. However, the critical limits often differ from port to port. Moreover, the effects of this approach towards the reduction of dredging efforts, while maintaining the accessibility of the port, are also unknown.

In this thesis the practical application of the NBA is being researched in combination with the effects it would have on the dredging strategy and the accessibility of the port. If a port has bed properties that imply the NBA could be used, it should also be researched what the effect will be on the port operations.

To find out what the effects of the NBA are on the accessibility of a port, the Port of Harwich has shared their data for this research. In the Port of Harwich several locations are present where mud will build up rapidly after (and even during) dredging works. With the data that has been shared by the Harwich Haven Authority, bed level models have been created, where the bed level is represented by several measurement techniques over the time. These bed level models are further used in a nautical traffic model to determine what the effects are on the accessibility of the port over time.

The results of this research show possibilities to implement the NBA within a port. By using variable bed levels, regularly surveying these bed levels and starting dredging works when necessary, a port can implement the NBA.

When a port authority has proper knowledge on its bed characteristics and changes their port operations to implement the NBA. The port can benefit by maintaining their accessibility for deep draughted ships, while lowering their dredging efforts.

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1 Introduction

1.1 Background

Port authorities are always searching for the most efficient way to provide their services and maintain (and extend) their competing advantage over other ports. To be an attractive port for shipping companies, several factors play a role.

The main factor for ports to be attractive towards shipping companies is by having low costs for ships off call. Ports directly charge shipping companies for the use of their facilities and in exchange port authorities maintain these facilities. There are also indirect costs involved for ships if they must wait for port infrastructure to be available. When the number of berths is insufficient, or when the water depth is insufficient during arrival, a ship must wait for availability. To reduce the waiting costs, a port should have high accessibility for ships. An important aspect of this accessibility is the nautical guaranteed water depth that can be maintained economically. The costs for maintenance should be kept to a minimum. Therefore, ports are looking for more cost-efficient and creative ways to maintain their guaranteed bed level.

1.1.1. Accessibility of a port

The term accessibility is used for the quality to reach or enter a location; in ports this is often used as a factor of time a ship can enter a port (Bakker & van Koningsveld, 2022). The accessibility can be limited due to port areas (i.e., berths, turning basins, anchorage areas, waterways) being temporarily occupied, or services are temporarily not available (e.g., tugs and pilots, cranes at the terminal, strikes of port personnel or crews). The accessibility of a port can also be influenced by changes in the MBL design (Bakker et al., 2024). Authorities of ports in tidal waters tend to design a nautical guaranteed depth that is only sufficient for the deepest-draughted ships during flood tide (Bakker et al., 2024). Consequently, these ships may have to wait on a window when the water levels are sufficient, a so-called tidal window.

The accessibility of a port for a deep draughted ship that wants to visit the port is determined by water level factors, ship related factors and bottom related factors (PIANC, 2014). It is generally measured as the number of accessible tides over a certain period. There is an optimum between the additional waiting times of ships and the reduction in dredging costs. It should be prevented that a ship will have to wait for several days on a high enough flood tide. However, some degree of port inaccessibility is generally accepted to prevent excessive costs of maintaining an always accessible port.

1.2 Maintained bed level

The MBL is a fixed level that is guaranteed to be above the actual bed level. It equals the ports dredge level corrected by some safety margins (Bakker & van Koningsveld, 2022).

While this research focuses on ports with soft, muddy beds, it is important to know how a “hard” bed level is determined. Since the mud stays on top of a harder bed level, and the mud layer itself may eventually also consolidate into a hard bed level (Rijn & Barth, 2018), knowledge about the harder bed types is the basis for the sailing through mud concept. Figure 1-1 shows how the allowable ship draught is structured in ports with hard beds.

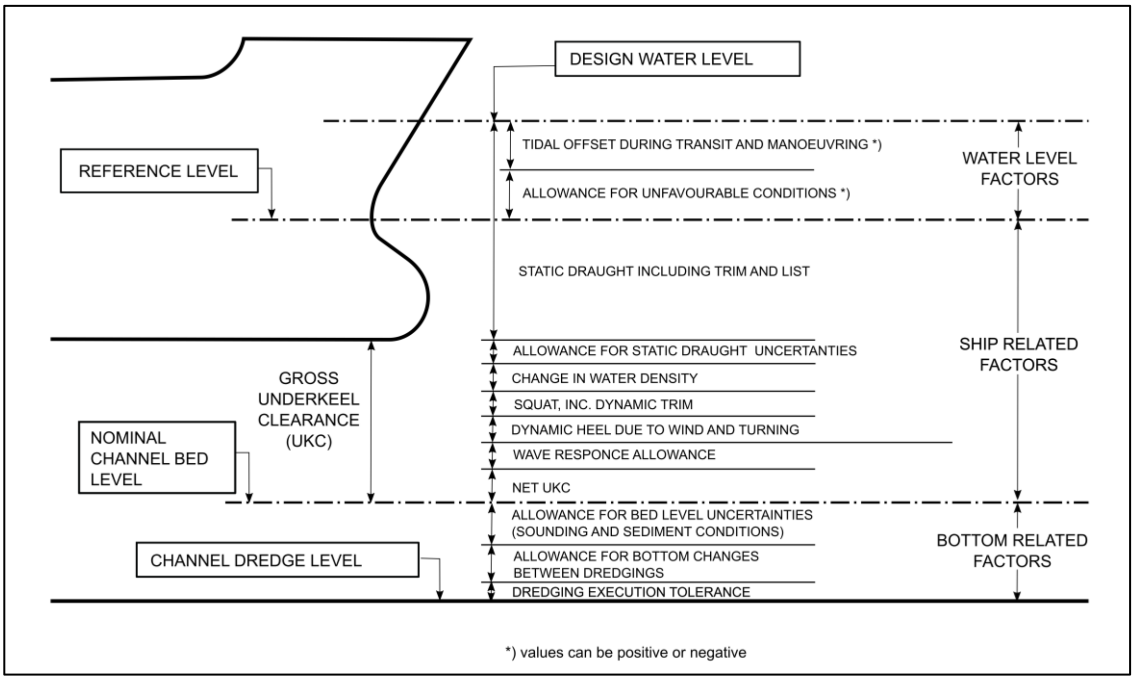

Figure 1-1 channel depth factors affecting the vertical design of approach or navigation channels *(PIANC, 2014)*

1.2.1. Maintenance of the seabed in a port

The bed material that enters the port by river disposal, tidal inlet and other means of bed material transport must be disposed regularly to guarantee a certain bed level in the port. Typically, the maintenance of the bed level in a port is performed by trailer suction hopper dredgers (TSHD's) for guaranteeing accessibility (Aarninkhof et al., 2018). Traditionally a TSHD would regularly visit a port and dispose the bed material by removing the material and dispose the material (far) outside of the port.

Nowadays, port authorities of ports with extensive mud sedimentation are using several other maintenance dredging methods where the economical and the environmental aspects of material disposal and material resuspension play a large role. Some examples of these dredging types are;

- Water injection dredging – used in European ports (Verhagen, 2000; Kirichek et al., 2021)
- Recirculation dredging – used in Emden (Wurpts & Torn, 2005; Gebert et al., 2022)
- Tiamat – tested in Harwich (Spearman & Benson, 2022; Neumann et al., 2024)

The effects these dredging types have to the bed are different and depend on a wide range of port specific factors such as: bed material, hydrodynamic conditions, and bed level (Aarninkhof et al., 2018). However, what they have in common is that the material is during dredging only transported vertically in the water column and thereafter through natural current been transported horizontally. While with the classical way of dredging, material is transported horizontally through pipelines or barges/hoppers over large horizontal distances. Due to this difference, the resuspension dredging methods are more economically feasible.

The material is not taken out of the water column and therefore these methods of dredging have some environmental implications within the port area (Miró et al., 2022). Other implications are in the navigability of the port. When muddy bed material is resuspended into the water column, bed level measurement techniques could give bed level results which are not satisfactory to the designed bed level (Fettweis et al., 2011).

Even though a measurement or survey would result in a bed level higher than the design bed level, a ship with the design draught might still have a proper navigability through the port channels and basins, since the resuspended material has low shear stress properties and is therefore navigable (McAnally et al., 2016). This effect of material near the bed, which is navigable, is the basis of the Nautical Bottom Approach (NBA) (Kirichek et al., 2018).

In practice dredging engineers from Harwich Haven Authority have also noted that bed level surveys do not always reflect the navigable bed level (J. Warner, personal communication, April 18, 2023). Example of this is their experience with bed level surveys after dredging. While they can see in the dredger logs that the draghead of the dredger has been dredging at a certain level, a multibeam might reflect a bed level of up to 2 metres higher than this dredged level. This experience from dredging engineers is a subject of this research, particularly the implementation NBA should be researched.

1.2.2. The Tiamat dredger

To reduce dredging costs, the Harwich Haven Authority has developed a new dredger type known as the Tiamat. The Tiamat is an agitational dredger based on the direct disposal dredging technique used in the Port of Emden.

Tiamat consists of a frame carrying one pump to inject water into the sediment overlying the bed of the harbour, and a second pump to extract diluted silt, pump it up and release it into the water column. Designed to be mounted onto a small workboat or multi-cat of between 25-27m that has an A frame, Tiamat is lowered into the water to the depth required. While pumping dredged material up, it utilises the power of the tide and currents, promoting self-replenishment within the estuarian system, through the natural re-suspension of sediment – thus, “Dredging with Nature” (Haven Dredging Ltd, 2024).

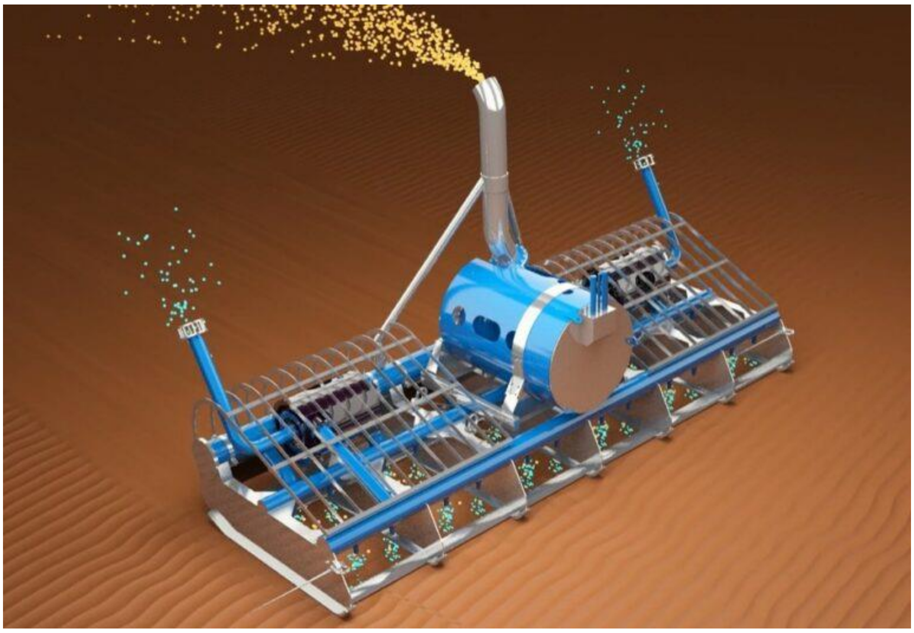

Figure 1-2 3D-design of the Tiamat dredger (by Harwich Haven Authority)

1.3 Nautical Bottom Approach

Currently some ports are already using the NBA to determine whether a ship can enter the port. The port of Emden in Germany is an example of this, in 1994 the port authority already developed a dredging strategy focused on not extracting from the bed but increasing the density of suspended material in all harbour basins (Wurpts & Torn, 2005). Moreover, the Ports of Rotterdam and Zeebrugge are also experimenting with the NBA (Kirichek et al., 2018). Nowadays other ports have done research to their navigable beds, however research to the effectiveness of implementing the NBA on the port operations is not extensive.

The Nautical Bottom is defined as: "*The nautical bottom is the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability*" (PIANC, 2014). researching the use of the Nautical Bottom, often the terms approach and concept are added to describe the use of the Nautical Bottom for determining the maximum ship draught that is allowed.

The NBA does not use a static, MBL where the three before mentioned bottom related factors should apply to. It rather uses the interaction between the hull of the ship and the bottom or muddy layers to determine whether a ship can enter a port. In muddy areas, the definition of nautical bottom could be interpreted as the level where the navigable fluid mud ends, and the non-navigable seabed begins (PIANC, 2014).

In tidal ports the bed levels and their navigability properties are constantly changing due to the hydrodynamic conditions. Costs for maintaining the measured bed level to be guaranteed below the designed bed level can raise drastically as a result. However, using change in bed level as a variability in combination with the NBA might have a beneficial impact on the operational side of a port authority. For a port authority, to be able to adapt the NBA is still a large step due to the lag of research to the effects of this implementation. For port authorities getting knowledge about the effects on the accessibility of their port after implementing the NBA could help with taking steps towards an NBA driven port operation.

1.4 Physical characteristics and critical limits for NBA

Maintaining port and channel bed levels involves considering bed materials, sedimentation, and dredging uncertainties. This section examines challenges with soft and muddy beds and the role of yield stress and density in determining navigable depths.

1.4.1. Bed level

The hard channel bed itself must be at a safe distance below the deepest point of the ship. It is defined as the nominal, proclaimed, nautical guaranteed, or advertised channel bed level or depth. The actual depth of the channel should always be at least this proclaimed value (PIANC, 2014). The word safe in the first sentence already implies there is room for several interpretations. A port where the bed contains mainly of rock and thus hard material that will have a large risk of damaging a ship's hull when there is contact, a large safety distance should be applied. When a port has more sandy material at the bed, the bed is still considered a hard bed, while the risk of damaging the hull of the ship decreases. This risk of damage will continue to decrease when the bed material has softer characteristics (PIANC, 2014).

In the design stage of channels and port facilities, three bed level factors are considered: allowance for bed level uncertainties, allowance for bottom changes between dredging and dredging execution tolerance. The first two of these factors are especially interesting in this research. The allowance for bed level uncertainties allows for uncertainties in the measured bathymetric survey data, in section 1.5 this will be explained in more detail.

When a port must deal with higher sedimentation rates, either maintenance dredging should occur more often (sometimes even continuously), or the design level should be at a greater depth to allow for more siltation. Both options are very expensive and energy consuming, which is not in favour of port authorities. Furthermore, ports should for either option do frequent surveys.

The above-mentioned guidelines are common for ports with a hard bed when it comes to designing the bed level, however, ports with a high siltation rate often have trouble with maintaining their channels due to the high rate of bed level change. Therefore, according to PIANC, special design considerations could be applied in ports with muddy beds (PIANC, 2014).

In ports the bed level is established by a dredged level, this is the lowest level that has been influenced by human interaction (e.g., dredging). However, what happens on top of this level is interesting for this research. Dredging engineers from Harwich Haven Authority have noticed that even though they know a dredger has dredged on a certain level and has removed material (by reviewing the dredger logs), a multibeam sensor could still measure bed levels of up to two meters higher than where the draghead of the TSHD has been according to one participant of the interviews with HHA personnel (full transcript can be found in Appendix A.1).

This indicates there is a layer of material, which is not the hard bottom, however, gets detected by echo sounding. To determine what this layer consists of, and whether it would be acceptable to sail through, other measurement techniques than multibeam echo sounding can be used.

1.4.2. Yield stress versus density

Typically, the level of the bottom-water interface is determined with high frequency acoustical measurements. This way the upper layer of the bed can quiet easily be measured with modern techniques (see section 1.5). These techniques can create depth maps where the depth is measured with certainties of less than 10 cm over large port areas. However, these high frequency acoustical measurements do not apply to find the level where the mud is still navigable, since this level goes deeper than the mud-water interface measured by the devices.

A full characterisation of fluid or partially consolidated mud is very complex and depends on many parameters or sets of influencing factors, these include: hydrodynamic and electrostatic forces; strength of inter-particle action; visco-elasticity; viscosity (zero shear and maximum viscosity of the fluid phase preventing sedimentation); size and shape of the particles and creep recovery (Claeys, 2006; Shakeel et al., 2021).

Due to this complexity, mud rheology is for engineering purposes often simplified by means of a Bingham model that is rheologically determined by two parameters (Bingham, 1916). These are (differential) dynamic viscosity and yield stress or initial rigidity, being the shear stress that must be overcome to initialise material flow. Figure 1-3 shows the rheological properties of mud compared to an actual Bingham fluid and a Newtonian fluid. It should be noticed that mud acts more like a fluid after it has been stirred, this phenomenon is called thixotropy.

In general, yield stress increases with density (Shakeel et al., 2020): a larger fraction of solid material will lead to a more Bingham-like behaviour. On the other hand, density is not the only determining parameter, so that there is no unique relationship between density and rheology (Fusi & Farina, 2020). Therefore, the density is not a correct representation of the yield stress. However, for practical reasons a critical density level is often selected to determine the nautical bottom level (PIANC, 2014).

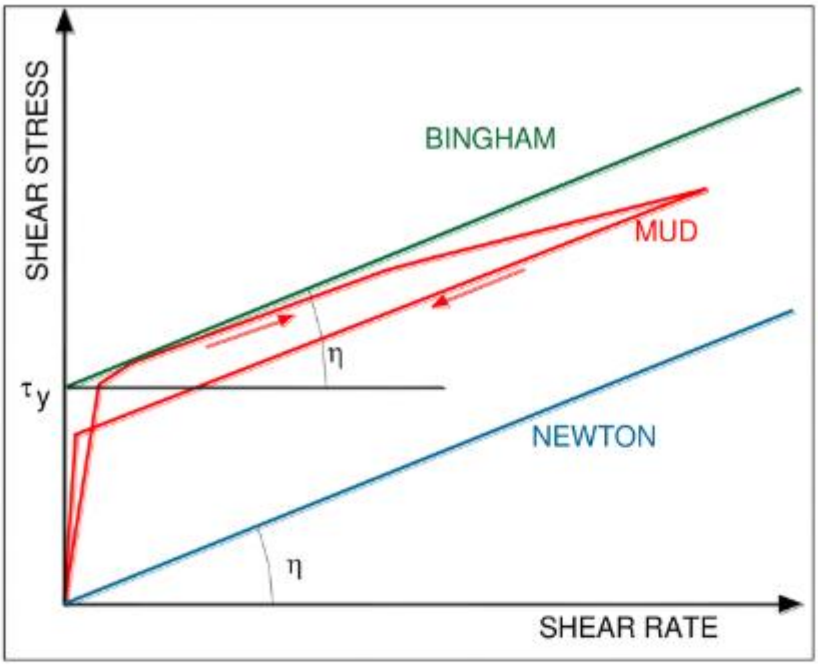

Figure 1-3 Rheological properties of mud *(Kerckaert et al., 1985)*, *(Wurpts & Torn, 2005)*

1.5 Surveying techniques

To determine the level where the bed is located, several different types of devices are used. These devices use different techniques (and parameters) to determine bed levels.

1.5.1. Multibeam echosounder

The multibeam echosounder, or shortly multibeam is at this moment the most used device to determine bed levels on large areas in ports and waterways (Jackson & Richardson, 2007). A multibeam is a type of sonar, it emits acoustic waves from a device attached to the ship, the time it takes for the waves to reflect off the seabed and return to the receiver is used to calculate the water depth (see figure 1-4). This device is so much used because it is easy to use, it has high accuracy, and a large area can be measured in a relatively short time span. The downside of the multibeam echosounder is that due to the high frequencies (more than 100kHz), the wave lengths is small. Therefore, the signal will reflect immediately on the water-mud interface, and not penetrate the mud layer. For ports with a hard bed (sand or rocky), this is not a problem (Gaida et al., 2019), since ships can only use this bed level to determine whether they can sail into the port. For ports with a muddy bed, the thickness of the mud layer becomes important for applying the NBA, however, the multibeam cannot measure this thickness.

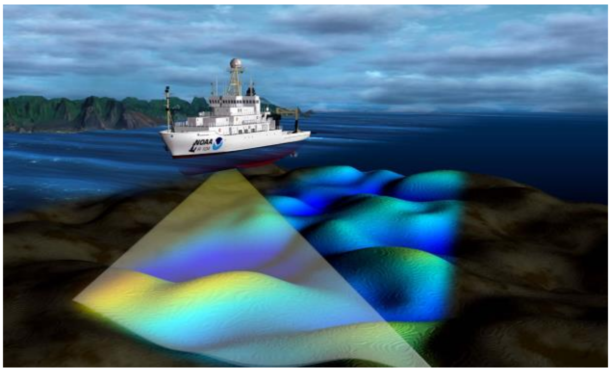

Figure 1-4 Collecting Multibeam Sonar Data By: NOAA's National Ocean Service

1.5.2. Dual frequency beam echosounder

A dual frequency echo sounder works on the same principle as multibeam echosounders, however this device only emits acoustic waves in one direction (normally vertically down) and can therefore only do measurements over the route the surveying ship is sailing, giving linear results.

The upside of this device is that it can use multiple wave frequencies at the same time, typically a low frequency of around 24 kHz and a high frequency of around 200 kHz are used. The low frequency waves can penetrate through the top of the mud layer and measure the “hard” bed underneath. The earlier results of these devices gave two lines describing the penetration depth of the soundings (figure 1-5), while newer iterations of the device (and software) also show information between and below the reflection levels. Figure 1-6 shows an example of a single beam survey in the Port of Rotterdam, the blue line corresponds to the top of the mud layer, this is also the level measured by a multibeam. The green dots show lower reflections of the bed, the red line corresponds to the level where the yield stress is non-navigable.

