Potential benefits of standardisation of bed protections at waiting places at ship locks in the Netherlands

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by

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Executive summary

In the near future, Rijkswaterstaat has the task to replace or renovate a lot of ship locks. They are either at the end of their technical lifespan or no longer meet their current functional requirements. This offers the possibility of standardisation. The long-term project 'MultiWaterWerk' (EN: MultiWaterWork) focuses on the standardisation of lock components. This thesis contributes to this by researching the potential benefits of standardisation of bed protection design at waiting places of locks.

The desire for standardisation has arisen because of a lack of uniformity and clear design guidelines. Due to this, it is difficult to guarantee reliability and to estimate the building time and costs properly. Currently, the design of bed protection is based on empirical knowledge used to predict flow velocities and scour formation. The guidelines for designing bed protections are based on limited vessel configurations and bow thruster types. Consequently, designing bed protections with these guidelines can lead to both under and over-dimensioning of the bed protections. By standardising the design method, and thereby reducing mutual differences, costs can be saved and uncertainties can be reduced. Furthermore, better estimates of when maintenance is required can be done because data from similar locks allows for more reliable extrapolation. The research question of this thesis becomes:

What are the potential benefits of standardisation of the design of bed protections at waiting places of ship locks in the Netherlands?

This research focuses only on bed protections outside of the lock itself, at waiting places in the approach harbours. Furthermore, locks that are managed by parties other than Rijkswaterstaat, e.g. provinces, are not considered. Furthermore, this thesis is limited to ship locks for inland water transport; ship locks for sea-going vessels are not included. Lastly, this research only concerns the upper layer of the bed protection; the vertical composition and filter function is not taken into consideration.

First, a literature review was conducted to find which parameters are required to calculate the dimensions of a bed protection at a waiting place of an inland ship lock in the Netherlands. By researching Dutch guidelines, four categories of design parameters are identified:

- Ship dimensions: beam, and design draught
- Propeller characteristics for main and bow propeller: type, number of thrusters, used power, diameter, distance from propeller axis to the bed, and distance from propeller axis to the quay
- Hydraulic boundary conditions: design water depth
- Berth properties: berth type, slope angle, and bed material

Next, data on these design parameters were collected for all 99 waiting places where the most common bed protection is expected, which is riprap. Choosing only the most common bed protection type simplified the analysis on erosion. For approximately 60% of the waiting places where riprap is expected, data was available and acquired from RINK reports, see Figure 1.
Multibeam drawings were available as attachments to RINK reports and were used to acquire data on the state of the bed. At 15 waiting places, a riprap or gravel protection was found; at 18 waiting places, it was certain no bed protection is present. At the remaining waiting places, it cannot be said with full certainty whether there is a bed protection or not. However for the waiting places where the bed was discussed in RINK reports, the assumption was made that there are no protections, else they should have been mentioned there. For 81 out of the 99 waiting places where a riprap bed protection was expected, this expectation was inaccurate.

Next, the locks were compared methodically. To group similar bed protections together, a classification analysis was applied. To determine which waiting places fall in which class, each parameter is divided