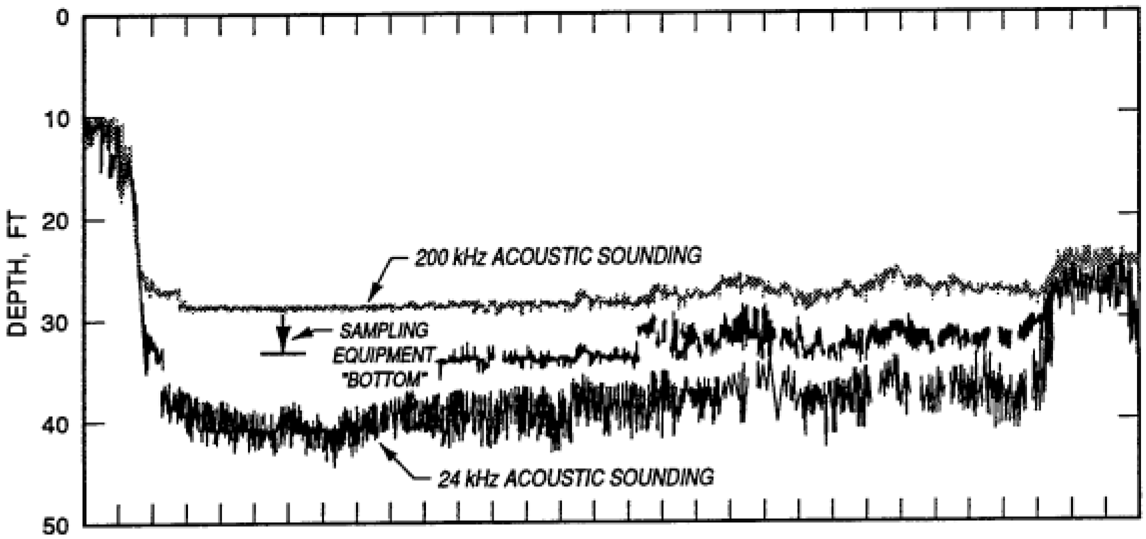

Figure 1-5 A single beam acoustic sounding result from *(Alexander et al., 1997)*

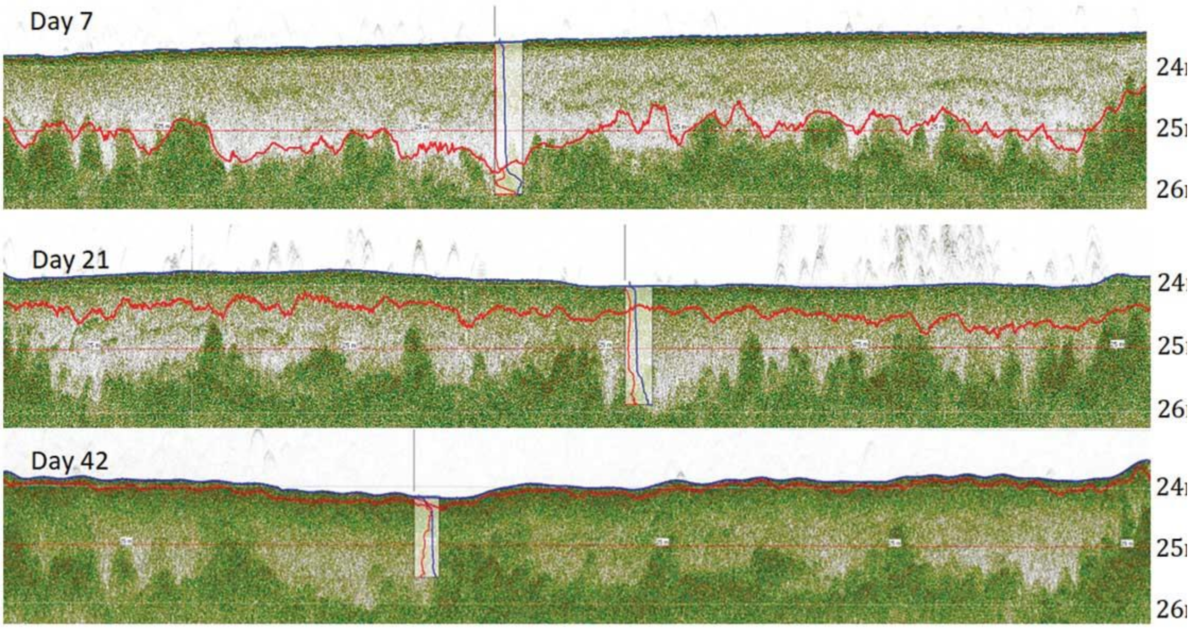

Figure 1-6 Cross section examples of a single beam survey in Port of Rotterdam included with yield stress graphs produced by the RheoTune device. The flat top layer is tipical for mud layers. From *(Kirichek & Rutgers, 2020)*

1.5.3. RheoTune

A device specifically designed to profile density and yield strength to measure the nautical depth, is the RheoTune (see figure 1-7). Contrary to the echosounders, the RheoTune must be lowered into the water column to do in-situ measurements. This means that only point measurements can be done and therefore it is very time consuming to do measurements throughout even a small port. However, it is a quicker (and less expensive) method to determine yield stress of the mud layers than to take samples and bring these to a laboratory to measure the yield stress.

Figure 1-7 The RheoTune device by *(Stema Systems, 2024)*

The RheoTune is a versatile system to be operated from the smallest ship or stationary installation. To increase productivity an intelligent winch system is available for fully automated operation. The RheoTune is optimized to integrate with the SILAS acoustic profiling system (Stema Systems, 2024). The measurement principle of RheoTune is based on a tuning fork which is positioned at the tip of the device. Tuning fork-based measurement devices measure the fluid's response to oscillation frequency and amplitude of vibration of their tuning fork (Meshkati et al., 2022). Figure 1-8 shows some typical results from a Rheotune device.

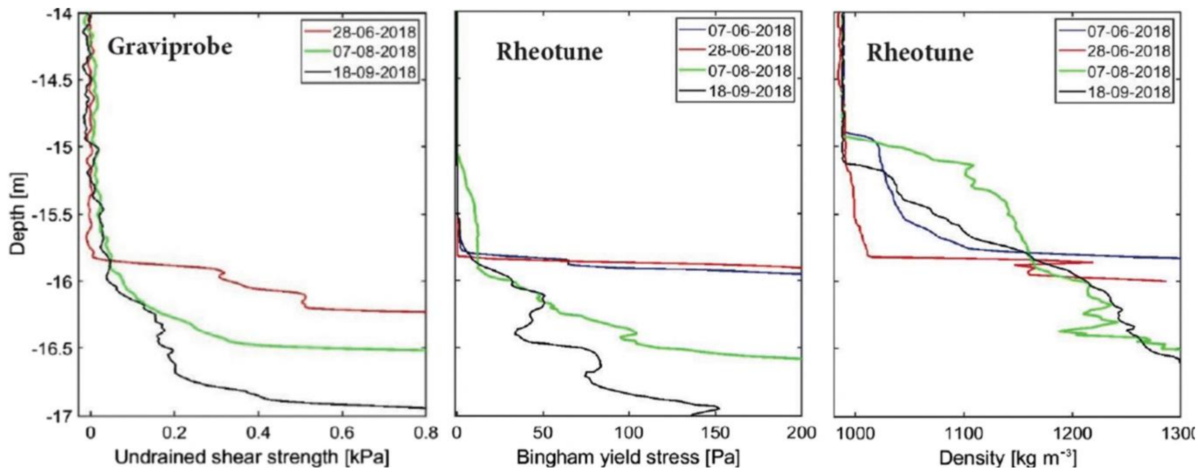

Figure 1-8 Some Rheotune results (yield stress and density) compared with Graviprobe results (undrained shear strength) in 2018 in the Port of Hamburg. From *(Kirichek et al., 2020)*

The data delivered by the RheoTune typically consists of the time, depth, yield stress, water temperature and fluid density. Although the measured density is based on calibrations specifically for a port, or even better for a specific location within a port.

1.6 Interviews

During this research interviews with the construction and dredging manager, hydrographic surveyor and some pilots of Harwich Haven Authority (HHA) have been conducted. These interviews were taken as conversations with the specific persons. By having these conversations, practical information from several standing points of view was gathered. The full interviews can be found in appendix A.

1.6.1. Construction and Dredging manager

Jim Warner is the construction and dredging manager of the HHA. Through several conversations he shared his knowledge on the difficulties with muddy layers within the port. This also included the already used measures the HHA has implemented. Jim also shared his knowledge about the transport network of the port and the dredging work occurring in the port.

1.6.2. Pilots

Though two separate conversations four pilots of the HHA have been interviewed. The pilots have shared a lot of knowledge on the practical side of pilotage work, and especially within the port of Harwich. Next to this they shared their experience with sailing through the muddy areas in the port basins of Harwich.

Notables are the so called “difficult” moments they have had. Often, they knew they were sailing through the navigable mud. However, their difficulties with piloting the ship were never completely devoted to the muddy layer. There was always some extra influence from wind or tide.

1.7 Research objectives and questions

1.7.1. Research objectives

Although the NBA has been implemented in several European ports, there is a number of knowledge gaps. Particularly, there is a knowledge gap on quantifying added water depths by implementing the NBA. Furthermore, the influence of different surveying equipment on port accessibility is not known. And finally, the methodology for analysing different MBL’s is currently missing. The main research objective is to study the optimized accessibility of a port by implementation of the NBA and by designing new MBL's. Due to the difficulties of efficiently determining the thickness of the mud layer, and therefore, the level of the nautical bottom, one of the objectives of this research is to find ties between the surveyed bed data and an applicable NBA.

1.7.2. Research questions

To achieve the research objectives outlined in section 1.7, the thesis' main research question is:

"How can the accessibility of a port be optimized by implementing the Nautical Bottom Approach?"

To answer this main question and accomplish the further objectives, three sub questions have been set up:

- *"How the influence of the nautical bottom on the accessibility of the port can be assessed?"*
- *"To what degree does port accessibility with implemented NBA depend on surveying equipment (Rheotune and singlebeam)?"*
- *"To what degree could the maintained bed level design be optimized?"*

By addressing these sub questions, this research intends to optimize bed level designs within ports by implementing the NBA while also maintaining their port accessibility numbers.

2 Methodology

To answer the defined research questions, the following methodology is proposed. Firstly, a literature study has been conducted, with the goal of getting knowledge of the MBL, currently used methods, the NBA, opportunities to improve the current available traffic systems (by implementing NBA). Next to the literature study interviews with relevant persons (e.g., port authority personnel, pilots, dredging experts) have been conducted. Next to the literature study and interviews, data of bottom levels, mud layers, shipping traffic, etcetera is gathered from Harwich Haven Authority who are willing to share their data and expertise to support this research.

The second question will involve the information gathered with the first question to determine how currently used data can be used as input for a port accessibility model. The data provided by the Harwich Haven Authority will be used to determine how bed levels evolve over time and how the several surveying techniques could be used as a basis for the port accessibility model. The port accessibility model used for this research will be the OpenTNSim model (TU Delft, 2022). This model is used within scientifical research with several kinds of research objectives related to shipping traffic within a port. Although this model has been widely used in various research applications, modifications are necessary to incorporate a variable bed level into the model.

To determine whether a port could benefit from implementing the NBA, the developed modifications in the OpenTNSim model will be utilized for the third sub question. A reference case simulating the current shipping system in the Haven Ports without the NBA will serve as the reference. To set up the model, bathymetric, ship movement, and hydrodynamic data provided by the Harwich Haven Authority will be used as input to the model. The gained knowledge of the first part of this research will be used to set up cases which contain several possible uses of the NBA. Additionally, to identify the benefits of a fully implemented NBA, some hypothetical (extreme) cases will be modelled with OpenTNSim.

2.1 Case study

Many ports in the North Sea area have problems with siltation in their port facilities (Wurpts & Torn, 2005; Neumann et al., 2024). To research the effects of the NBA in a port, a case study is carried out with the port of Harwich as subject (Spearman et al., 2014). The Harwich Haven Authority (HHA) has made data available to use within this case study.

The port of Harwich is located along the southeast coast of England, in an estuary where the Stour and Orwell rivers end into the North Sea (figure 2-1). The location of the port near the Channel, makes it an ideal location for trading purposes.

Figure 2-1 Areal image of the port of Harwich and the location of Harwich in England (from OpenSeaMap)

2.1.1. Hydraulic conditions in Harwich

The estuary system has a low fluvial input – the mean total fluvial discharge into the Stour and Orwell Estuaries is less than 5 m^3s^{-1}, based on Environment Agency data and the UK National River Flow Archive (Spearman et al., 2014). The tidal range is meso-tidal (3.6 m mean spring tidal range at the estuary mouth). Waves inside the estuary system are locally wind-generated (Spearman et al., 2014) although within the estuary swell waves propagate from offshore. Typical wave heights are 0.2 - 0.3 m in the Stour and 0.1 - 0.2 m in the Orwell (Spearman et al., 2014). However, during strong westerly winds, the wave height can rise up to 1 m throughout much of the Stour Estuary.

2.1.2. Siltation in Harwich

The shape of the Harwich estuary ensures there are siltation hotspots. These hotspots are likely caused by spatially varying morpho-hydrodynamic interactions. Figure 2-2 shows a pre-dredge multibeam survey, of the 19th of December 2022, the red areas are areas where the water-mud interface is at least 2 meters higher than the guaranteed MBL.

Figure 2-3 shows a multibeam survey which is a post-dredge survey from 11th of January 2023. Normally after maintenance dredging the bed level should be below the guaranteed MBL, however it is obviously visible that this is not the case at these four areas in the port.

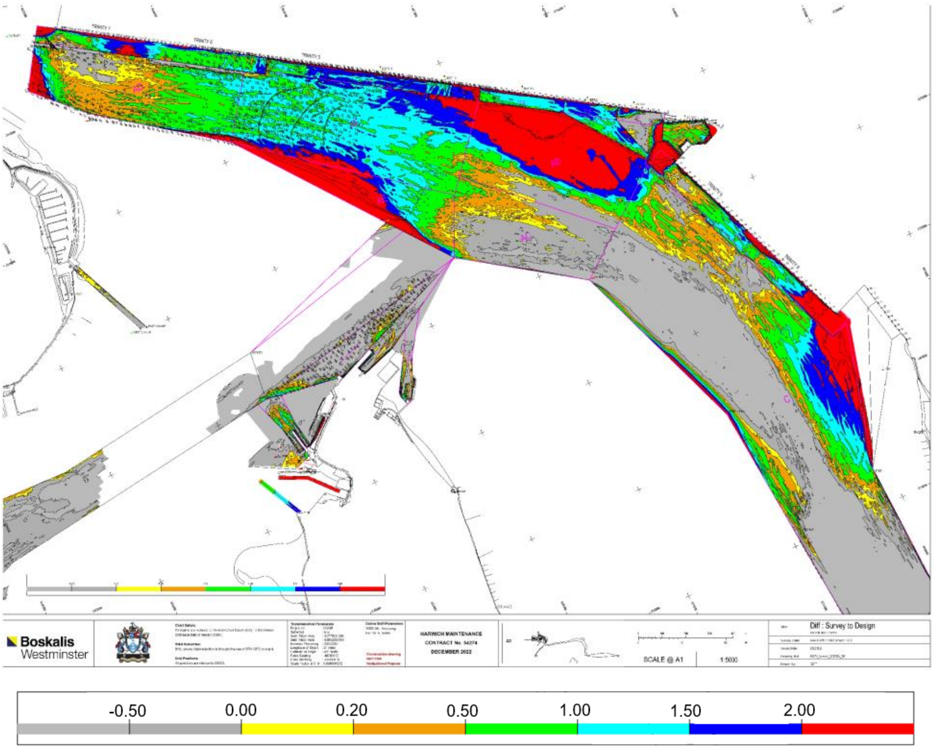

Figure 2-2 Pre-dredge survey of Port of Harwich on the 19th of December 2022. The image shows the difference between the design dredge level and the survey in metres. Coloured areas are above design level, grey areas are below design level. Image is taken from survey PDF; full PDF can be found in appendix C.

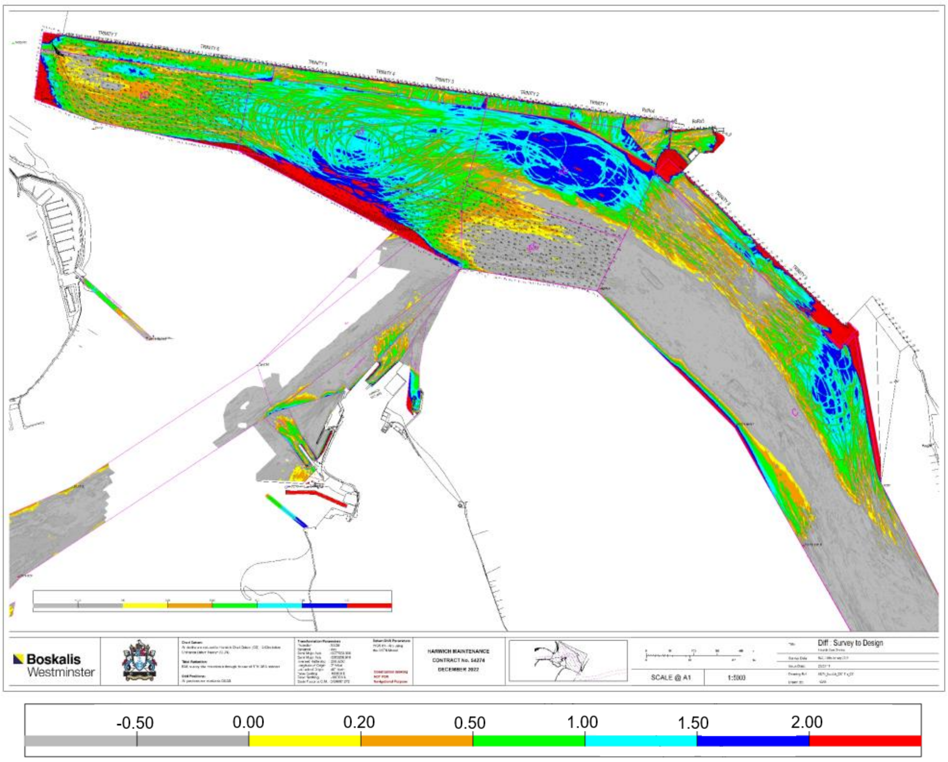

Figure 2-3 Post-dredge survey of Port of Harwich on the 11th of January 2023. The image shows the difference between the design dredge level and the survey in metres. Coloured areas are above design level, grey areas are below design level. Image is taken from survey PDF; full PDF can be found in appendix B.

In this research the Rheotune device has been used within these hotspots where sediment piles up. The locations where the Rheotune device has been let down into the mud layer have been shown in figure 2-4. Not all survey locations have been used for the purpose of this research, these are the locations near the Ro-Ro terminals and locations 1 to 33. The locations near Trinity Container Terminal and on the opposing side of the waterway have been grouped as shown in figure 2-4. These groups have been chosen due to their respective locations towards each other. In the results part of this thesis, these groups are used to compare the bed levels.

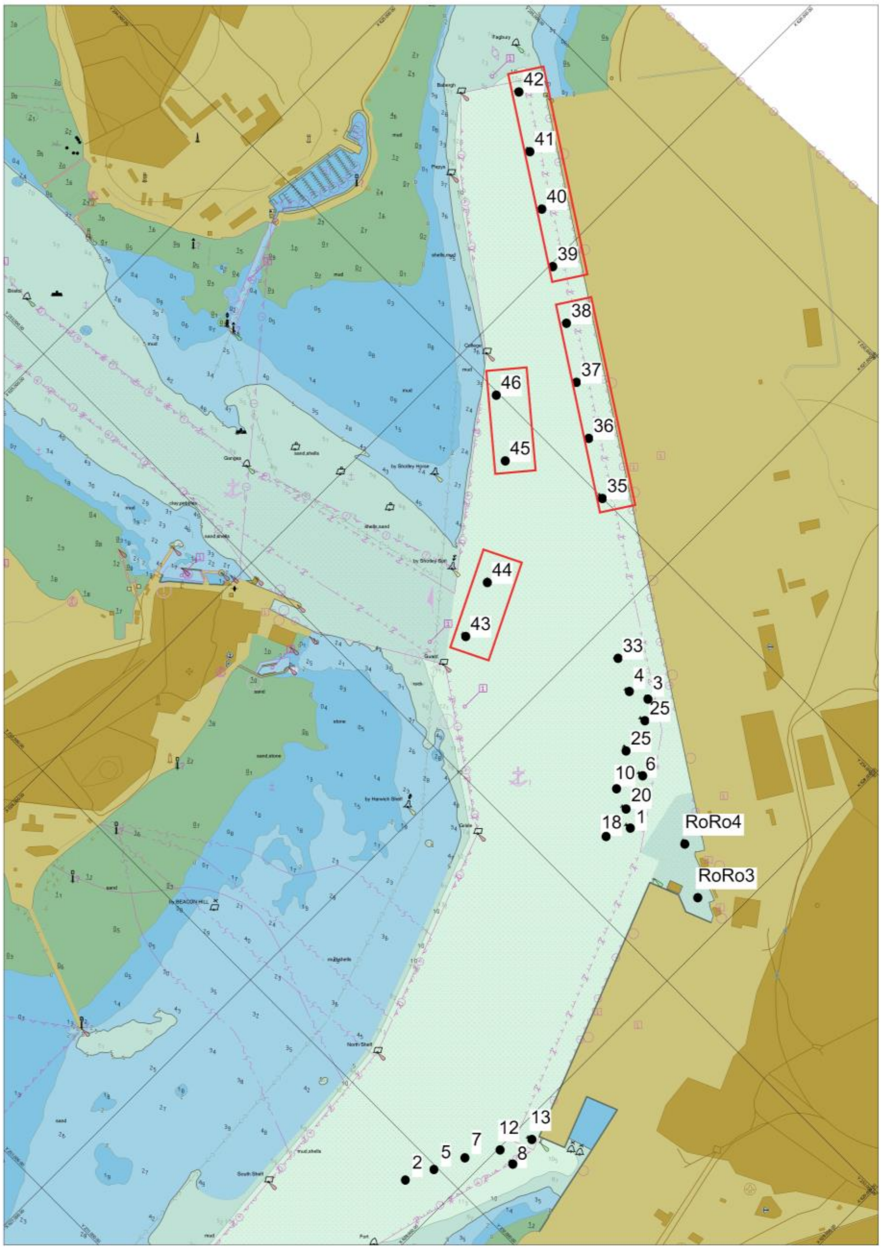

Figure 2-4 Rheotune locations within the Port of Harwich, the locations used for this research are highlighted by the red rectangles.