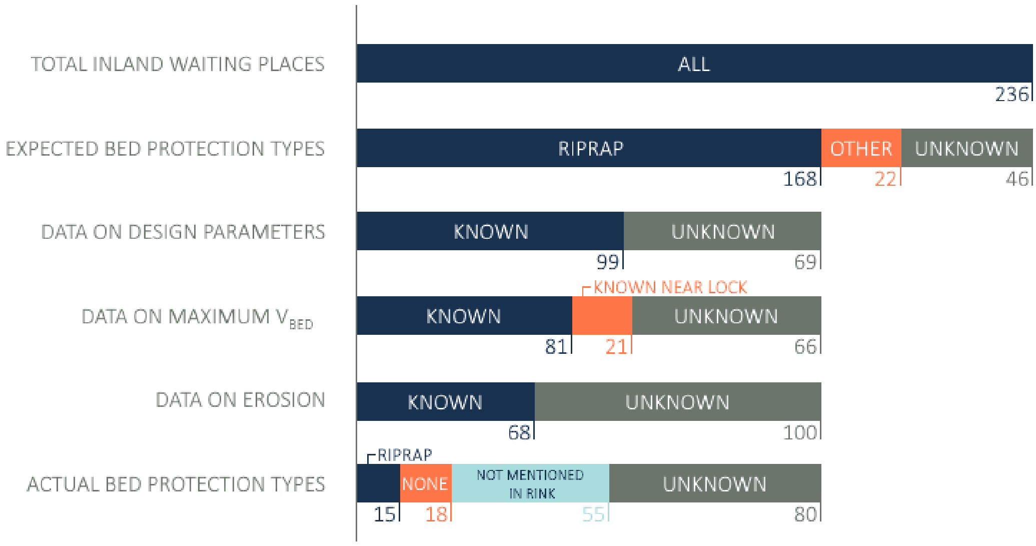


Figure 1: Overview of occurrence of bed protection types and availability of data for the most commonly expected bed protection type

into a number of ranges, k. When two waiting places fall into the same range for every parameter, they fall into the same class. Each range is assigned a letter, so that the class becomes a string of letters. Both the number of ranges and number of parameters included in the classification analysis were determined carefully. Using the formulas researched in the literature review, the design parameters listed above are condensed to three parameters: bed material, berth type, i.e. quay or piles, and maximum expected near-bed flow velocity. They were split up into the following ranges:

Table 1: Ranges per parameter used in the classification analysis

Bed material		**Berth type**		**Max V_{bed} [m/s]**	
Fine	F	Piles	P	0 - 1	A
Sand	S	Quay	Q	1 - 2.5	B
Gravel	G	Combination	C	2.5 - 4.5	C
Cobbles	C			> 4.5	D
10-60 kg rocks	R				

Classification of the whole dataset resulted in 19 different classes. There is too much variation in erosion and design vessels between all waiting places to find one standard solution for all of them. More similarities were found for waiting places in the same CEMT-class or corridor: in CEMT-class II and VI, similarities were found that show potential for standardisation of the design per CEMT-class. Waiting places in CEMT-class IV already have similar solutions for bed protections and might therefore be standardised. For waiting places of CEMT-class V, too much variation was found. Therefore, the waiting places of CEMT-class V were analysed per corridor. In these corridors, only waiting places in the Nederrijn-Lek corridor show enough similarities for standardisation to be beneficial. In the Meuse and Twente channels, the observed scour hole depths differ too much; so where bed protections are required, they should be optimised per waiting place. Other corridors contain so few waiting places that the effort for standardisation does not outweigh the potential benefits. The actual scour holes were not all in accordance with the expectation. Especially where larger velocities were expected, no larger scour holes were found. A reason for these anomalies could be that actual use deviates from the assumed use in the design, e.g. used power of thrusters. Actual loads on the beds could thus be similar.

For the groups with a low degree of variation - CEMT-class II, VI, and the Nederrijn-Lek corridor - no scour holes were observed that require protection. One standardised solution could be to allow these holes and not protect the bed. However, due to the number of uncertainties, there is a not insignificant chance that in waiting places where no data was acquired, larger scour holes have developed. Also in the Meuse, no large scour holes were found. However, the holes were found in protected beds, making it likely that at these waiting places higher bed-loads occur. Because the scour and assumed maximum near-bed flow velocities vary a lot between waiting places, the potential for standardisation in the Meuse is low. In the Twente channels, there is also too much variation in scour holes for standardisation to be beneficial.

For corridors and CEMT-classes with a good potential for standardisation, standardising the design assumptions concerning ship dimensions and propeller characteristics might be beneficial. A potential standard design vessel per corridor or CEMT-class can lead to a more reliable estimation of the expected scour at the waiting places. Furthermore, estimations for new bed protections at waiting places on lifetime, building duration and cost, and required maintenance will be more substantial because there are more reference projects to compare the new waiting places to.

The main recommendations are to store the data in a more structured and accessible manner, and to standardise ship dimensions and propeller characteristics per CEMT-class and corridor. If a standard were to be developed, it is interesting to review whether the observed scour holes are more in accordance with the new-found expected near-bed flow velocities than with the current expected near-bed flow velocities.