2.1.3. Bathymetry within the port

During the tests with the Tiamat dredger (section 1.2.2) extensive bed level measurement campaigns have taken place. This suit ideal as a test case for this research. Firstly, the measurements of the Rheotune are calibrated for Harwich. Then these measurements are used to create several bed level models through the different devices.

As previously stated in section 1.5.1, the most common way of determining the bed level in a port is by using multibeam echo sounding. While this method is quick and relatively economically affordable, it does not give information about what is below the water-mud interface. The multibeam survey will give an upper limit of the mud layer, which could potentially be used to determine the lower limit of the mud layer. However, to get there, the layer thickness of the navigable mud should be determined. Although this is dependent on time, location and other circumstances, the level where the navigable mud ends, and the hard bottom starts could potentially be approximated by coupling the data of the several measurement techniques.

Next to coupling between the measurement techniques, also the influence of dredging activities, recently visited deep draughted ships and time effect of mud should be coupled to determine the level of the nautical bottom. By combining all these influences to determine at what level the nautical bottom is located, a port could potentially implement the NBA. A port authority could use the NBA to change their policy for the draught of incoming ships or change their dredging policy.

2.1.4. Surveying campaign

As already explained in section 1.5, several surveying techniques and conditions are used to determine at what level the bed of a port can be found. The explained techniques are all used (either as established surveying methods, or experimentally) in Harwich Haven. These surveys are used as input to a variable depth in the shipping model.

From October 4th until November 2nd, 2021, the Tiamat has been dredging the several muddy areas in Harwich. During this month the Tiamat has been cycling through the dedicated Tiamat dredging areas (figure 2-5). Per area the dredger has been dredging for two to four days. There have been three cycles of dredging through all areas.

This dredging was combined with performing bed level surveying. One pre-dredging survey, four intermediate surveys and two post-dredge surveys have been conducted until November. The results of the measurements are used as comparison between the several techniques and to obtain a time-series of the bed level.

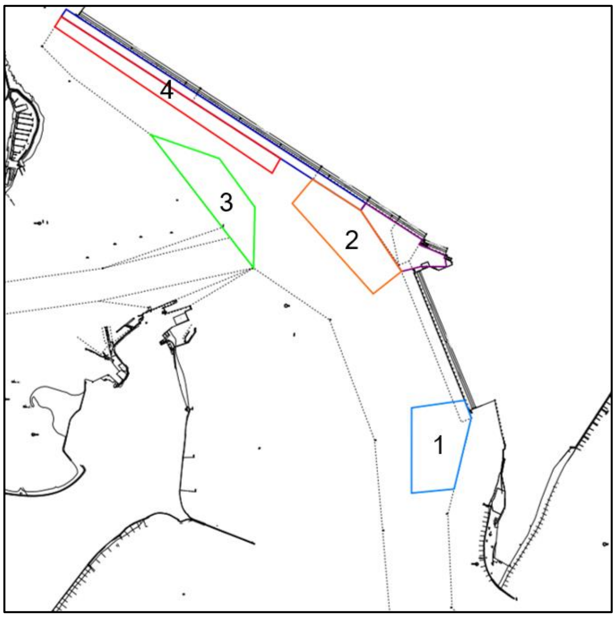

Figure 2-5 Dredging areas during Tiamat trial in 2021. The four areas have been dredged several times during the Tiamat trials

2.2 Accessibility model

While the level of the nautical bottom could be approximated by coupling the several measurements techniques, the level of the nautical bottom will influence the accessibility of a port. To assess the impact of the NBA on port accessibility, it is essential to quantify both the approach's effects and its influence on accessibility.

To quantify the usage of the NBA, the level where the navigable bed ends, and the hard bed starts is modelled. Contrary to the conventional bed level where the guaranteed level is a static number (although this number can vary through locations in the port), a bed level model that changes over time could be a proper approximation of the nautical bed. By using measurements from several moments in time, a timeline of the bed levels per location is created to see the change over time.

After an accessibility model to quantify the nautical bed level is created, the impact of using the NBA to the port operations should be determined. To be a port with high efficiency rates, incoming ships should not have to wait in the anchorage area due to lag of navigable water depth. For outgoing ships, the same applies, when the time waiting for sufficient water depth is limited, this increases the efficiency of the port. To quantify the difference in accessibility of a port by using a port accessibility model, a model which is capable of changing the bed level over time and location during a run should be used.

2.2.1. Nautical Traffic model

To examine the NBA in the means of the accessibility of a port, an accessibility model is set up. The specific accessibility model used in this research is based on the OpenTNSim model. This open-source model is developed by the TU Delft and partly adapted to fit the purpose of this research (TU Delft, 2022). The OpenTNSim model can be used to set-up a transport network model. It is designed to simulate and analyse inland waterway transport systems with a focus on ship movements, traffic management, and energy consumption. In the model a port traffic network is built with bathymetric and hydrodynamic input over time at the nodes of this network. Ships are randomly assigned to enter the network and assigned to go to a berth, however this is only possible when the route in the port is available (e.g. large enough depth, berth, and waterway availability) (van Koningsveld et al., 2023).

OpenTNSim is a python package for the investigation of traffic behaviour on networks. It can be used to investigate how water transport chains interact with the waterway network and its infrastructure. Simulations can be used to compare the consequences of traffic scenarios and network configurations (van Koningsveld et al., 2023). To use the OpenTNSim model, first the model is setup for the test case. Input to the model are the ports traffic network, hydraulic data, bathymetric data, and shipping data. The input parameters used during this research can be found in Table 2-1.

2.2.2. Port traffic network

The traffic network is built in the form of a graph (see figure 2-6 and figure 2-7). A graph is made up of vertices (also called nodes or points) which are connected by edges (also called links or lines) (Bender & Williamson, 2010). Although the traffic network of the port of Harwich is not very complicated, the graph is built as simple as possible. The only route a ship can use in this model is the route from the anchorage area, towards Trinity berth 7. This route is chosen since the ship will have to pass through the largest area of sedimentation. By using only one route, the comparisons in this research will focus on always the same route.

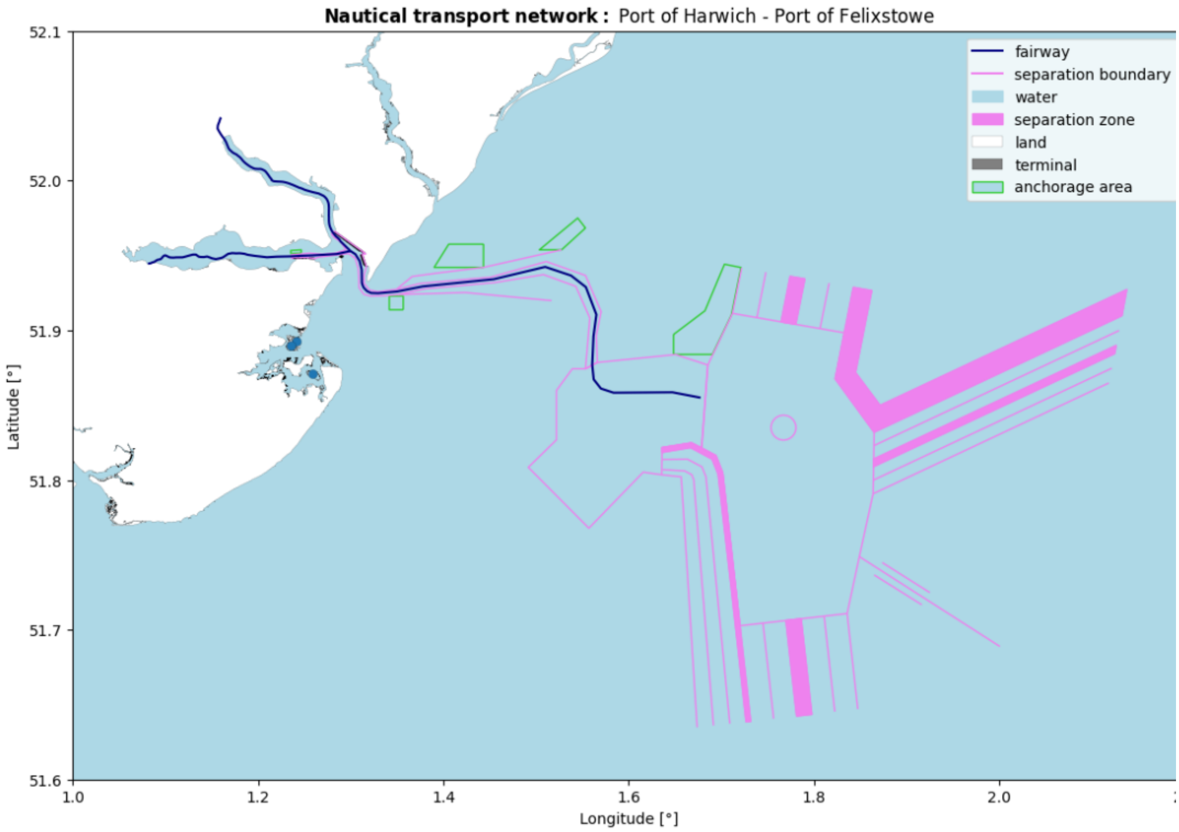

Figure 2-6 Nautical Transport Network of Harwich and outer area

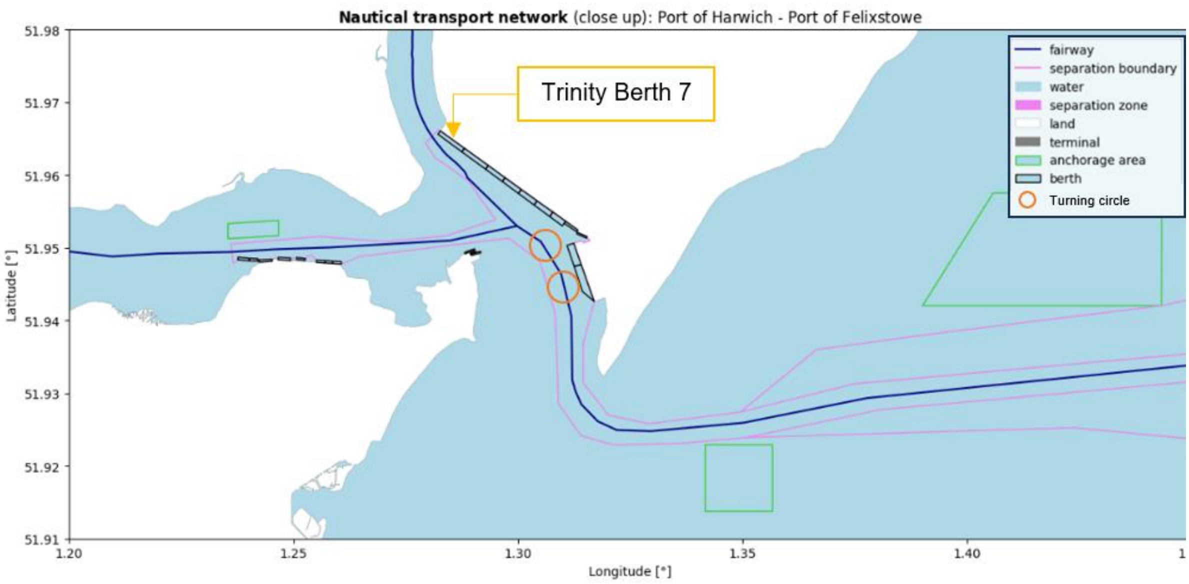

Figure 2-7 Nautical Transport Network of Harwich, with Trinity berth 7 marked. A ship will sail through the fairway into the port, then within one of the turning circles the ship will rotate. After being rotated, the ship will sail backwards towards Trinity berth 7.

Ship dimensions	**Hydraulic data**	**Bathymetric data**
Length: 400 meters	Spring tide: ~4 meter	MBL: -14.5 mCD
Beam: 61 meters	Neap tide: ~2 meter	Variable bed level
Draught: 14.7 meters		
UKC: 10% = 1.47 meters		

Table 2-1: input parameters for the OpenTNSim model used in this research.

2.2.3. Shipping data

In the model a ship is assigned to sail from the sea towards Trinity berth 7. This ship is a typical deep draughted ship that has visited Harwich during the period of the Tiamat testing. The ship has a length of 400 m, a beam of 61 m and a static depth of 14.7 m. The Harwich Haven Authority applies an underkeel clearance (UKC) policy of 10% of the draught of a vessel. The model calculates when this ship can enter the port and sail to the berth with intervals of ten minutes. Thus, the model can determine the moments in time when the port is accessible, based on which the port accessibility performance can be calculated. Also, the smallest UKC the ship has faced along the way is saved into the output data. Hence, only tidal downtime is included in the model. Cascading waiting times due to congestion are deemed out of scope in this research.

2.2.4. Hydraulic data

Hydraulic data is gathered through the open online databank provided by OceanWise (2023). This website provides historical hydraulic data and future astronomical water level expectations for several tide gauges in and around the port of Harwich. The tide gauge located near the Harwich Navyard is used for this model's hydraulic data. The hydraulic data of this location is used for all nodes within the model network. Although this is not a true representation of reality since there is a phase difference between the several tide gauges, the Harwich Haven Authority uses only this tide gauge to determine whether a ship could sail in or out of the port. Therefore, using only this tide gauge represents the HHA's vertical tide policy. The tidal range within the port is approximately 4 m during spring tide and 2 m during neap tide. There is not a policy about the current in the port.

2.2.5. Bathymetric data

Five bathymetric models are tested in OpenTNSim, namely: a static bed level model (the existing situation), three variable bed level models based on the survey measurements (see section 2.1.4), and a hypothetical bed level model.

The static bed level has been set up as a reference model. This bed level is fixed in time and space. This level is chosen to be -14.5 meters CD, since this is the design bed level for all the navigational areas (access channel, turning circle, and inner channel) where deep draughted ships make use of (Garmin Italy Technologies, 2024). The anchorage area and the berth have been set to -16.5 meters, to make sure to model does not reject a ship due to one of these locations having not enough clearance during waiting time and time at the berth respectively.

The variable bed level models have been setup to represent the surveyed data during the Tiamat trial period in 2021. Since there are a lot of surveyed locations, an interesting location has been selected. The selected location is location 40, the data of this location has been further used to simulate the accessibility.

The hypothetical bed level model has been setup, to gather knowledge about opportunities that might rise for example due to innovations in dredging technology. These contain static bed levels at higher and lower levels than the design bed level, as well as variable bed levels that might be interesting to compare to the variable bed levels based on the measured bed levels.

For all simulations a simulation run has been done with and without meteorological influence. During the testing campaign of the Tiamat in 2021 at several moments the weather had influence on the hydrodynamic situation in the port, therefore separating these results gives some extra information about the influence of the weather.

3 Results

In this chapter, the results of this research will be presented and discussed. First, the yield stress and density properties of the mud in Harwich will be visualized. These properties will lead to bed level models based on Rheotune data, which will be compared to bed level models surveyed with single- and multibeam methods. Lastly, these bed level models will be used as input for a port accessibility model to compare designed, realistic, and hypothetical bed level situations.

3.1 Properties of the mud layer

The yield stress and density measured with the Rheotune have been compared by plotting graphs with on the X-axis the density and on the Y-axis the yield stress. For every new measuring date, the results have been given different colours, to distinguish between measurement moments. At location 45 within the Port of Harwich the comparison graph (figure 3-1) shows a clear sudden growth of the Yield stress between 1150 kg/m³ and 1200 kg/m³.

Although the graph at location 45 shows a clear comparison between density and yield stress measured by the Rheotune. At other locations this comparison is not as clear, and a lot of scatter can be found in the graphs. Locations 43 (figure 3-2) shows this for example, at some dates the yield stress already starts increasing at a density of 1050 kg/m³. Graphs for more locations can be found in appendix B.1.

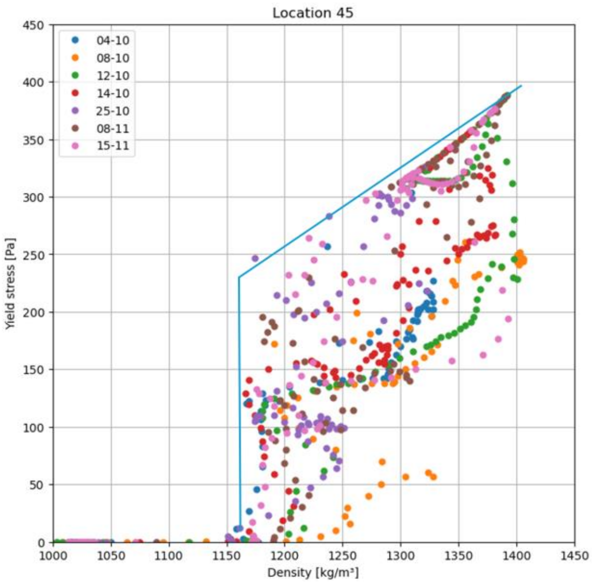

Figure 3-1 Yield stress versus density at location 45

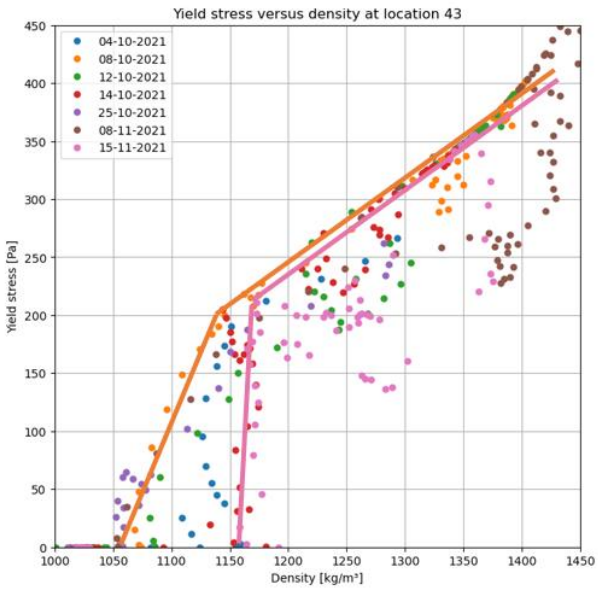

Figure 3-2 Yield stress versus density at location 43

3.2 Comparing surveyed bed levels

To visualize what the bed level over time does, some graphs showing the bed levels from the Rheotune over time have been setup. To visualize the differences between Rheotune and single- and multibeam for location 40, a graph comparing the several datapoints over time has been created. By comparing these graphs and using this as input the nautical traffic model, the effects of the NBA to the accessibility can be found.

The level measured by the Rheotune is not as accurate as the depth measurement of the multi- and singlebeam devices. Therefore, the bed level measured by the Rheotune is calculated by using the bed level measured by the multibeam device and adding the difference of the several measured levels from the Rheotune. The difference is determined by comparing the levels where the Rheotune measures a density of 1050 kg/m³, which corresponds to water-mud interface, and 1200 kg/m³, which corresponds to the critical limit for NBA used in many European ports (PIANC, 2014).

Figure 3-3 shows the change in level where 1200 kg/m³ is exceeded for the locations 39, 40 and 42 (see figure 2-4). In this figure the Rheotune signal of location 40 shows a course as it would ideally be expected; during the start of the trials the 1200 kg/m³ level is declining from -14.15mCD till -14.45mCD, thus the Tiamat is lowering the navigable bed level. After the level almost reached -14.5mCD (the dredge level) and the Tiamat dredging stops, the level starts slowly raising again to -14.20mCD.

In appendix B.2 the other surveys with the Rheotune device have been plotted grouped as described in section 2.1.2. For all the locations the bandwidth between the maximum and minimum level of the 1200 kg/m³ is less than one meter.

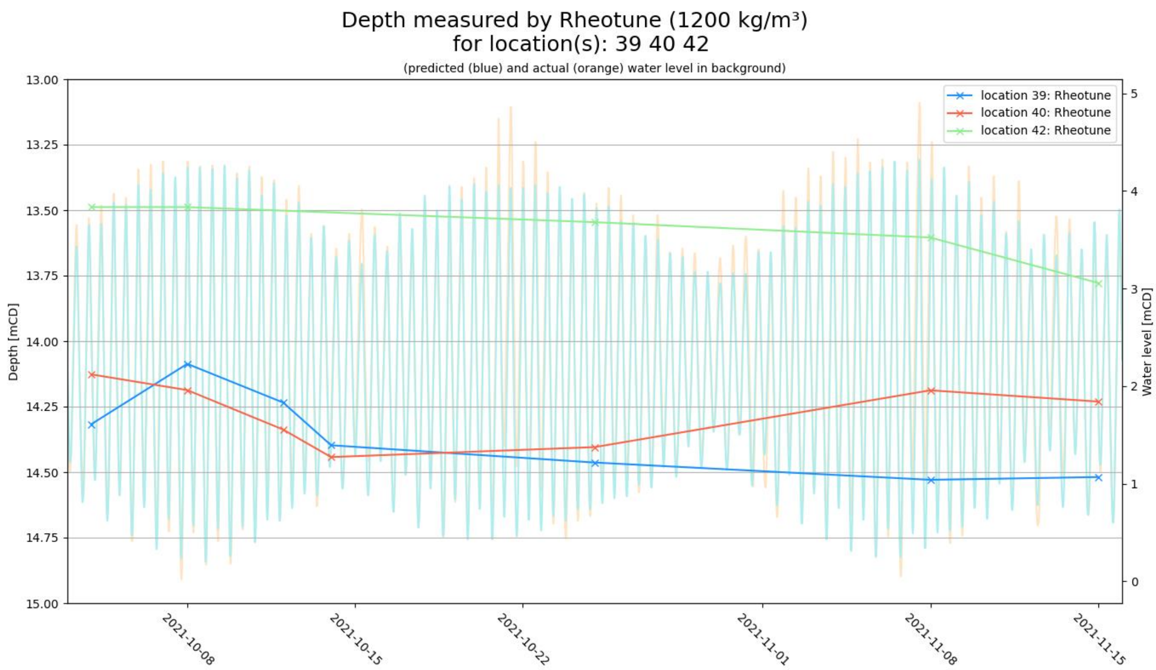

Figure 3-3 1200 kg/m³ mark of location 39, 40 and 42 (see Figure 2-4) over the time during the Tiamat test

Hereabove the change of the 1200kg/m³ level surveyed with the Rheotune at location 40 has been shown. This location is also chosen to show the comparison between Rheotune, single- and multibeam in figure 3-4. The single- and multibeam surveys show approximately the same changes in bed level as the Rheotune. However, it is not a perfect match.

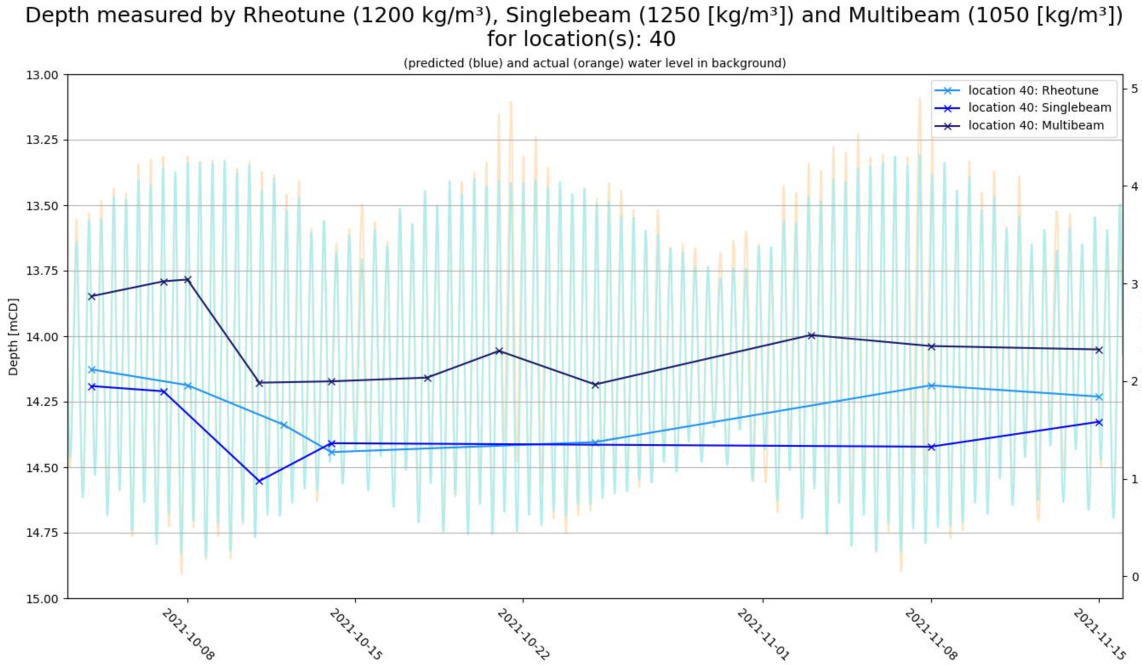

Figure 3-4 comparing the bed level course between the several measurement techniques at location 40

The same graphs have been made for all locations in the interest of this research. In appendix B.3 the other graphs can be found. Looking at the other graphs in appendix B.3, for most locations the Rheotune graphs show results where the level is around the level of the single beam and often just above. This means that using the singlebeam measured depths with low frequency normally shows the level which would marginally not be navigable.

Although at most locations and times, the Rheotune and singlebeam level are quite similar, there are some location and date combinations where the difference is larger. For example, at location 45 (figure 3-5) the first measurement moment gives a Rheotune level of approximately -14.4mCD, while the multibeam and singlebeam are at -13.5mCD and -13.75mCD respectively. Also, on the 11th of October a single- and multibeam survey has been taken, while the Rheotune measurements have been taken on the 12th of October. For some locations the difference between Rheotune and singlebeam are not that big, however there are several locations where the difference is 25 centimetres. This is also the case for location 40, see figure 3-4. One outlier even has approximately 60-centimetre difference between only one day, as can be seen in figure 3-6.

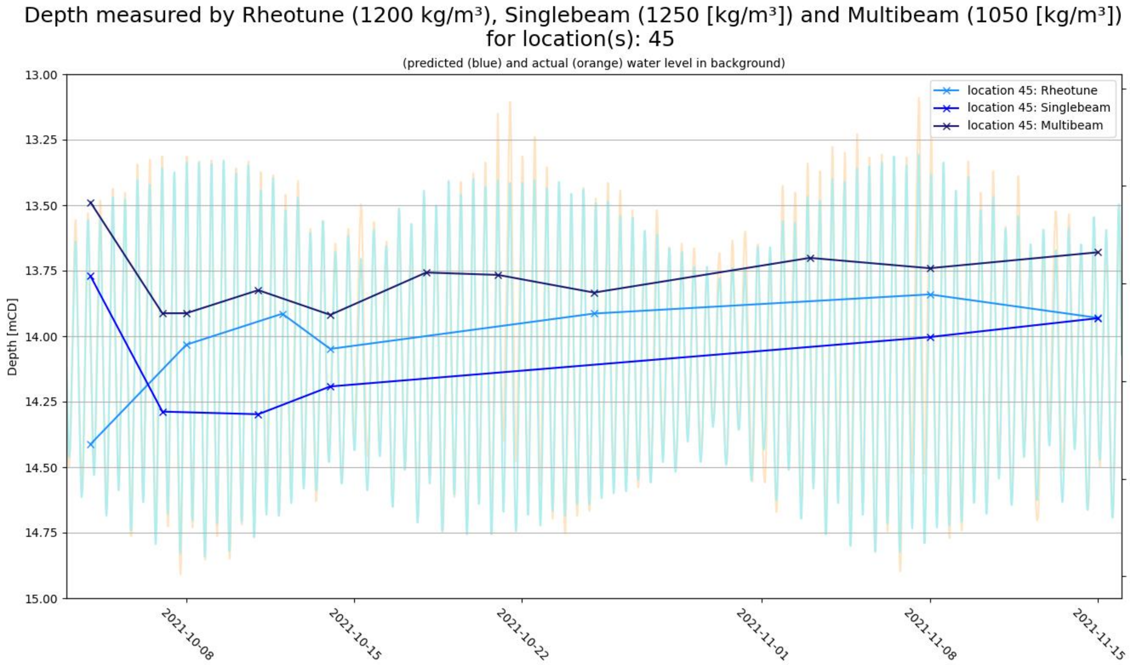

Figure 3-5 comparing the bed level course between the several measurement techniques at location 45.

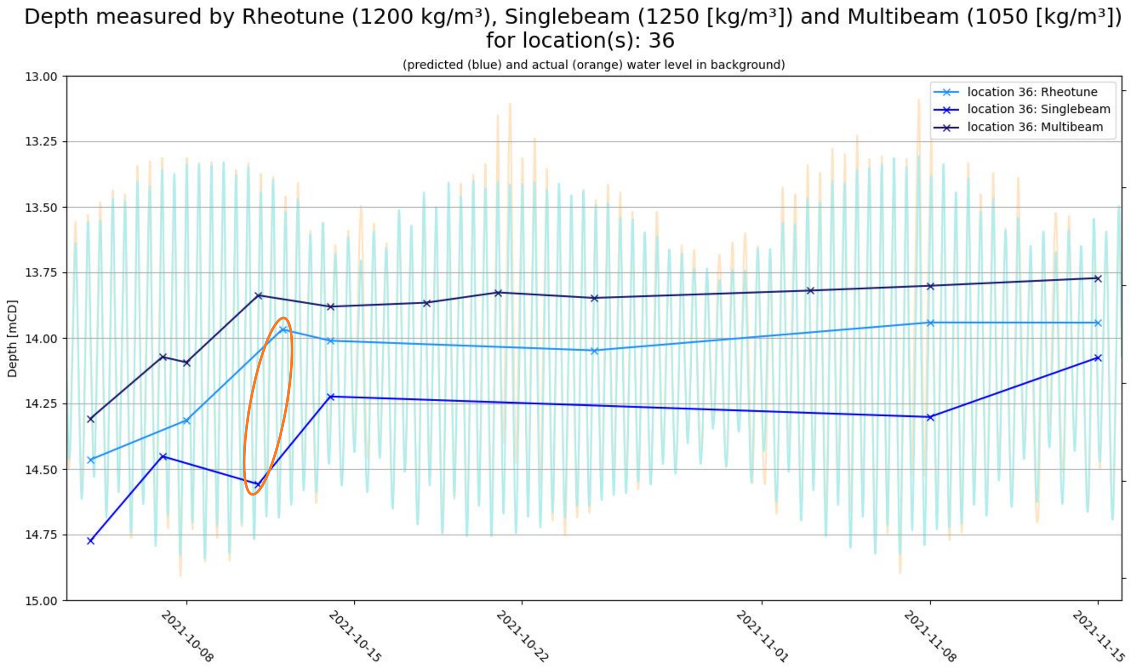

Figure 3-6 comparing the bed level course between the several measurement techniques at location 36. The difference between Rheotune and singlebeam are especially interesting between 11th and 12th of October.

3.3 Accessibility of a port with variable bed level

With the bed level models as input, the OpenTNSim model has been setup to calculate the accessibility of the port. The results of the OpenTNSim model give an insight in the way the accessibility would change by implementing the NBA, or how a port could hypothetically benefit from certain bed level changes.

3.3.1. Reference accessibility model

To compare the NBA between the surveyed data and the current bed level determination, a reference model is setup where the depth of the inner channel is 14.5 m minus CD. Figure 3-7 shows the results of the simulation of the reference model. The orange line shows the used bed level model during the simulation, the dark blue line shows the minimum UKC the ship has experienced during the travel, and the light blue blocks show whether the vertical tidal window was open at that specific moment. This graph shows the ship can enter the port during all flood tides. Furthermore, during ebb tide, there is not always a vertical tidal window for the ship to enter the port.

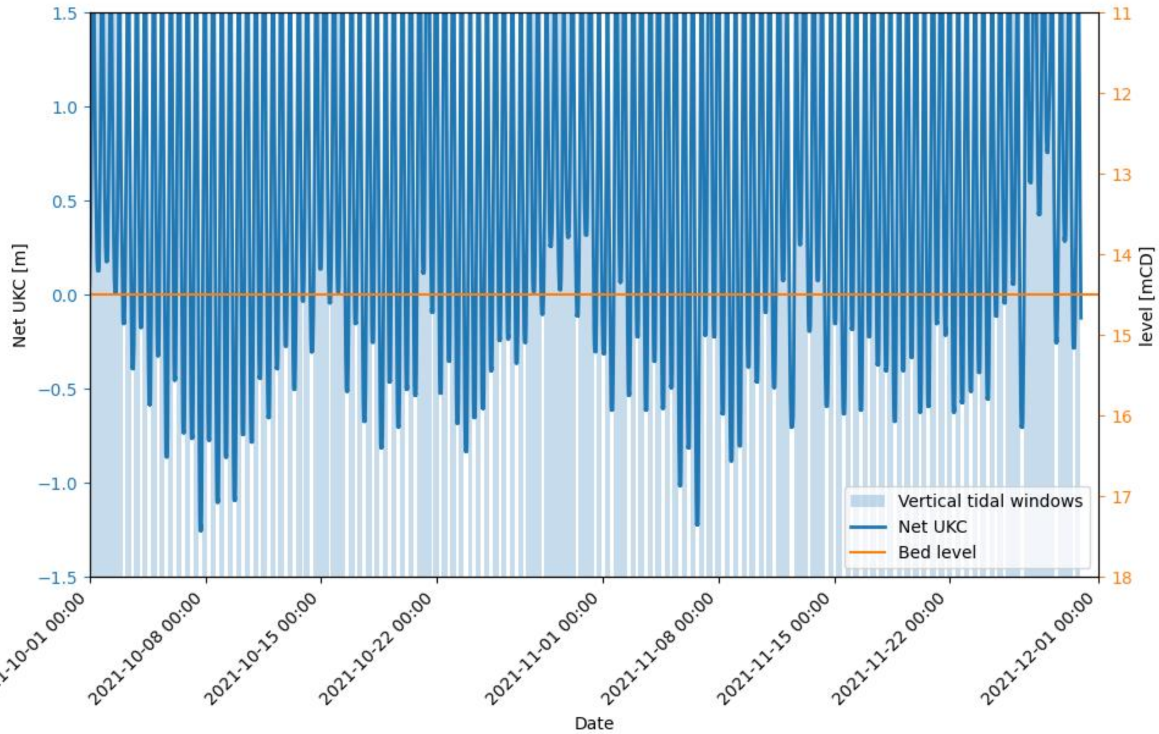

Figure 3-7 The vertical tidal window, Net UKC and Bed level for the base model, with meteorological influence in the water level

Figure 3-8 shows the percentage of accessible time and the percentage of accessible high tides. Measured over the tides, 100% of the high tides are available for the vessel to enter the port. This means that the vessel has a maximum waiting time of only one tide. If at some time this percentage would drop below 100, the vessel had to wait for another tide before it could sail into the port. The percentage of accessible time is measured over 10-minute intervals. After some spin up time, the vessel could enter the port for approximately 70% of the time.

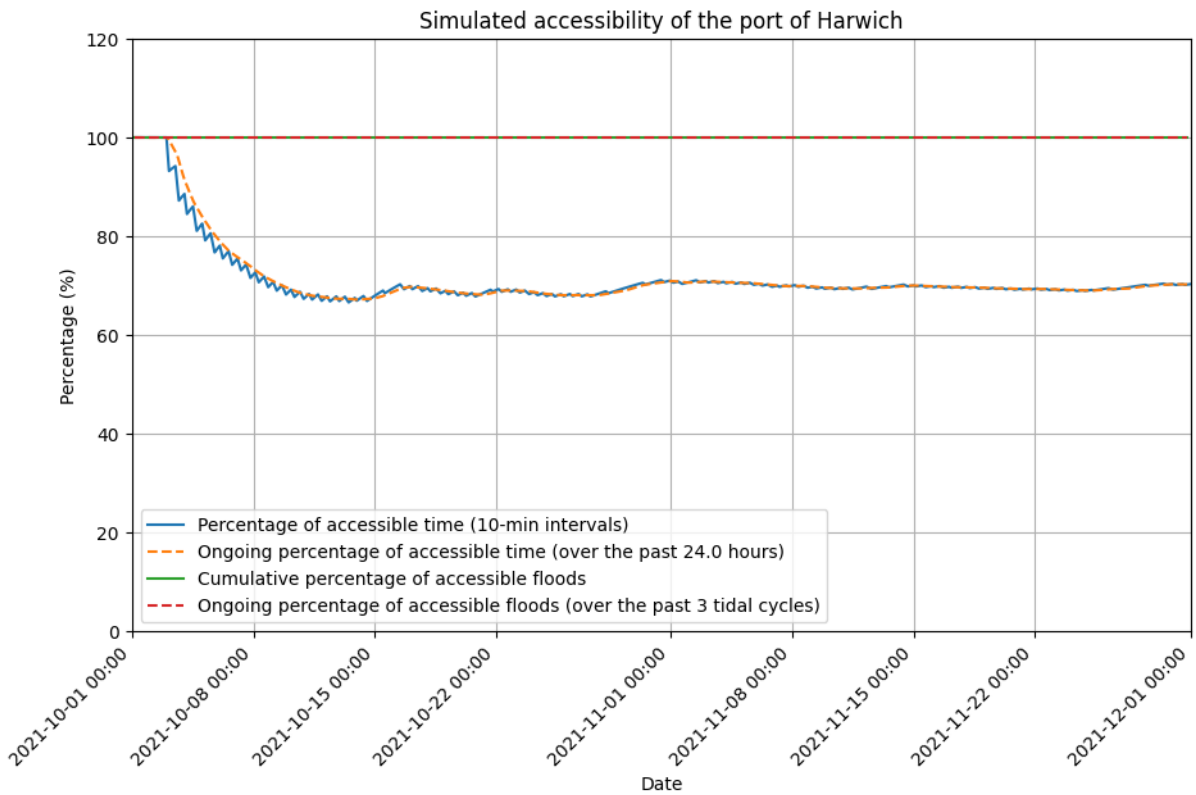

Figure 3-8 The accessibility of the port for the reference model (without NBA) with meteorological influence in the water level

3.3.2. Accessibility based on surveyed bed models

Location 40 has been simulated with the OpenTNSim for all three surveyed bed level models without meteorological influence in the water level. Figure 3-9 to figure 3-14 show the accessibility for the single beam and Rheotune bed level models increase compared to the accessibility with the multibeam bed level model. As these bed levels are lower than the bed level of the multibeam this is a logical result.

Also, it is interesting to see that even though the accessibility over time has stabilized after some time, the accessibility still fluctuates for around 5%. this indicates the small changes in bed levels (of approximately 25 cm) do still influence the accessibility of the port.

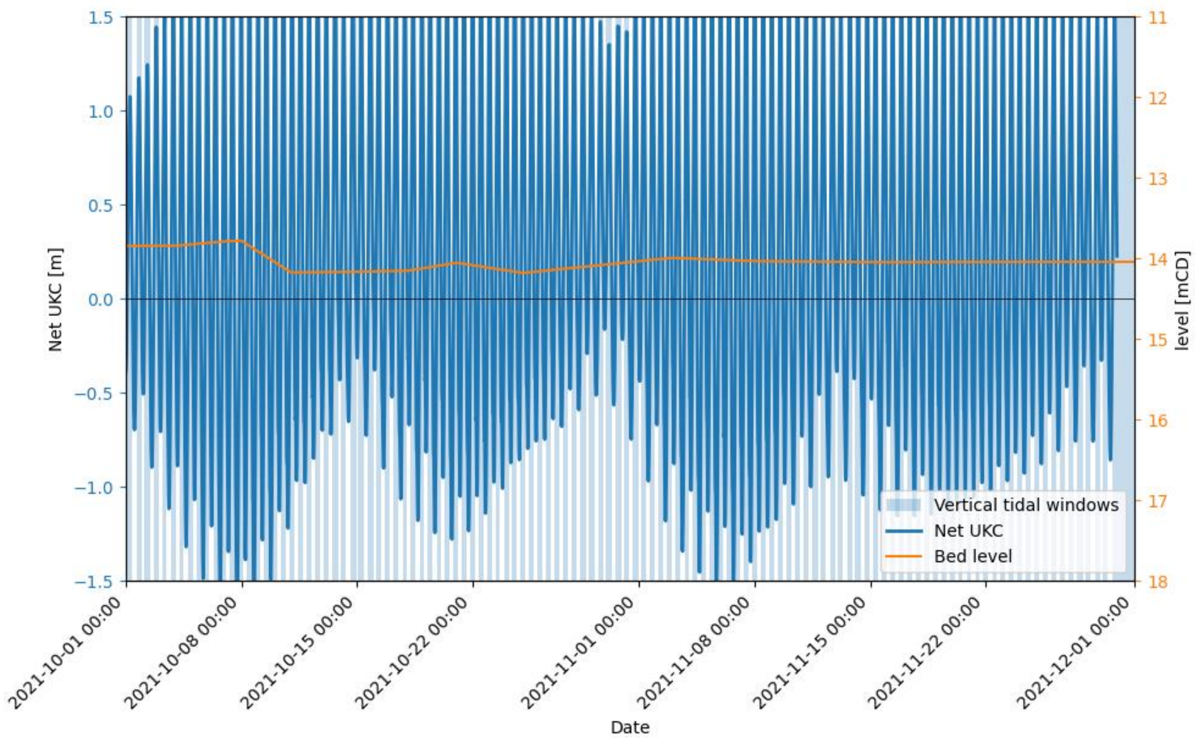

Figure 3-9 The vertical tidal window, Net UKC and variable bed level for **location 40**, where the bed level is taken from the **multibeam** surveys. The water levels in this model are without meteorological influence

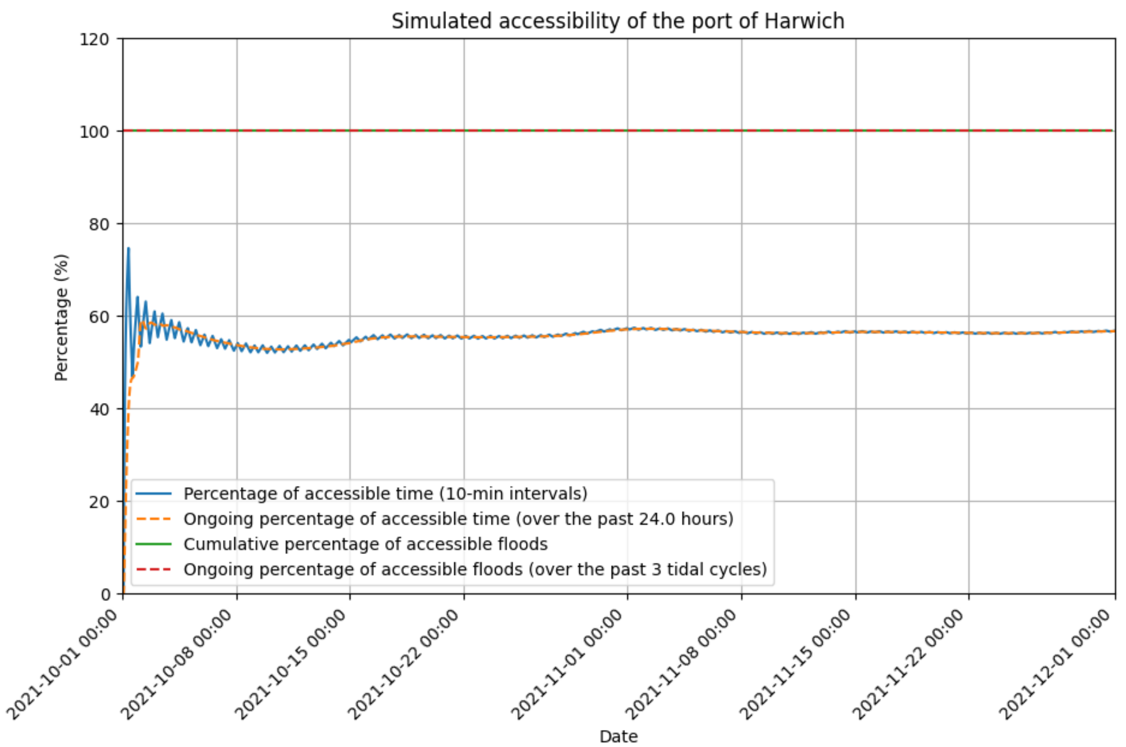

Figure 3-10 Percentages of accessibility for **location 40**. Bed level model from **multibeam** survey (without NBA), water levels are without meteorological influence