Nomenclature

α	slope angle
β_{cr}	coefficient including turbulence and frequency of load
Δ	relative density
ϕ	angle of internal friction
ϕ_{sc}	stability correction factor for the geometry of transitions
Ψ_{cr}	cricital Shileds stability parameter
ρ_s	rock density
ρ_w	density water
B_{cr}	critical stability coefficient of bed material
$B_{settling}$	width of settling strip
$C1$	coefficient depending on type of propeller
$C2$	coefficient to differentiate ducted from non-ducted propellers
C_L	lift factor
C_m	factor for rudder angle
D_p	propeller diameter
D_{50}	median diameter of particle
D_{85}	diameter of particle where 85% of total sample is smaller than this size particle
$D_{mattress}$	thickness of mattress
$D_{n,50}$	nominal median diameter of particle
f	percentage used power
g	gravitational acceleration
h_p	distance between propeller axis and bed
k_h	velocity profile factor
k_t	turbulence factor
k_{sl}	side slope factor
P_D	maximum installed power
S	depth scour hole
V_0	outflow velocity
$V_{b,max}$	maximum near-bed flow velocity
x_p	distance between outflow opening of bow thruster and quay wall

Contents

1

Introduction

1.1. Background

In the near future, Rijkswaterstaat has the task to replace or renovate a lot of ship locks. They are either at the end of their technical lifespan or no longer meet their current functional requirements. This offers the possibility of standardisation. The long-term project 'MultiWaterWerk' (EN: MultiWaterWork) focuses on the standardisation of lock components. This thesis contributes to this by researching the potential benefits of standardisation of bed protection design at waiting places of locks.

The desire for standardisation has arisen because of a lack of uniformity and clear design guidelines. Due to this, it is difficult to guarantee reliability and to estimate the building time and costs properly. Currently, the design of bed protection is based on empirical knowledge used to predict flow velocities and scour formation. In the PIANC (2015) guidelines, the state-of-the-art knowledge of the damaging effects of propeller jets on the bed is summarised. Also, PIANC (2015) presents two methods, Dutch and German, for the design of bed protections. The German method is based on research by Fuehrer et al. (1981) and Schmidt (1998), whereas the Dutch method is based on research by Blaauw and van de Kaa (1987), Verweij (1983), and Blokland and Smedes (1996). In both design methods, decisions and assumptions need to be made, e.g. the used power of vessels can vary, but one value should be taken as the governing value. With the current guidelines, it is possible that for two identical locks, different bed protections are designed because different assumptions were made for the design parameters.

Furthermore, the guidelines are based on limited vessel configurations and bow thruster types. Consequently, designing bed protections with these guidelines can lead to both under and over-dimensioning of bed protections. By standardising the design method, and thereby reducing mutual differences, costs can be saved and uncertainties can be reduced. Furthermore, better estimates of when maintenance is required can be done because data from similar locks allows for more reliable extrapolation. Standardisation must also lead to achieving Rijkswaterstaats sustainability goals (Van der Vorm, 2021). Standards have a major role in influencing the design of products and processes, where sustainability requirements can be established in the standard.

Bed protections are placed to prevent a quay wall or other structures from collapsing. When a ship cannot enter the lock immediately, she will have to wait in a mooring area before she can sail away. During these berthing and deberthing manoeuvres, bow thrusters and main propellers are used that exert a significant hydraulic load on the bed. The jet from the bow thruster is reflected on the quay wall towards the bottom; the jet from the main propeller hits the bed directly (PIANC, 2015). When soil is transported by the jets without replenishments, scour holes are created. When these extend towards the base of a structure, the structure may collapse as shown in Figure 1.1. By constructing a protection to cover the bed that is able to resist the hydraulic loads, both the bed and the structure are protected. Bed protections come in many shapes and sizes. They can be made from rock, concrete, asphalt, or a combination (CIRIA et al., 2007). Usually, a design for a bed protection is made per individual ship lock. The fact that current design rules can lead to different solutions for the same problem, has led to many different bed protections. This thesis aims to determine whether there are potential benefits if the design was standardised. This is done by researching how the existing bed protections have performed and how they were designed. In the present study, such an assessment is carried out on network level for the first time.