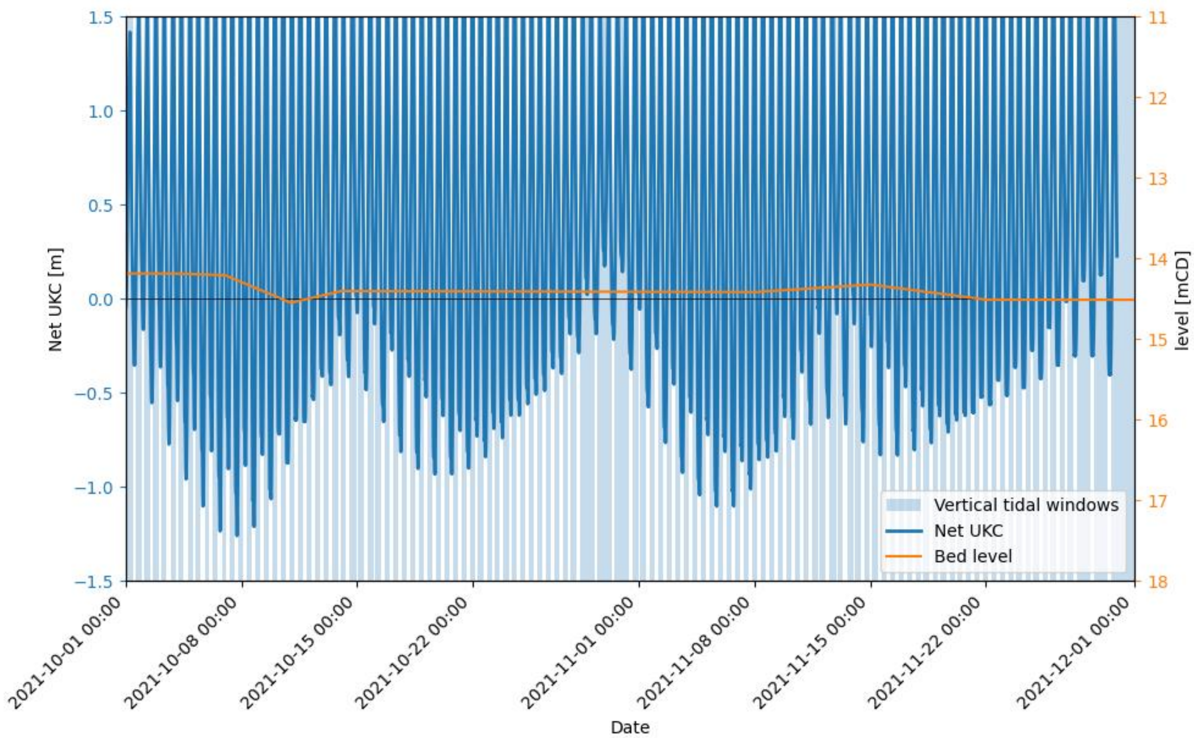

Figure 3-11 The vertical tidal window, Net UKC and variable bed level for **location 40**, where the bed level is taken from the **singlebeam** surveys. The water levels in this model are without meteorological influence

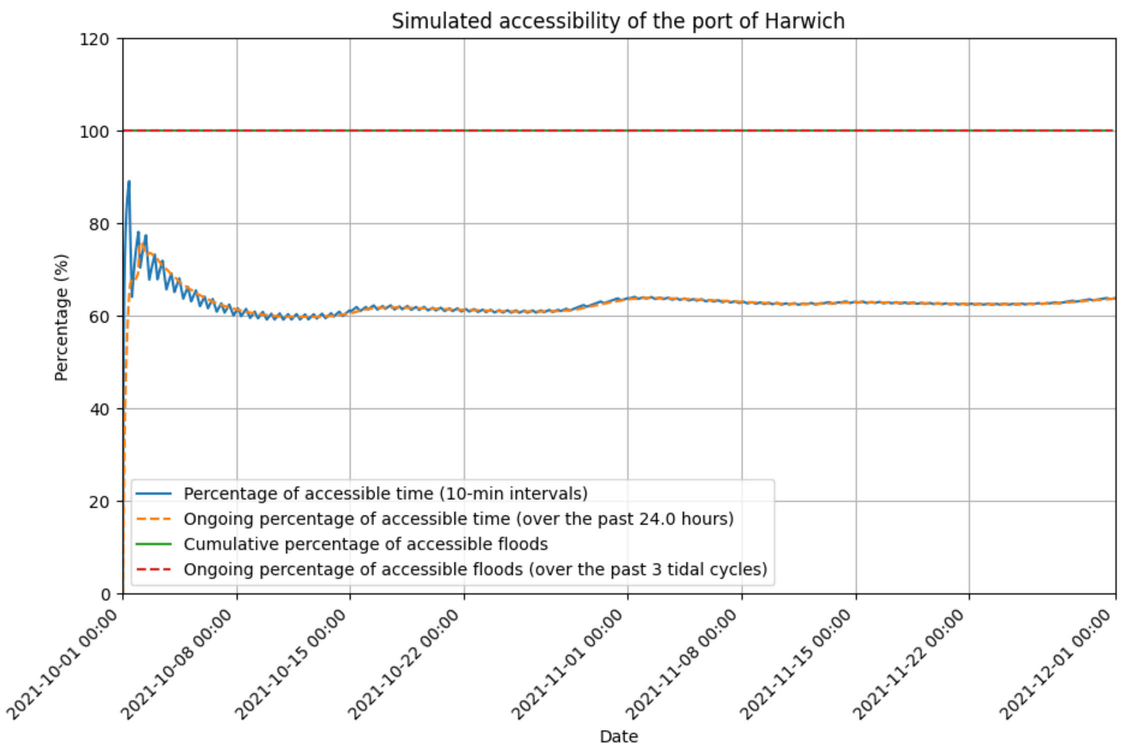

Figure 3-12 Percentages of accessibility for **location 40**. Bed level model from **singlebeam** survey (with NBA), water levels are without meteorological influence

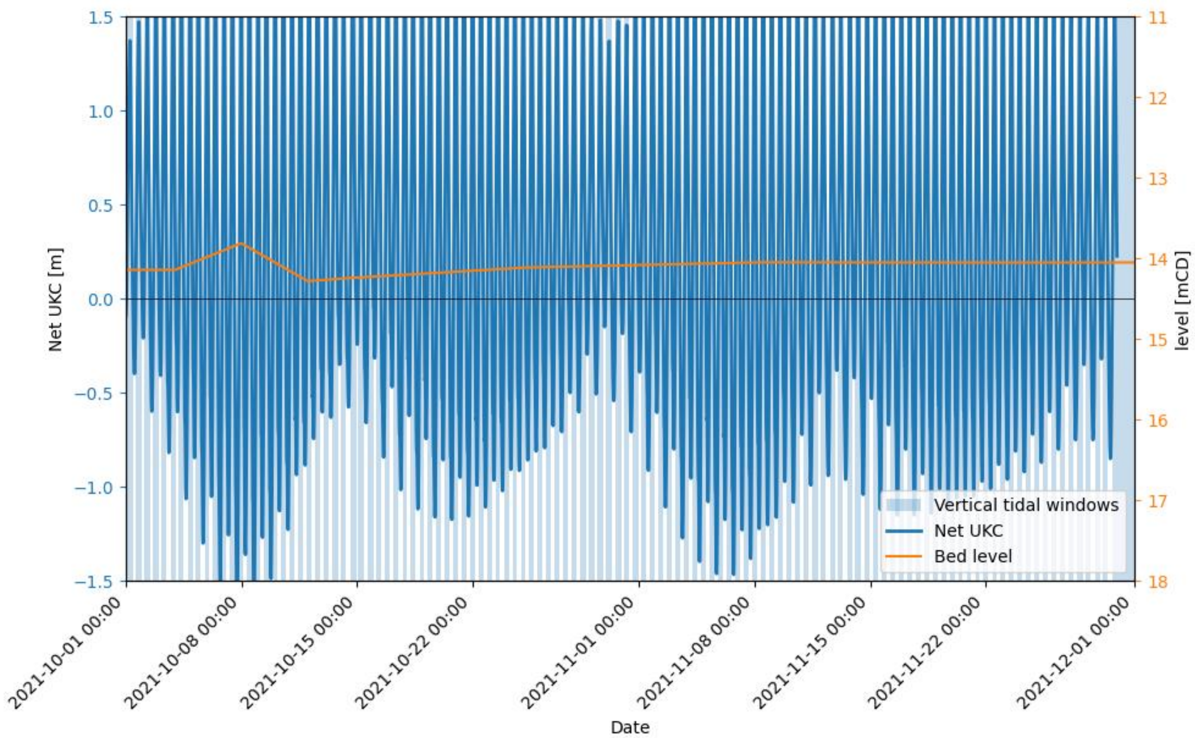

Figure 3-13 The vertical tidal window, Net UKC and variable bed level for **location 40**, where the bed level is taken from the **Rheotune** surveys. The water levels in this model are without meteorological influence

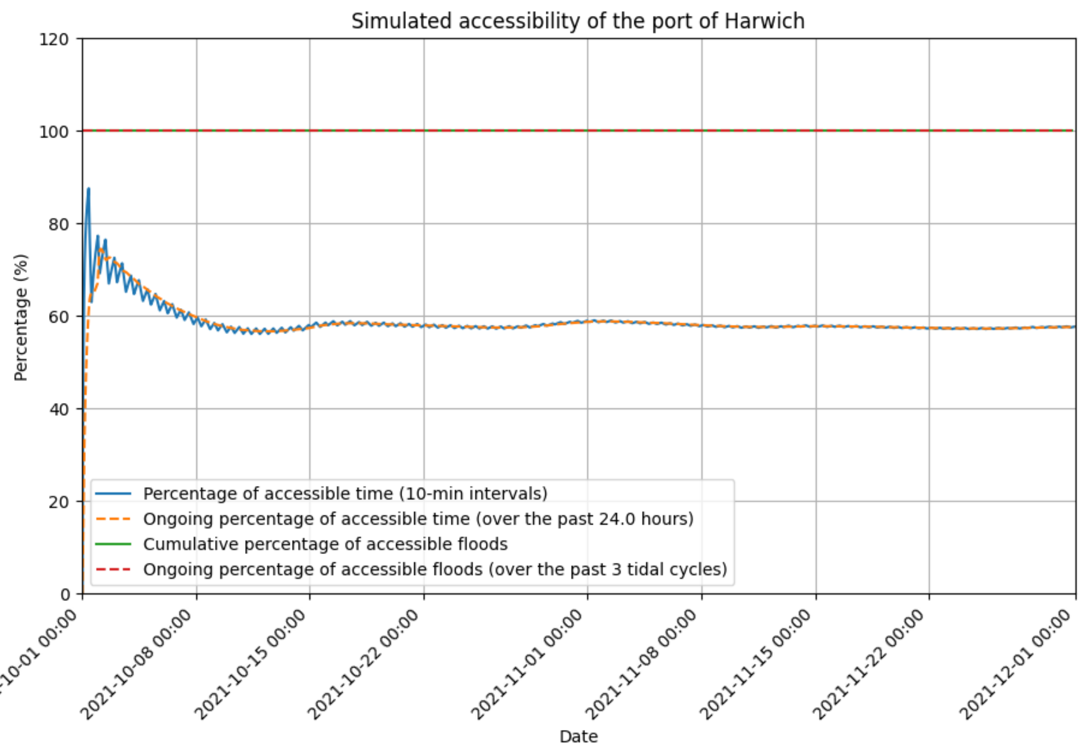

Figure 3-14 Percentages of accessibility for **location 40**. Bed level model from **Rheotune** measurements (with NBA), water levels are without meteorological influence

3.3.3. Hypothetical model

To also see what a hypothetical bed level model could do with the accessibility in a port, a "sawtooth" profile has been created. This profile resembles a port where the bed level quickly increases, and then the bed level is being reduced by dredging.

The increase in bed level is two meters in a timespan of approximately four weeks. This timespan corresponds to a bit less than two spring-neap tide cycles. Figure 3-15 shows the course of the bed level and the UKC change over time. The bed level change of 2 metres is chosen to see how a more dynamic bed level will influence the accessibility of the port.

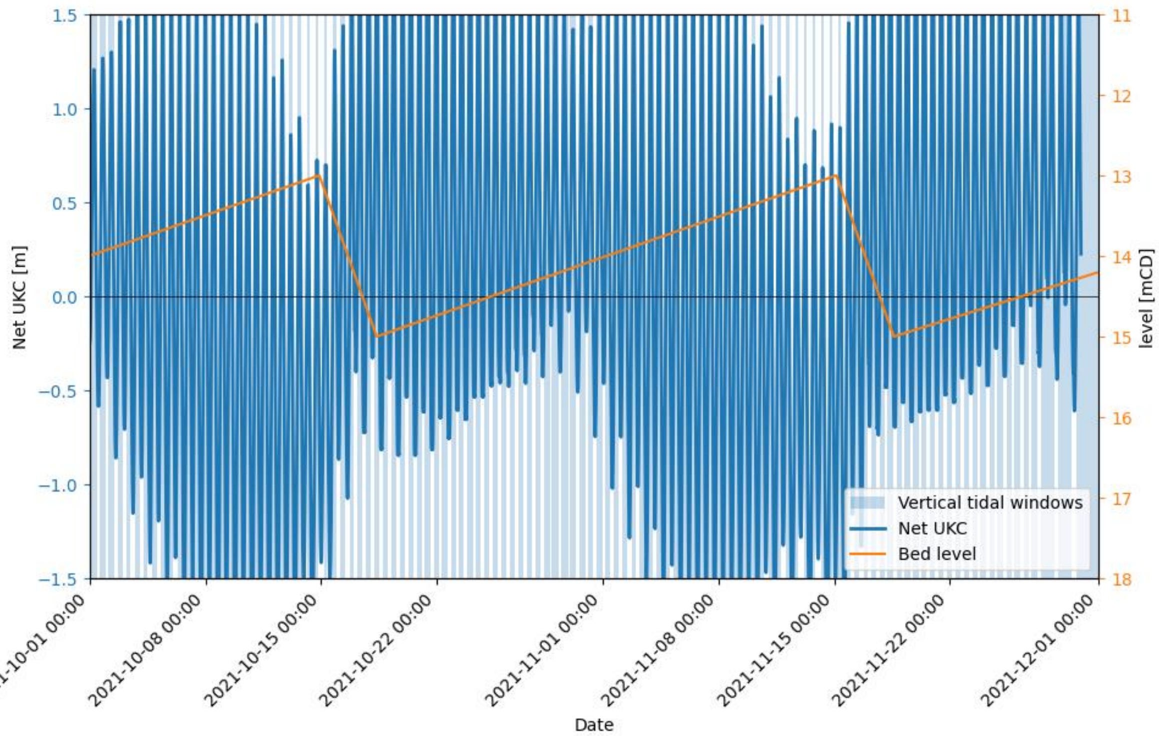

Figure 3-15 Bed level, Under Keel Clearance and tidal window for a sawtooth bed profile without meteorological influence

The hypothetical model results in an accessibility as shown in figure 3-16. The accessibility level over time will fluctuate with the bed level changes. Due to the relatively high bed level at the peak of the sawtooth, the average accessibility over time is quite a bit lower than for the MBL situation. However, by timing the moment of the dredging session to the most ideal moment of the tide, the accessibility per flood could be kept at 100% in this case.

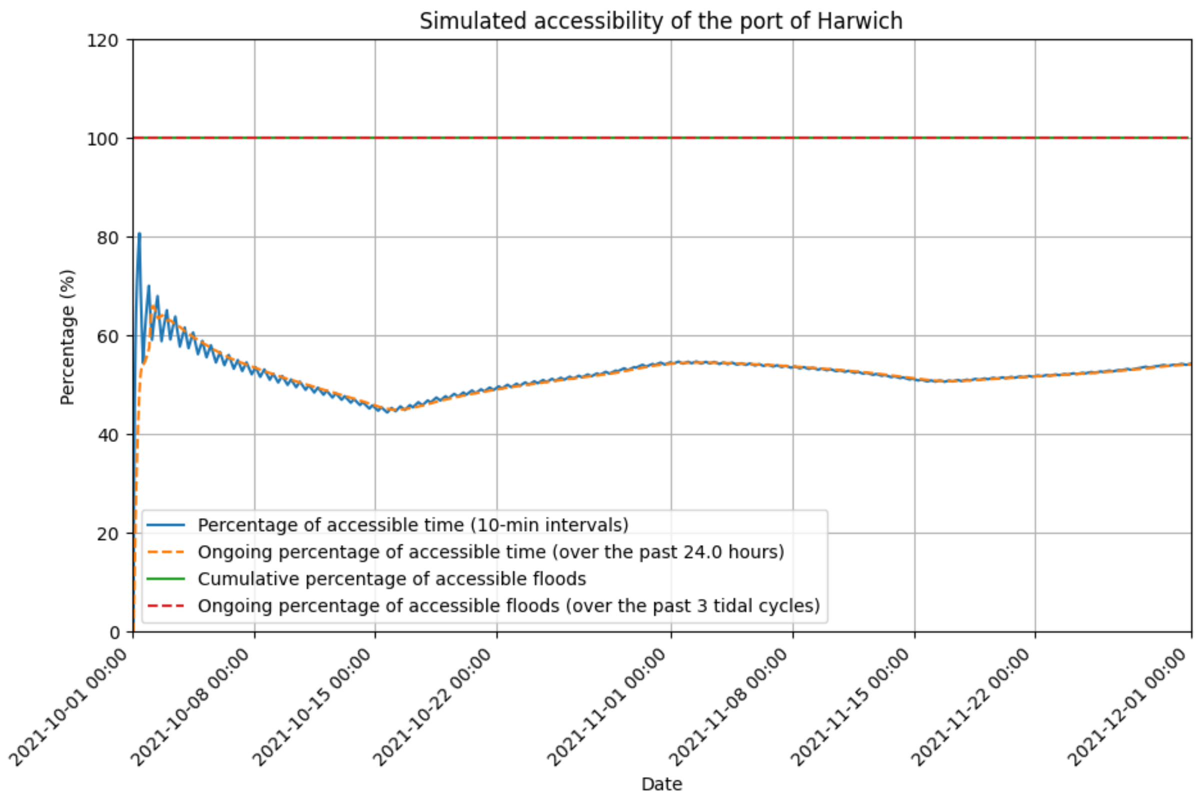

Figure 3-16 Percentages of accessibility for a sawtooth bed profile without meteorological influence

4 Discussion and recommendations

This chapter discusses the interpretation of the results, as found in chapter 3. Some limitations of the study will be acknowledged. Also, suggestions for future research and practical applications will be offered in the recommendations section.

4.1 Discussion

4.1.1. Mud properties

To apply the NBA within a port, the properties of the mud layer should be analysed properly. Due to the differences in content of the mud, ports all have their own interpretation of the implementation of the NBA. While looking at the Rheotune data of the several survey locations in Harwich, even within a port difference occur between locations and over time, these differences could go up to 1m. This phenomenon is in line with what Harwich Haven Authorities pilots experience during sailing through the inner channels of the Harwich port. Through interviews with several pilots of HHA it became clear the muddy bottom of a fairway can make a ship behave unexpectedly, even though surveys have been recently undertaken.

Although a density of 1200kg/m³ is used in the simulations of this research, the density of navigable mud in the Port of Harwich appears to be lower than this. Based on the Rheotune data, a density of 1150 kg/m³ appears to be a safe estimate where the yield stress of the mud does not exceed 50 Pa for the most locations in the Port of Harwich. However, this value is on the low side compared to other ports around the North Sea (PIANC, 2014). Also, the bed levels where this density has been found by the RheoTune have not been reported. Although specifically finding a correlation between these values is not part of this research, finding a proper correlation will be necessary to implement the NBA.

4.1.2. Time aspect of the bed level

As the surveyed bed levels with the three survey techniques showed how the bed level changes over time, the usage of the Tiamat dredger proved to help lowering the navigable bed level. Although the tuning between the Rheotune versus the single- and multibeam is not that clear, the Rheotune and singlebeam do often compare in results.

The difference over time of the surveyed bed levels did not show large changes in accessibility within the shipping traffic model. However, the use of a hypothetical variable bed level within the transportation model showed what a larger degree in bed level change could do with the accessibility. There is some potential to use the change of bed level to plan dredging works more effectively, for instance performing agitational dredging in sync with the neap- springtide cycle could increase efficiency.

4.1.3. Ship related components

Although the main focus of this research has not been on the ship related components such as manoeuvrability and resistance forces, these should still be kept in mind for implementing the NBA. Interviews with pilots, who sail the waterways in the Harwich port on a daily basis, gave a practical insight in the difficulties the mud layer could give for navigating. Pilots experience lots of unexpected challenges during pilotage, however in practice it is difficult to give a clear explanation to specifically point to the source of a difficult pilotage, in general there is a combination between waterflow, wind force and bed related forces, that can initiate a ship to make sudden manoeuvres, or to need more (or less) tugs than was expected beforehand.

4.2 Recommendations

4.2.1. Bed levels

To start using a variable bed level instead of using a static designed bed level ports should adapt their port operations. When a variable bed level is used to determine the vertical tidal window for a certain ship, regular surveys should be carried out. By researching what effects certain influences have to the muddy bed, surveys could be planned at moments when critical bed level changes appear. For example, every two weeks at least one survey should be carried out, however, after a storm a survey should always be carried out within an x number of tides.

Furthermore, calibrations between the survey methods could be researched in more detail. By researching the correlation between the RheoTune and the singlebeam, the relation between both results can be calibrated more precisely. With a proper correlation between the RheoTune and the singlebeam, time consuming Rheotune surveys will not have to be carried out as regularly.

4.2.2. Adaptability to use the NBA

For port authorities it could be interesting to research the effect of some short-term approaches when the vertical tidal window is not sufficient for an incoming ship. If a ship with a too large draught is planned to visit a port within a short time, the port could plan an agitational dredger before the ship is visiting. The effects of this adaptive dredging could be interesting for port authorities. Another measure to be adaptable is having the possibility to adjust the number of tugboats when necessary. According to the pilots of Harwich Haven Authority this measure is already used sometimes, however it is unknown when the use of more (and stronger) tugs is not efficient anymore.

4.2.3. Port of Harwich specific

The data provided by the Harwich Haven authority was very useful for this research, however it was quite limited due to the time span, frequency, and the circumstances of the combined bed surveys. By increasing the time span of the surveys, seasonal effects can be determined, also by increasing the frequency a timeseries will be more accurate. During the surveying campaign the Tiamat dredger was dredging for some time, it will also be interesting to see what the effect would have been when no dredging would occur. Therefore, carrying out a surveying campaign through a longer timespan would benefit the Port of Harwich.

Due to the limited bed level changes of the hard bed in Harwich Haven during the surveying period, the effects of a variable bed level to the accessibility of the port were also limited. As the hypothetical variable bed models showed, a port with larger bed level differences could see more effect from implementing the NBA.

5 Conclusion

The objective of this research is to study the optimized accessibility of a port by implementation of the NBA and by designing new maintained bed levels. To reach this objective, one main question and several sub-research questions were defined. These questions contribute to concluding on the research objective. In this chapter, the main question will be addressed concluded with addressing the sub-research questions in sequential order.

5.1 Main research question

In this section the main research question is addressed:

"How can the accessibility of a port be optimized by implementing the Nautical Bottom Approach?"

To optimize the accessibility of a port by implementing the NBA several measures can be taken. Firstly, by regularly surveying the navigable bed level the maximum allowed ship draught during a high tide will be determined. Secondly, when the accessibility of a port is not sufficient anymore, the navigable bed level must be lowered to increase the accessibility again. By using an agitational dredging method, the navigable bed level is lowered by implementing the Nautical Bottom Approach. However, agitational dredging must be alternated with conventional (TSHD) dredging.

5.2 The influence of the nautical bottom

To determine the influences of the nautical bottom towards the accessibility of a port, a port authority should have knowledge of the bed within their port. This paragraph describes the conclusion made to answer the sub question:

"How the influence of the nautical bottom on the accessibility of the port can be assessed?"

By evaluating data from Rheotune, singlebeam and multibeam, several bed level models can be made. Contrary to conventional bed level designs with a static MBL, a variable MBL can be implemented in ports where the NBA can be applied. By using time-varying bed level models in a transport model, the accessibility of the port can be assessed with influence of the nautical bottom.

5.3 The implementation of the NBA

The assessment of the bed level between conventional multibeam surveying and the techniques used to research a mud layer differ. Therefore, also the results between these techniques differs. This paragraph describes the answer to the sub question:

"To what degree does port accessibility with implemented NBA depend on surveying equipment (Rheotune and singlebeam)?"

The surveying data used in this research has been the main resource to assess the accessibility within a port. Especially the data from the Rheotune device did not always give clear results about the bed levels and rheologic properties of the bed. By combining the results of the Rheotune, singlebeam (and multibeam), bed level models can be setup to use as input to a nautical transport model.

5.4 Optimization of the maintained bed level design

To decrease the dredging efforts a port must perform to welcome a deep-draughted vessel, a port authority can reduce their dredging costs. This paragraph describes the answer to the sub question:

"To which degree could the maintained bed level design be optimized?"

In OpenTNSim a model with a static bed level and a model with a variating bed level have been conducted to compare the effect to the accessibility. A small change in bed level could already change the accessibility within the port. By also conducting a model in OpenTNSim with a hypothetical bed level model, effects to the accessibility of the port were exaggerated. This showed the possibility to adjust the dredging frequency to the spring-neap tide cycle. By implementing the (agitational) dredging efforts at the right moment, a deep draughted ship could still enter the port at high tide during neap tide.

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Appendices

A. Interviews

During a visit to Harwich Haven Authority on the 18th and 19th of April 2023, several persons within the Harwich Haven Authority have been spoken to. This appendix consists of the interview notes of these conversations.

A.1 J. Warner BEng (Hons) CEng MICE MRICS

Position: Construction and Dredging Manager

Company: Harwich Haven Authority

As the Construction and Dredging Manager of HHA and one of the committee members of this Master Thesis, Jim has been the main contact for the practical side of this study. During the visit in Harwich, several topics have been discussed as well as a tour through the port. The conversations sometimes went through several topics at the same time; therefore, the knowledge has been written down per topic. Next to the visit in Harwich, Jim also provided knowledge through meetings.

A.1.1 Muddy layer

There are three spots which easily silt up, this is due to the river towards Harwich has a quiet larger discharge. This silt up mostly occurs next to berth 9, in front of berth 1, 2, 3 and on the corner of Shotley. This results in about 5 to 6 maintenance dredging sessions per year with an 8000-9000 m^3 dredger.

After dredging there is still about 1.5 to 2 meters of silt above the dredged level, mostly in front of berth 1,2,3. Pilots know the multibeam levels are levels of the silt.

Most ships have an UKC of more than 1.5 to 2 meters, so they will not go through this mud. About 100 ships per year will have a smaller UKC above the dredged bed level.

Along the fairway at roughly points 254-256 the southern side of the fairway silts up; this narrows the fairway at this point (about 1 to 2 dredging sessions per year) but is not a concern for the accessibility of the port.

Rheotune samples have been taken during dredging trials, although this is for short periods (1 to 2 months). Long term measurements (for a period of about a year) have not been done.

The area next to berth 9 is the area which is the most worrying part of the harbour, it silts up quiet quickly and ships at this berth are deepest. Ships coming from berth 9 will be tugged with the front out and then will forward out of the harbour.

Some harbour authorities have their own PIANC equivalent. These have also defined what the nautical bottom is, the biggest difference is that it states there should be no unexpected higher levels at the bottom.

In the channel from Parkstone (where Stena is) to the entrance of the port mud will be washed away by the currents.

A.1.2 Harwich channel and berths network

For big ships there is one way from approximately point ips_254 until (and including) the port basins), between 256 and 259 is also one way traffic. Between 254 and 256 ships can pass each other as the last moment.

Smaller ships can pass through the upper and lower channels, but the depth is restricted (so quiet small ships)

There are roughly two turning point, one a bit further than the berths 8 and 9, ships heading for these berths will turn over here and then berth. Other ships will turn a bit later in front of berths 2 and 3 and then back up into their berths. While a ship is turning, the fairway is in use, only smaller ships might be able to pass. The decision between turning points is up to the pilot. Normally ships will turn before they berth, only on special occasions a ship will turn after berthing.

The tidal window Harwich is very simple, the design depth of the channel is the same for the whole stretch. Ships can only start sailing into the channel when there is enough depth and can only leave the port when there is enough depth.

A.1.3 Layout of the Felixstowe port and priorities between berths

Berths 8 and 9 are built at the location where roro 1 and 2 used to be. roro 3 and 4 are still used quite often. Berths 1 and 2 are not used anymore for container ships, if the harbour would be expanded, probably building a new quay wall in front of these berths and deepening the berth. There is the possibility to also build a berth 10 next to berth 9, however this will not be likely as this would also involve extending the flood defences.

Berths along the quay of berths 3 to 7 are also divided between north and south, a ship can be half in one berth, and half in another. The location of the ships is mostly determined by the occupation at that moment, to evenly use cranes and to have room to do maintenance to a crane.

Priorities:

Berths 6, 7, 8 and 9 are “reserved” for the largest ships (360 – 400m) the other berths do not really have a preference system, although smaller drafted ships would normally go to the berths with smaller depths.

A.1.4 Dredging works

Maintenance dredging of the channels and berths is done by HHA, and only the deepening of the channels is done by HHA, the terminal operators themselves are responsible for the depth of their berths.

The port operator of berth 8 and 9 is planning to deepen their berths to 18 meters, to be able to accept ships with a depth up to 17 meters, however the tidal window for these ships will be very marginal.

HHA is testing a new dredger type, the Tiamat, this dredger sucks the mud from the bottom of the channels and deposits it immediately back into the water column at a higher level. The small silt particles will therefore stay in the water column and can flow away by the current of the tide. The Tiamat has only been tested, it had done some work, however the fluid mud also deposited more on the locations where eddy’s form in the estuary, so it is not yet determined whether this is something that will be useful for the port to displace the silt particles out of the estuary.

A.1.5 Navigable bottom

In his expertise as a Dredging Manager, Jim has thought a lot about solutions to define where the bottom is and whether a ship can navigate into the port. One of the ideas would be to define a navigable bottom:

The bottom should not be determined with for instance a number of depth as it has been done for centuries, it might be an idea to make it a value as balance between bottom behaviour (density, shear stress), bottom levels, ship type, ship size, ship power, wind force, current force, number of tugs available. As all these values have influence on the ability to pilot a ship towards, or from the berth.

Navigable bottom would be a term which could be used to determine this; however, this would need a lot of research to determine how this would work. For Harwich this might be an idea, however, to make regulations about this will not be something to do for Harwich, as this is a broad thing.

A.2 M. Scanlon

Position: Hydrographic Surveyor

Company: Harwich Haven Authority

Meredith Scanlon is the Hydrographic Surveyor within the Harwich Haven Authority; she provided knowledge about the surveying campaigns in the port and especially during the Tiamat testing. Also did she provide the data which was necessary for this study.

A.2.1 Surveying

Multibeam measurements are done often, it takes approximately 1,5 days to cover the complete harbour and access channel.

Single beam measurements take approximately 1 week to cover the whole harbour and access channel, although, this will have less area covered.

HHA is busy with trying to find a correlation between single beam and RheoTune, or other density measurement devices, an external company is working this out into a model. Results of this research are not published yet.

A.3 Ian Love and Nick Thomas

Positions: Pilots

Company: Harwich Haven Authority

During the conversation with pilots Ian and Nick, they have taught me a lot about how they work in general, and what kind of difficulties they experience during pilotage and especially with the influence of fluid mud.

There are roughly three places where ships will turn, in front of berth 8, berth 9, and in front of 2 and 3 for berthing into 7. All three turning points have a stretch of about 150 meters, due to ebb and flood tide. Turning direction also depends on ebb or flood tide, to let the tide “help” turning. Moving towards and from the berth is also depending on ebb or flood tide, whether first the bow or the stern will be pushed or pulled.

For dealing with the mud, in the outer channel of the port there are not really locations where the mud has an interference with the ships, this only starts in the port. First at the narrowing of the channel in front of berth 9, here the ship will slow down and the pressure wave from behind the ship will overtake the ship. This makes manoeuvring difficult at the start.

Difficulties were explained as mostly where a ship would start accelerating without putting more effort in it, or the ship not accelerating with putting a lot of effort in it. However, the pilots are not certain if this is always due to mud or other influences. This is also confirmed with Jim, as he has one time received three instances where the pilot thought mud has had interference during a difficult situation, however the most recent multibeam charts would not agree with mud being at the specific location.

The pilots would advise to only have a look at the berths (6,) 7, 8, 9 as only the ships berthing in these berths are ships that “feel” the bottom. At berth 9 this is the most problematic. Berth 7 (and 6) has difficulties with sailing into the channel after turning, here the mud starts to build up and ships start behaving odd at times.

If ships have an under-keel clearance of 10% which is the standard advised under keel clearance of the PIANC, there are no difficulties that can be related to the bottom. When the under-keel clearance becomes less than the 10%, even above muddy bottoms, the ship starts to feel the bottom, this is not necessarily a problem if it is an even bottom, funny things start to happen when the mud is at one place beneath the ship and not beneath other places.

One important notice is that ships with equivalent length (of 400 meters, or 360 meters), are not equipped the same. The older ships are equipped with more thrust power since they were “over engineered” as shipping companies would expect this power was needed. However, these ships are most of the time sailing on oceans where the extra manoeuvrability is not needed, therefore they are stripped of power. It also saves shipping companies more (fuel) costs.

Newer ships are equipped with less power, as a result tugboats will have to compensate for this lack of power, this will directly be an expense for ports, as they will need stronger/more tugboats. There is also a difference between shipping companies, as some shipping companies have ships with less power due to their manufacturer.

Pilots get on board of a ship at the anchorage area, then they have enough time to set up before getting into the channel.

A.4 Mark Murrison and Simon Browne

Positions: Pilots

Company: Harwich Haven Authority

Pilots will always have their own style and approaches, therefore having conversations with different pilots was very useful. During this conversation some new thoughts came up, that had not been discussed in the previous conversation with Ian and Nick.

The pilots think determining whether sailing through the mud has an impact is hard to define. The same locations and issues as yesterday had been mentioned.

The tugs used in the HHA are Maersks, the pilots/HHA will determine the number of tugs that are necessary. They think it would be interesting to know where the balance between dredging, sailing through mud, and using more tugs would be. However, they also could not really determine how to define when they would have trouble/lower berthing velocity due to the mud.

There is a difference in behaviour between ships with different (bottom shapes), some have better manoeuvrability than others.