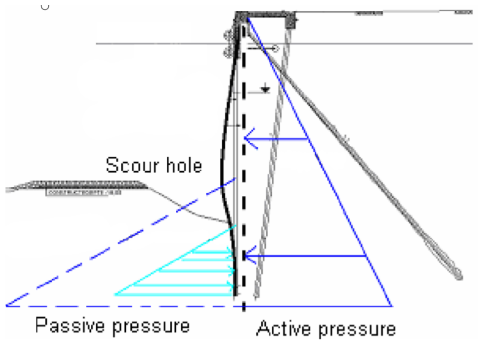


Figure 1.1: Collapse of a quay wall after a scour hole is created, adapted from Roubos and Verhagen (2007)

Ship locks and their bed protections have a long design lifespan, oftentimes one hundred years (Vrijburcht, 2000). Because of increasing ship sizes and growing attention for sustainability, locks do not meet the current requirements. Larger ships with larger thruster capacity and lower underkeel clearances may berth at waiting areas (Roubos & Verhagen, 2007). This results in higher loads on the bed protection, which has led to more research into the flow characteristics. For example, Tukker (2021) and Deltares (Van der Vorm, 2021) are researching the decrease of the flow velocity from a bow thruster, which appears to decrease faster than is described in current guidelines. In the Netherlands, a committee dedicated to optimising the design of bed protections, the CROW-propeller jet group, does extensive research to update the guidelines accordingly (Van der Vorm, 2021). Rijkswaterstaat is also a partner of this group and so the present thesis is also connected. From a sustainability perspective, bed protections should use as little material as possible and preferably the most sustainable materials. In the Netherlands, the sustainability of a protection is oftentimes represented with the Environmental Cost Indicator (ECI) (Prinssen et al., 2019). Riprap protections have the lowest ECI value and are therefore preferred from a sustainability perspective (Schipper et al., 2021).
Not only Rijkswaterstaat has expressed interest in standardising bed protections. The Port of Rotterdam has similar goals and has developed her own methodology to design bed protections, where a lot of attention is paid toward flexibilisation. The port mostly uses riprap protections, penetrated with colloidal concrete, but is also experimenting with making deeper quay walls without bed protections. (Blokland et al., 2018)

Moreover, Germany has encountered a similar challenge: the condition of the locks is becoming more and more critical due to age and usage and technical reports have shown that almost all locks are due for a complete overhaul or even a replacement. The Federal Waterways and Shipping Administration (WSV) claims that standardisation of hydraulic structures is a necessary step for the maintenance and operation of the infrastructure, especially in times of limited budgets and (human) resources. Because of the increasing complexity due to multi-layered requirements and lack of personnel, they urge that standardisation and improvement of equipment (eg. with IT infrastructure or software) is necessary. Therefore, the possibilities of standardisation of a lock component will be discussed in the current study. (Wacholz, 2015)

1.2. Research questions and approach

The objective of this report is to investigate resemblances between waiting places with regard to physical properties and design parameters to gain insights into the potential benefits of standardisation of bed protections at waiting places at ship locks in the Netherlands. By standardising the design approach, cost, construction time, and reliability estimates become more predictable. The objective of this research can be summarised by asking the question:

What are the potential benefits of standardisation of the design of bed protections at waiting places of ship locks in the Netherlands?

To arrive at the answer to the main question, 3 sub-questions will be answered in this report. The first sub-question revolves around the design of the bed protections. A literature review is conducted to find which parameters influence the dimensions of the bed protections at waiting places in front of locks and which guidelines should be followed to determine those dimensions. The accompanying research question is defined as:

Which data are required to design bed protections at waiting places in the Netherlands?

The literature review will result in an overview of the parameters that are required to design a bed protection at a waiting place. The next step is to find information on the waiting places. Only the bed protections, where the most common material is expected, are researched to simplify the analysis on erosion. With the collected data, it can be determined whether the expected bed protections are present. The question is threefold:

a) What types of bed protections are expected in the approach harbours of inland ship locks in the Netherlands and which type is most common?

b) For this most common type, what data are available and how can they be collected?

c) For this most common type, what is the state of each bed and are the expected bed protections present?

The next step is to compare the waiting places of which data are collected. By researching the variation between waiting places and whether the actual erosion is in accordance with literature, the potential of standardisation can be estimated. If there is little variation in design parameters and the actual erosion is as expected or similar, the potential benefits of standardisation would be high. If the waiting places vary too much, there are fewer benefits. The number of parameters that are required to calculate a bed protection is high, which makes the comparison between the protections difficult. Therefore, the design parameters are condensed into three: material of upper layer of the bed, berth type (piles or quay wall), and maximum near-bed flow velocity. A classification analysis is done to group similar waiting places together and methodically compare the waiting places. The accompanying sub-question is:

Can similarities between the bed protections be found regarding the design of bed protections at waiting places that show potential for standardisation?