B. Plots

B.1 Yield stress versus density plots

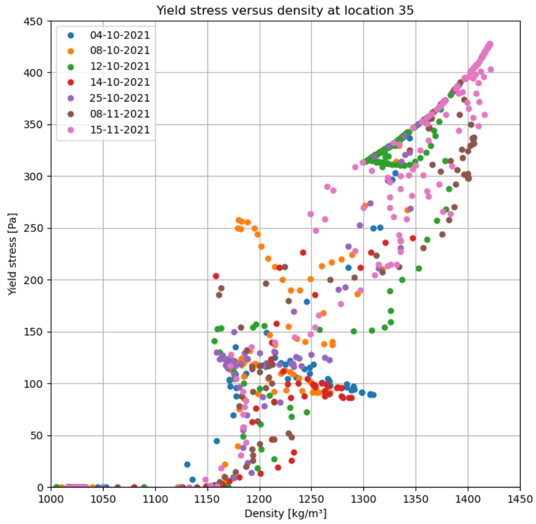

Figure B-1 Yield stress versus density at location 35

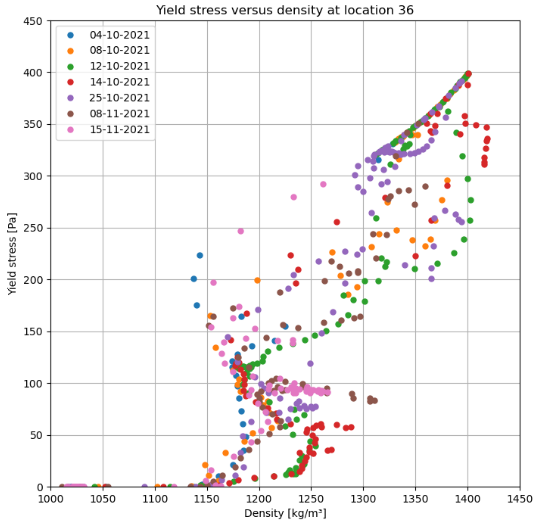

Figure B-2 Yield stress versus density at location 36

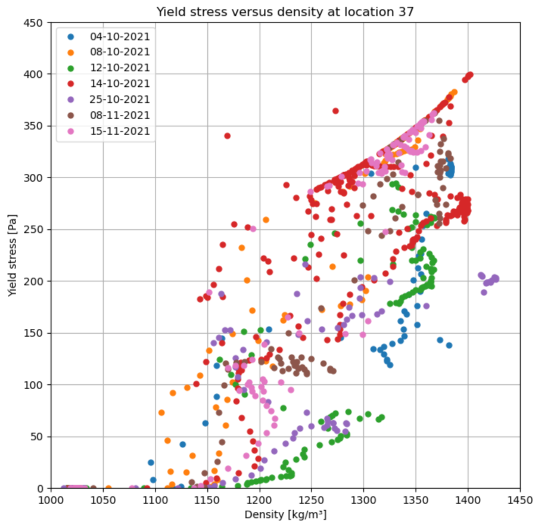

Figure B-3 Yield stress versus density at location 37

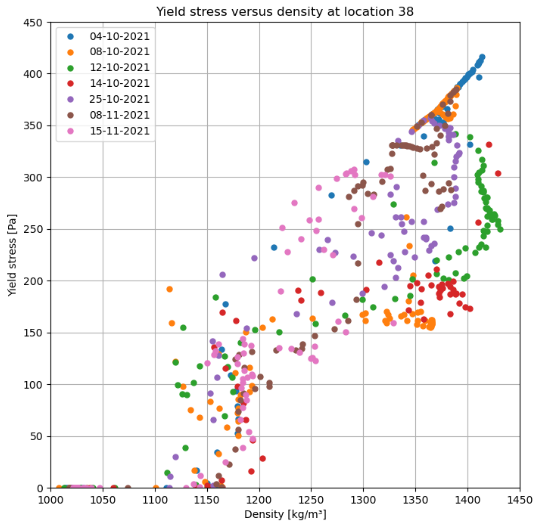

Figure B-4 Yield stress versus density at location 38

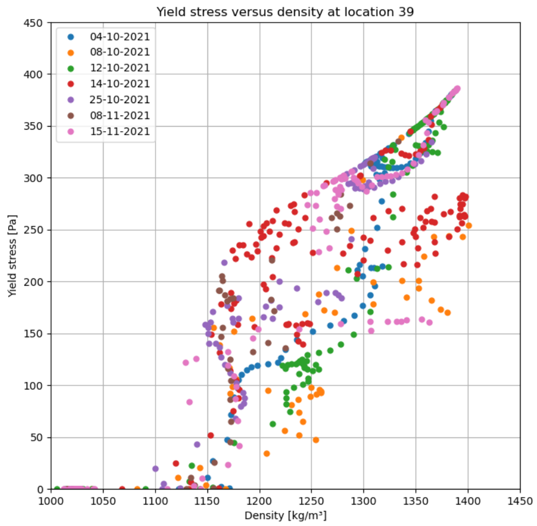

Figure B-5 Yield stress versus density at location 39

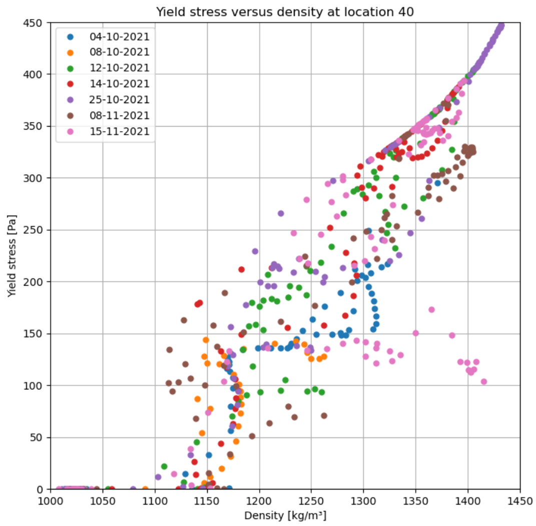

Figure B-6 Yield stress versus density at location 40

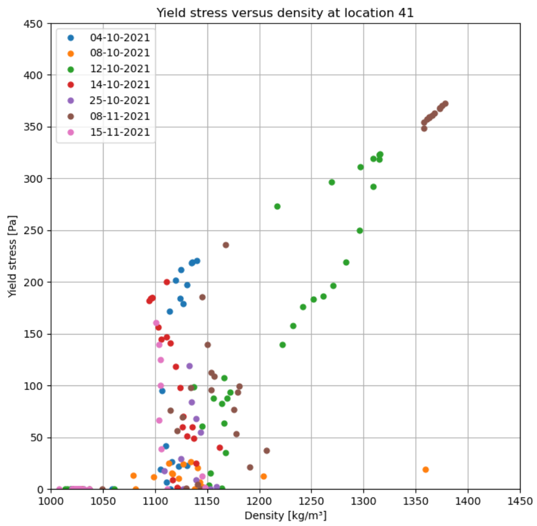

Figure B-7 Yield stress versus density at location 41

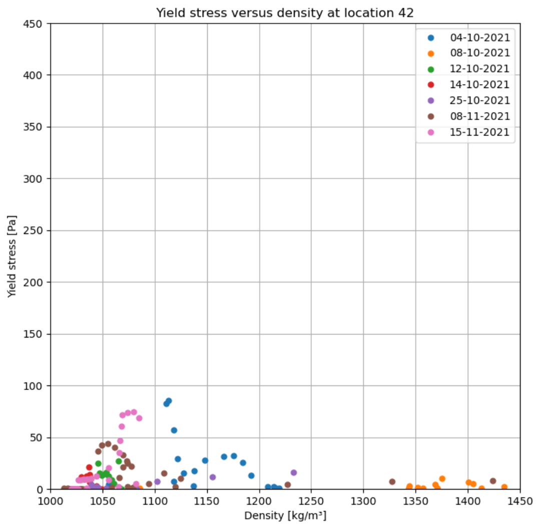

Figure B-8 Yield stress versus density at location 42

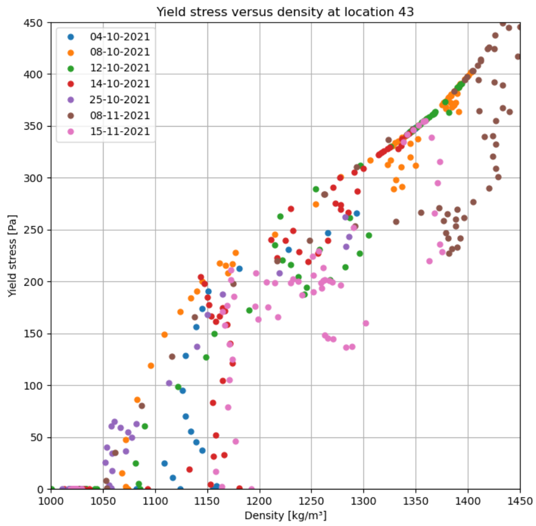

Figure B-9 Yield stress versus density at location 43

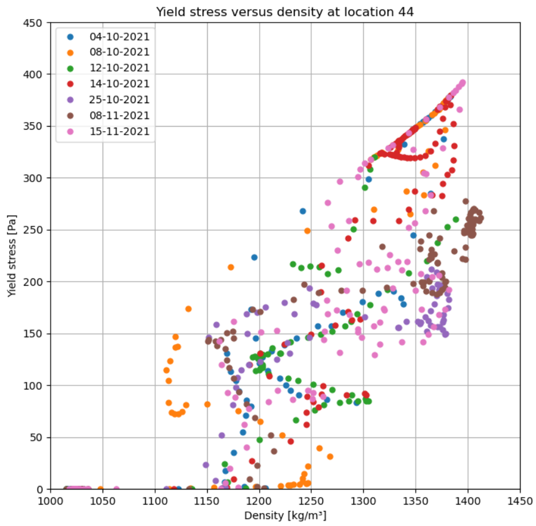

Figure B-10 Yield stress versus density at location 44

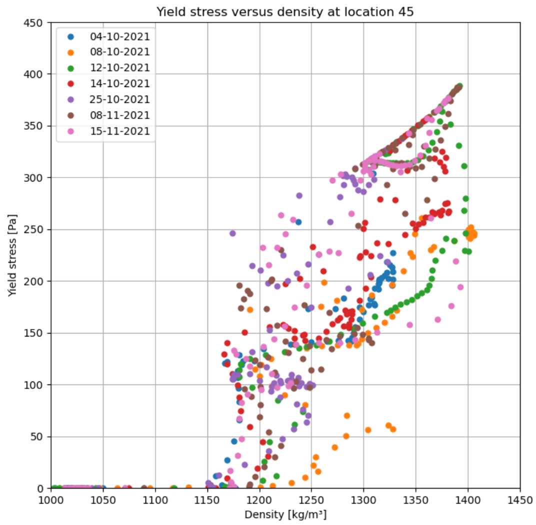

Figure B-11 Yield stress versus density at location 45

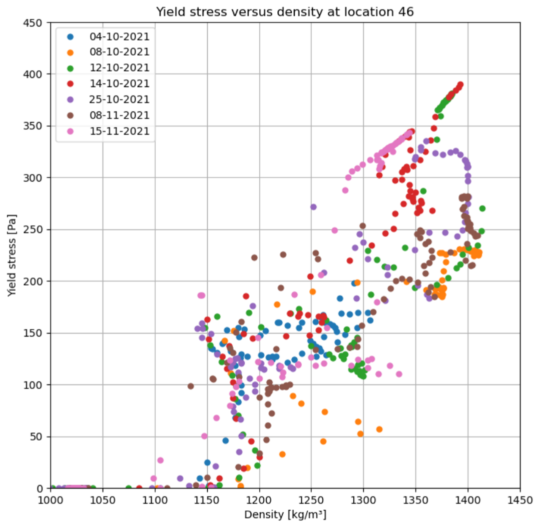

Figure B-12 Yield stress versus density at location 46

B.2 Depth where Rheotune reached 1200 kg/m³ over the time

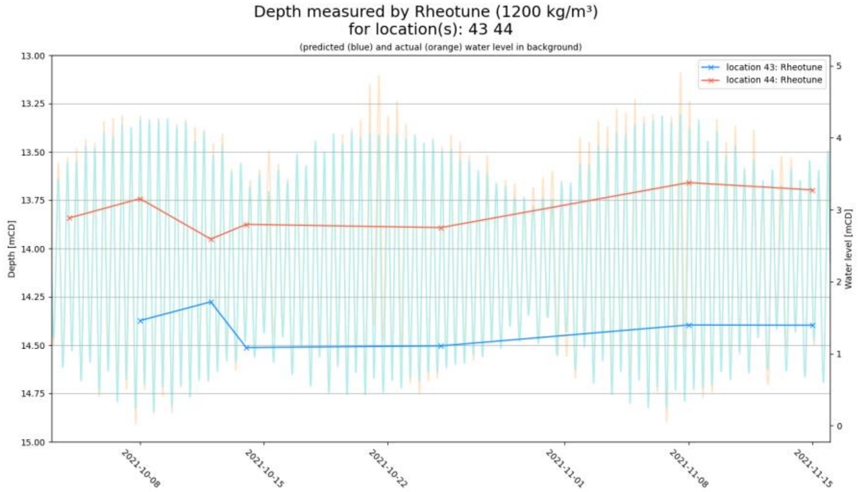

Figure B-13 1200 kg/m³ mark of locations 43 and 44 over the time during the Tiamat test

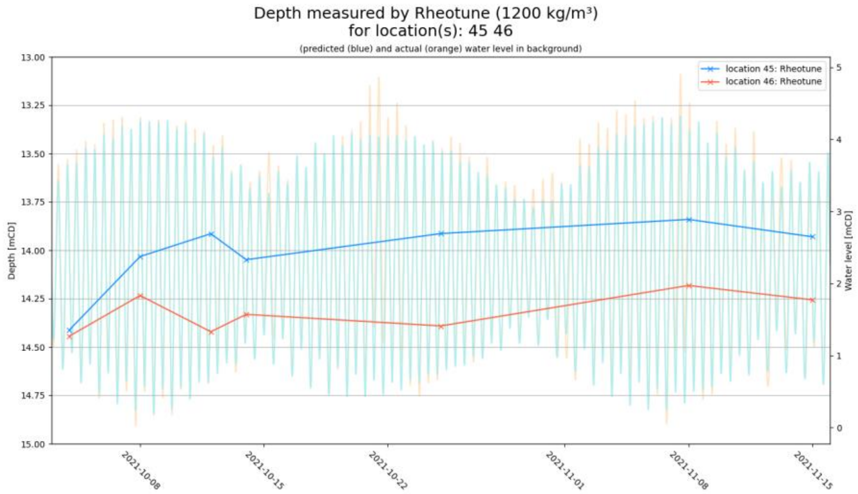

Figure B-14 1200 kg/m³ mark of locations 45 and 46 over the time during the Tiamat test

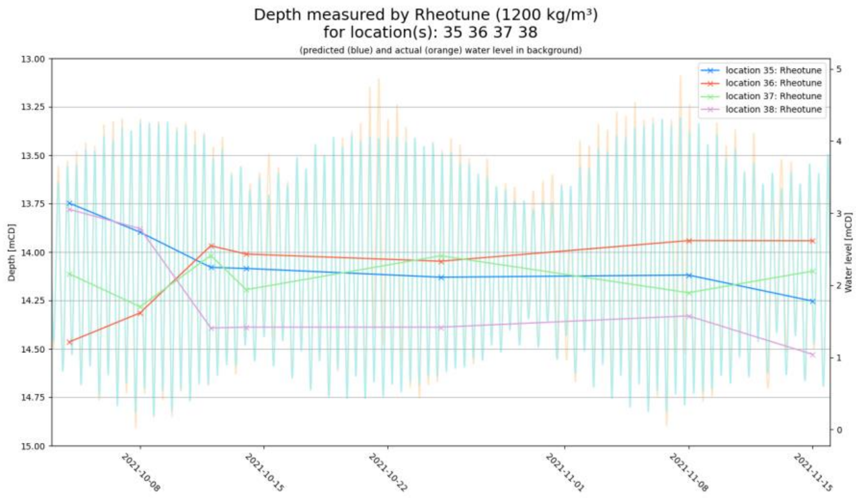

Figure B-15 50 1200 kg/m³ of locations 35, 36, 37 and 38 over the time during the Tiamat test

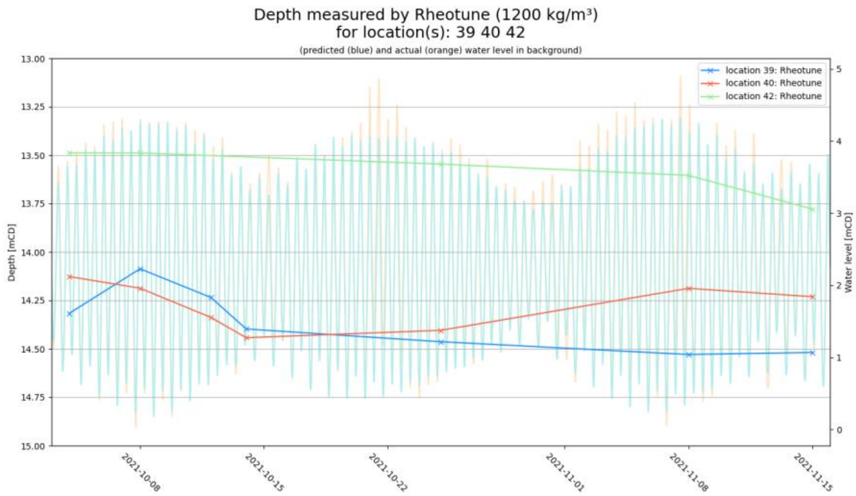

Figure B-16 1200 kg/m³ mark of locations 39, 40 and 42 over the time during the Tiamat test

B.3 Bed level graphs

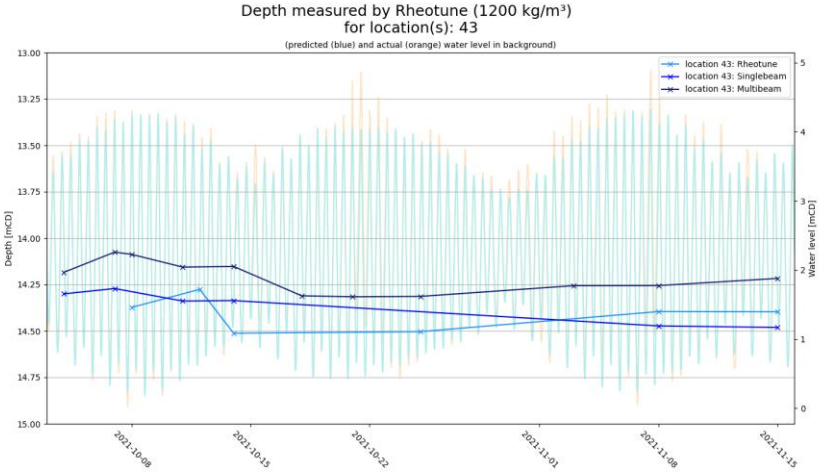

Figure B-17 comparing the bed level course between the several measurement techniques at location 43

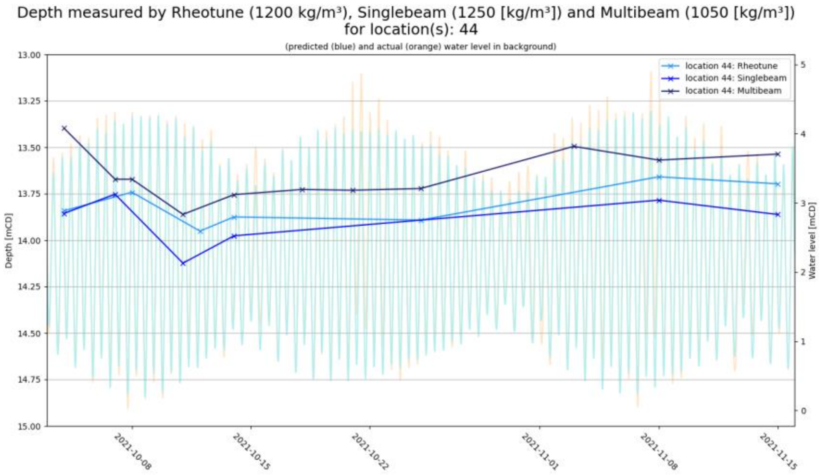

Figure B-18 comparing the bed level course between the several measurement techniques at location 44

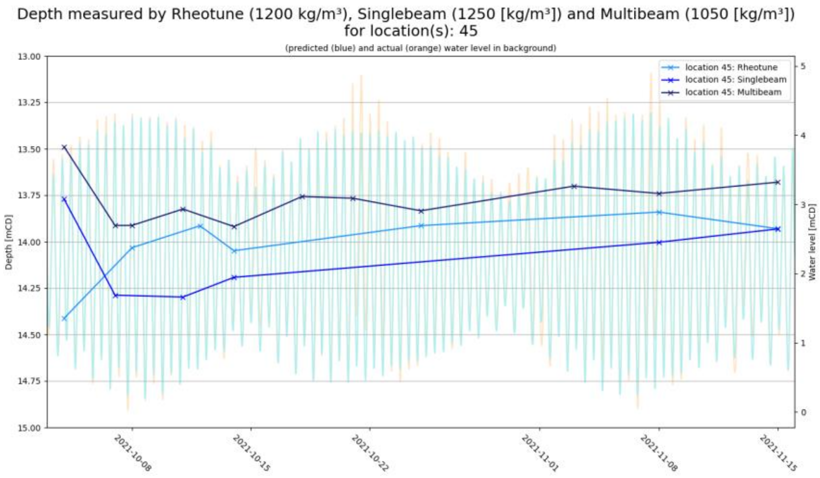

Figure B-19 comparing the bed level course between the several measurement techniques at location 45

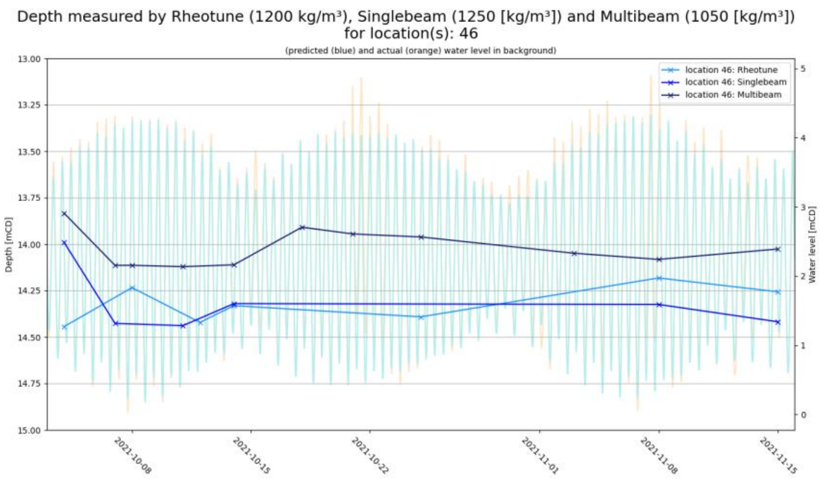

Figure B-20 comparing the bed level course between the several measurement techniques at location 46

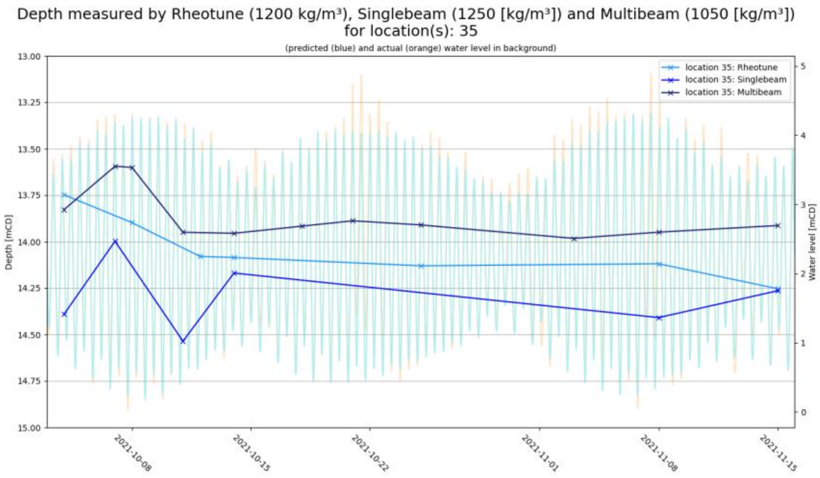

Figure B-21 comparing the bed level course between the several measurement techniques at location 35

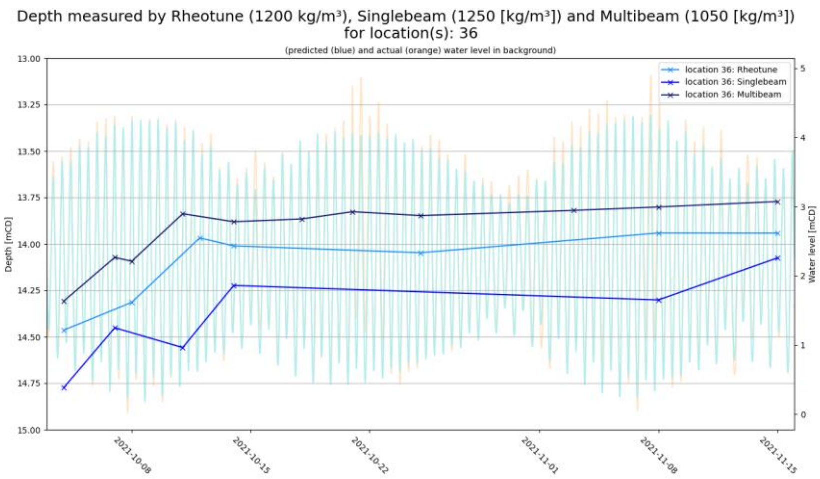

Figure B-22 comparing the bed level course between the several measurement techniques at location 36

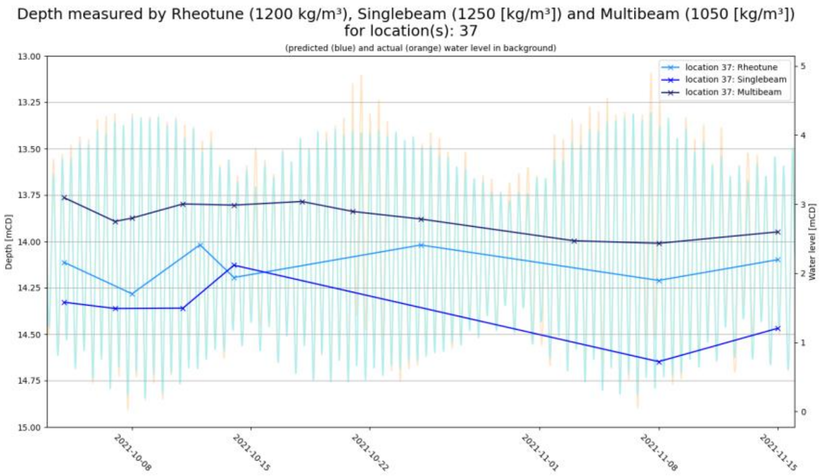

Figure B-23 comparing the bed level course between the several measurement techniques at location 37

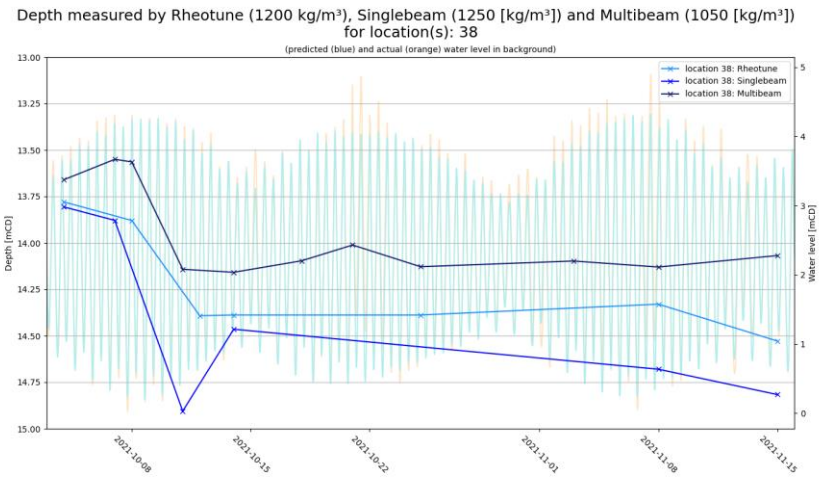

Figure B-24 comparing the bed level course between the several measurement techniques at location 38

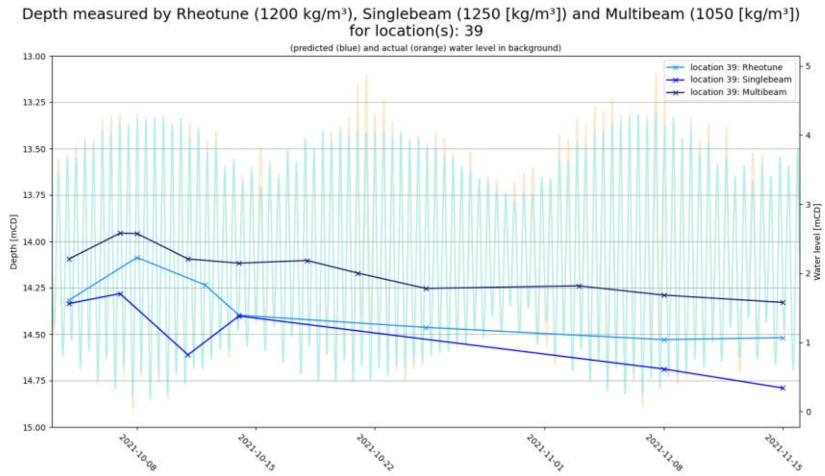

Figure B-25 comparing the bed level course between the several measurement techniques at location 39

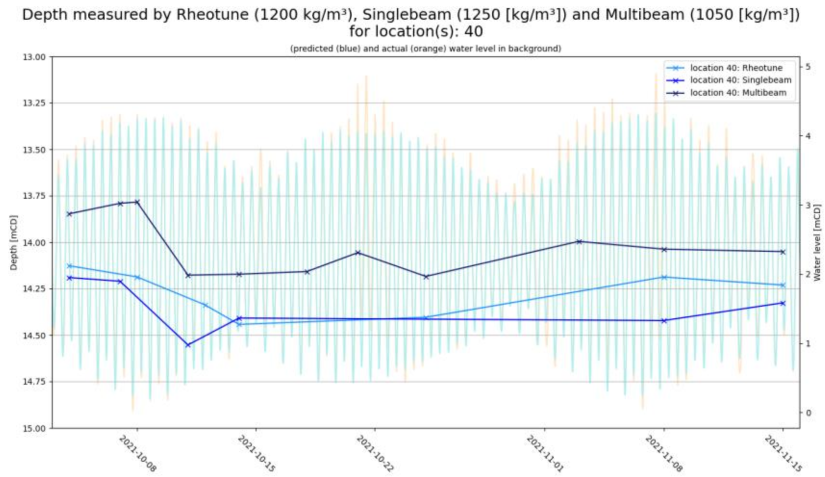

Figure B-26 comparing the bed level course between the several measurement techniques at location 40

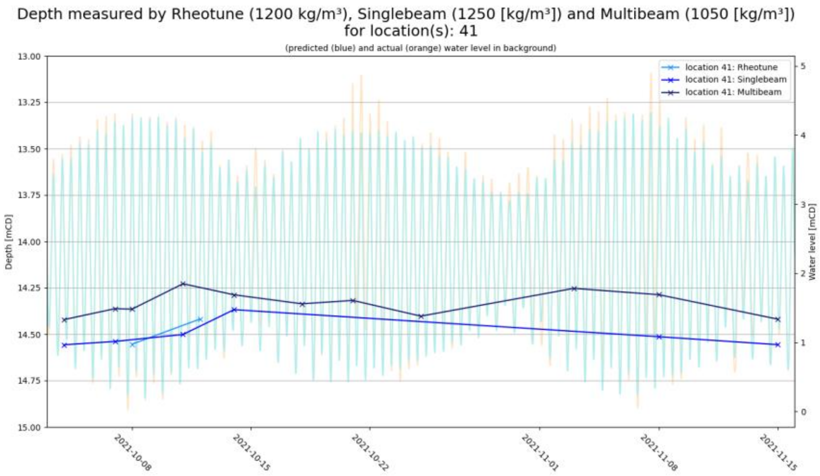

Figure B-27 comparing the bed level course between the several measurement techniques at location 41

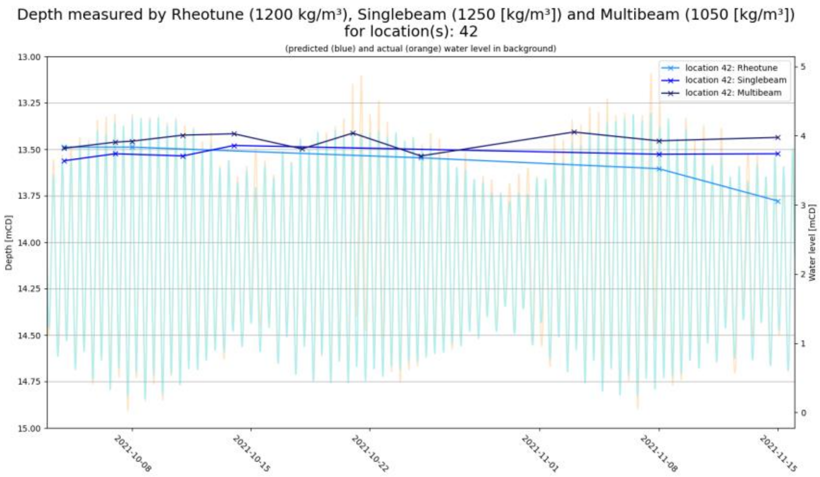

Figure B-28 comparing the bed level course between the several measurement techniques at location 42

B.4 Shipping simulations

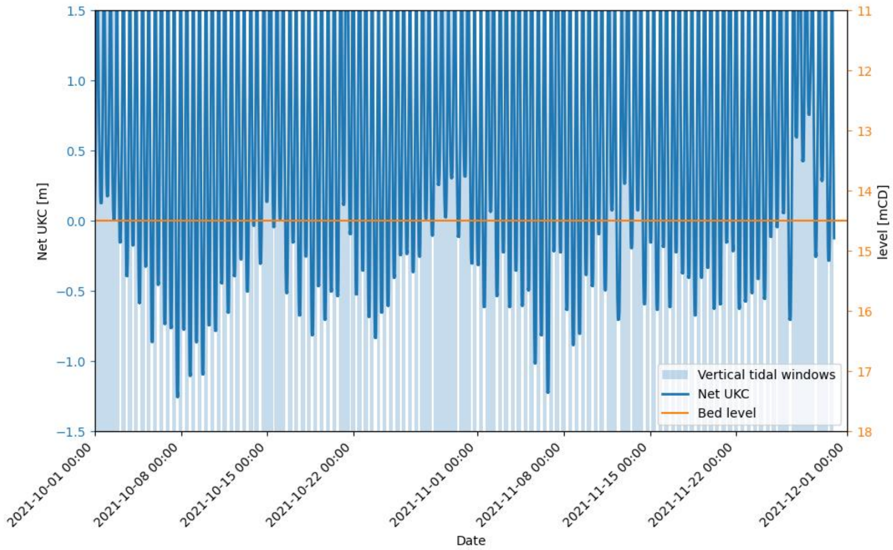

Figure B-29 Bed level, Under Keel Clearance and tidal window for the base situation with meteorological influence

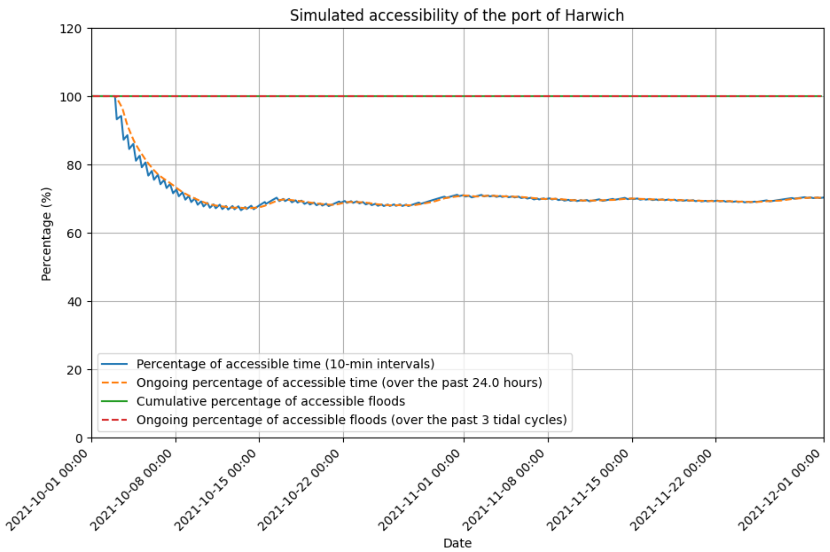

Figure B-30 Percentages of accessibility for the base situation with meteorological influence

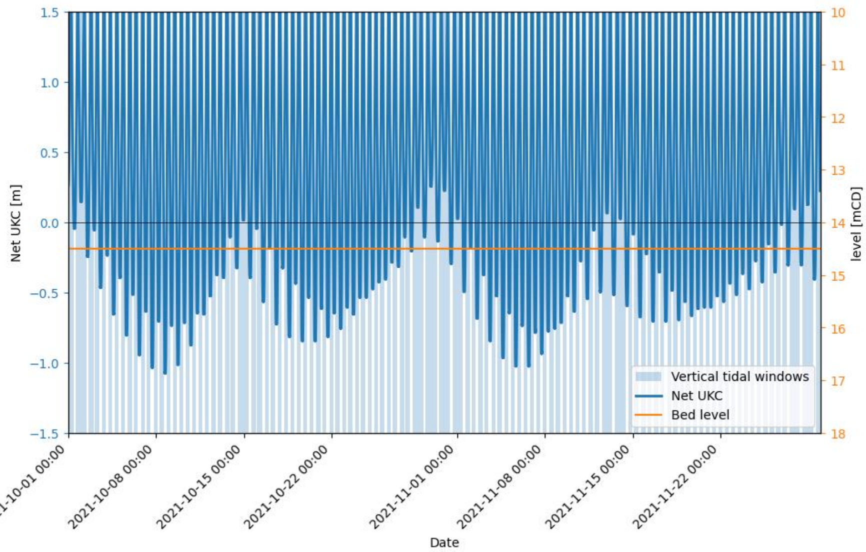

Figure B-31 Bed level, Under Keel Clearance and tidal window for the base situation without meteorological influence

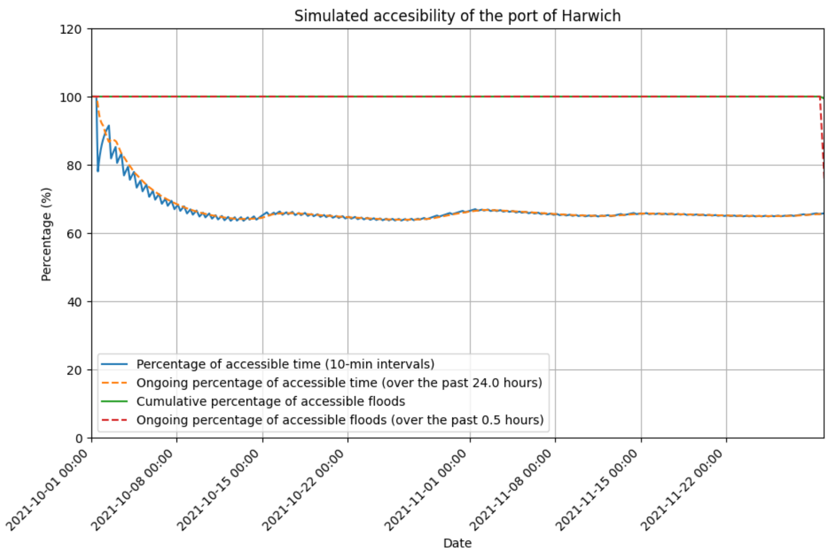

Figure B-32 Percentages of accessibility for the base situation without meteorological influence

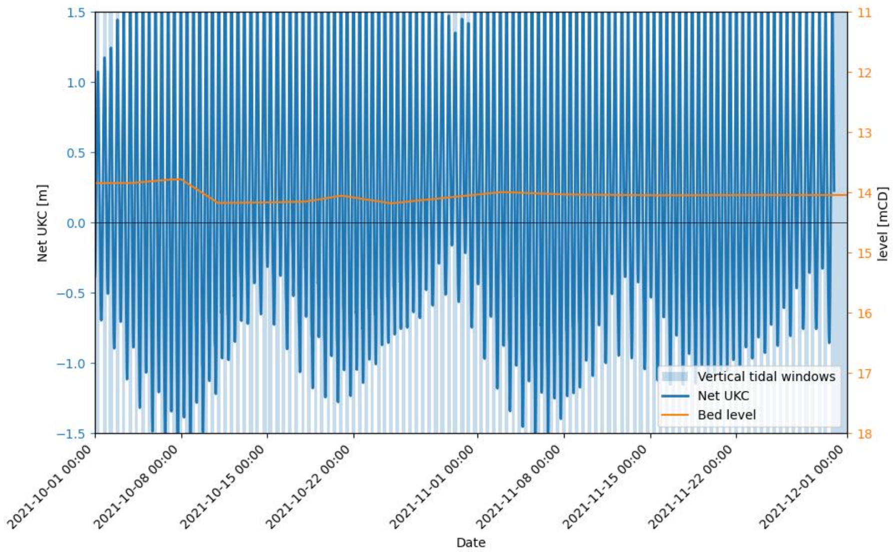

Figure B-33 Bed level, Under Keel Clearance and tidal window for location 40 multi beam without meteorological influence

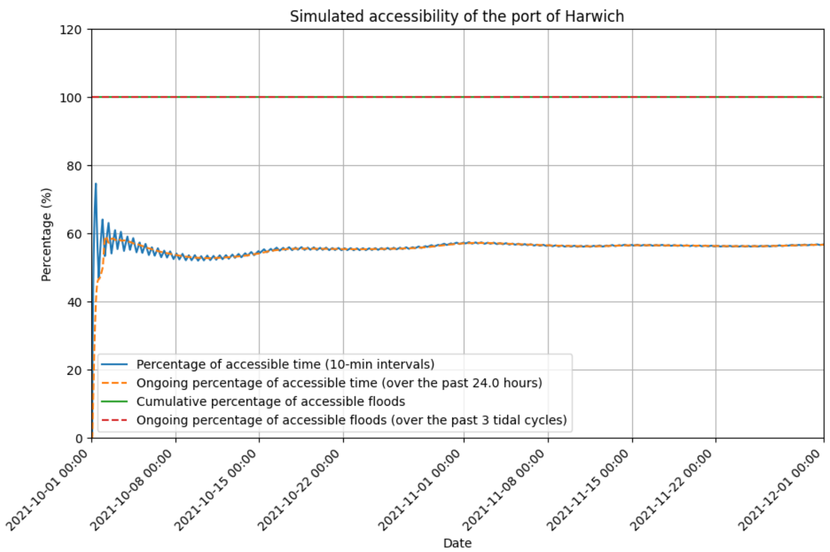

Figure B-34 Percentages of accessibility for location 40 multi beam without meteorological influence

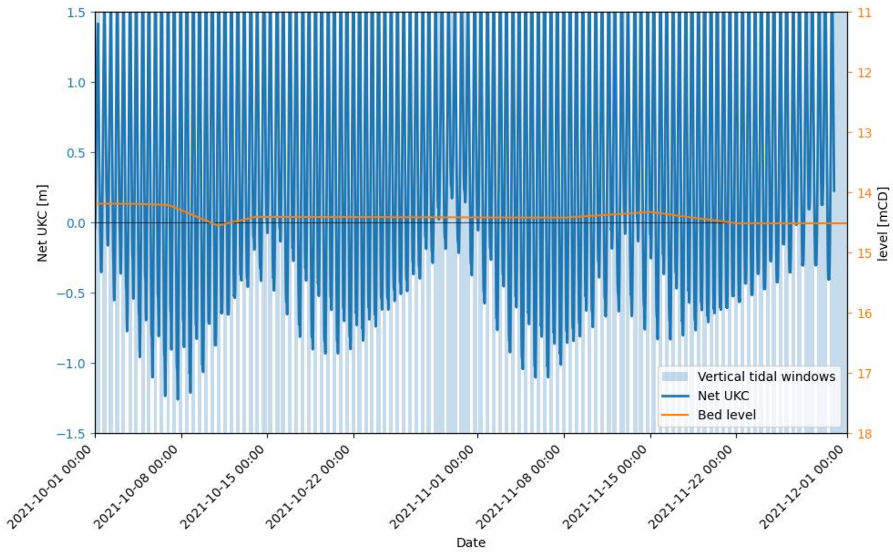

Figure B-35 Bed level, Under Keel Clearance and tidal window for location 40 single beam without meteorological influence

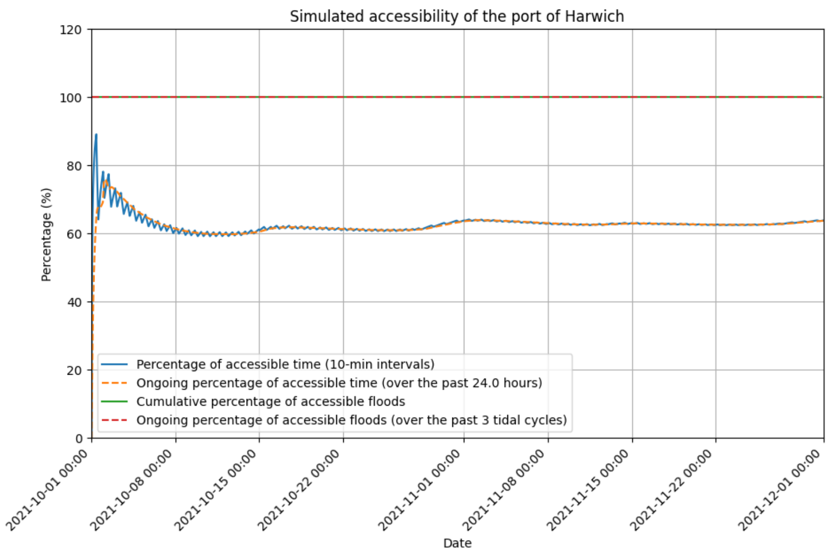

Figure B-36 Percentages of accessibility for bed profile of location 40 single beam without meteorological influence

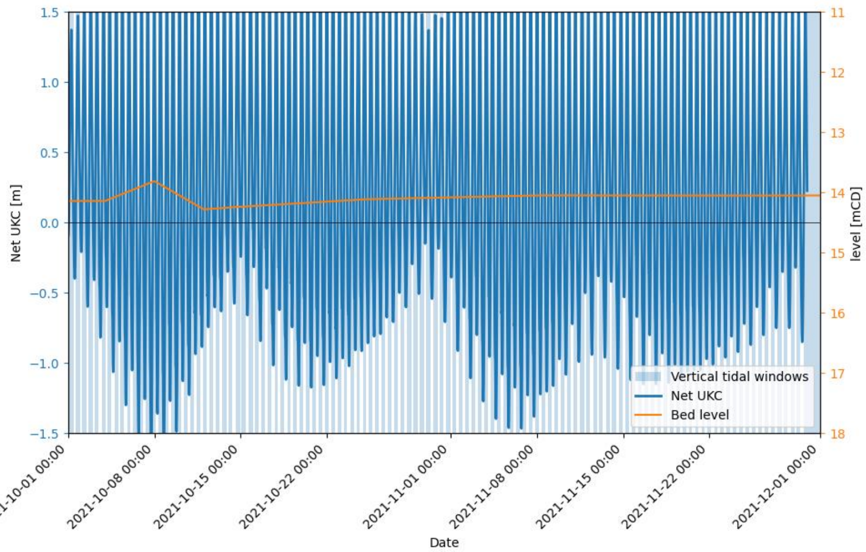

Figure B-37 Bed level, Under Keel Clearance and tidal window for bed profile of location 40 Rheotune without meteorological influence

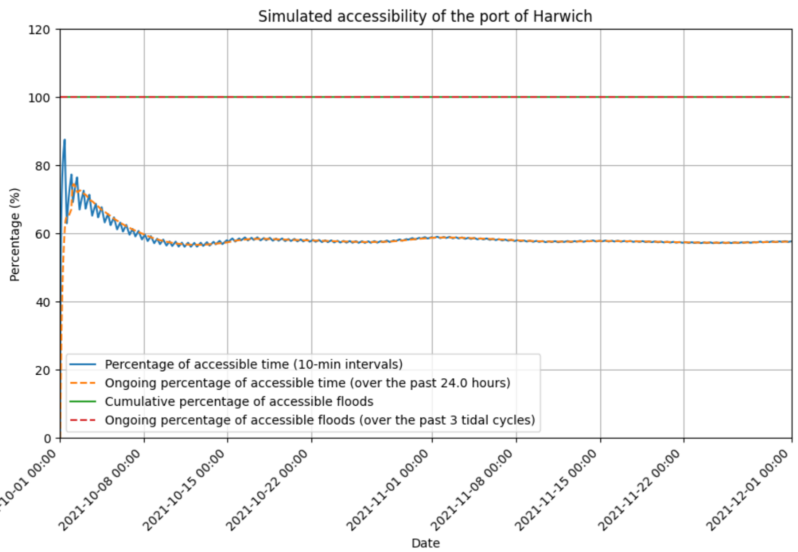

Figure B-38 Percentages of accessibility for bed profile of location 40 Rheotune without meteorological influence

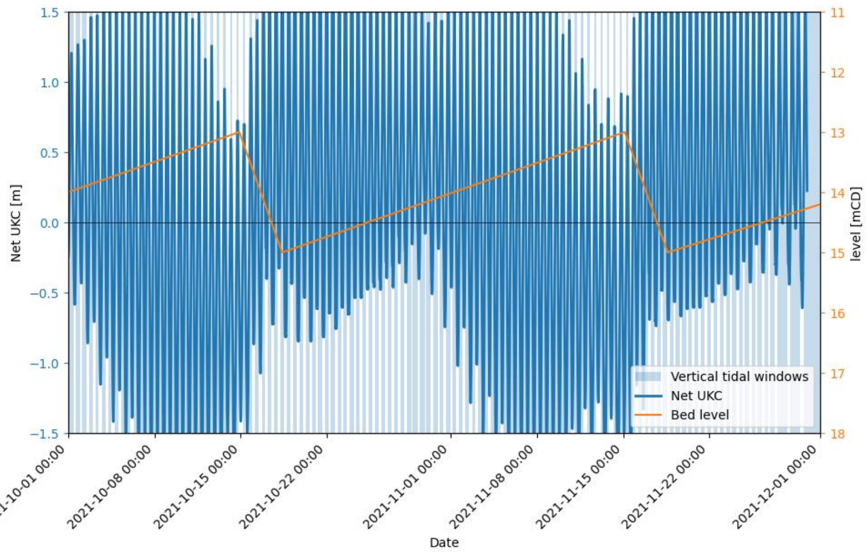

Figure B-39 Bed level, Under Keel Clearance and tidal window for a sawtooth bed profile without meteorological influence

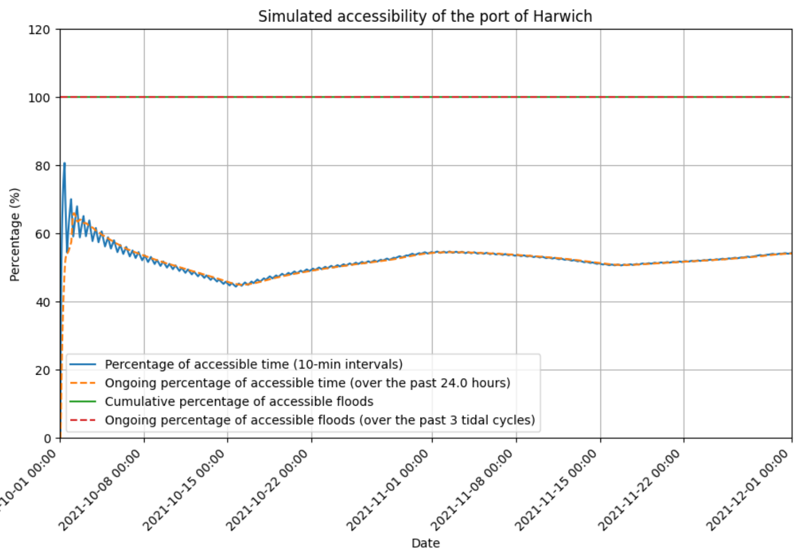

Figure B-40 Percentages of accessibility for a sawtooth bed profile without meteorological influence

C. Surveys 2022-2023

This appendix contains survey results of a maintenance dredging operation operated by Boskalis Westminster between 19th of December 2022 and 11th of January 2023. The first page contains the pre-dredge survey, the second page contains the post-dredge survey.