Next to the three parameters, erosion data is used to compare the waiting places. The comparison is done per size waterway and per corridor (= shipping route) to find similarities indicating that standardisation might be possible. For waiting places on one corridor, it is expected that similar design vessels are used and that the design parameters are thus also similar. For waiting places in the same size waterway, also similar design vessels are expected. Many similarities between waiting places are an indication that standardisation of these bed protections is beneficial. If significant variations in the state of each bed and expected load are found, it is more beneficial to optimise the bed protection per waiting place.

1.3. Scope

This research will focus only on bed protections outside of the lock itself, at waiting places in the approach harbours. Figure 1.2 shows the layout of an approach harbour. When the traffic is two-way, the layout is symmetrical on the other side of the lock. Of each ship lock, both the upstream and downstream sides will be taken into consideration. Rijkswaterstaat manages 89 lock complexes in the Netherlands. Other locks are managed by for example provinces and are not considered. Furthermore, this thesis is limited to ship locks for inland water transport; ship locks for sea-going vessels are not included. The location and number of waiting places of the lock complexes are shown in Figure 1.3. The total number of waiting places is 236. There are 68 inland lock complexes with at least one waiting place. Lastly, this research only concerns the upper layer of the bed protection; the vertical composition and filter function is not taken into consideration.

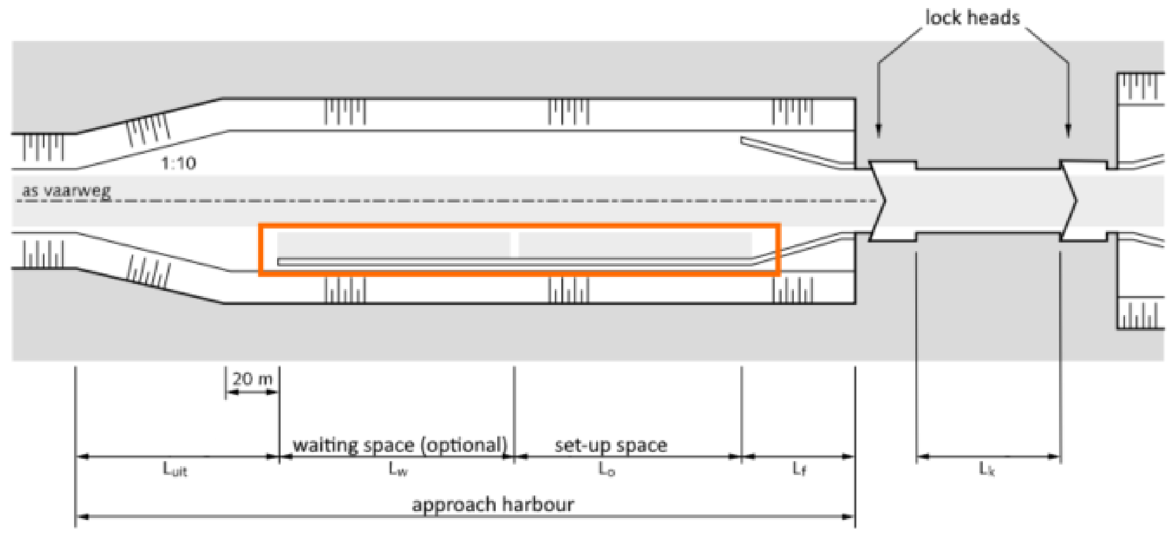


Figure 1.2: Schematical drawing of a lock with approach harbour. Together, the waiting space and set-up space, which are framed, form the waiting places and are thus the area of interest, adapted from (RWS WVL, 2020)

1.4. Structure of the report

After this introduction, the result of an extensive literature research is represented in the second Chapter. This literature research summarises the current guidelines and methods to design bed protections at waiting places in the Netherlands. In the third Chapter, data are collected to obtain an overview of the current bed protections and the availability of the data. Chapter 4 then explains how the waiting places can be compared to obtain insights into the potential benefits of standardisation. In Chapter 5, the results of the comparison are discussed. Chapter 6 gives a discussion on the research that is done and in Chapter 7 a conclusion is given. Also the recommendations for further research are presented in Chapter 7.

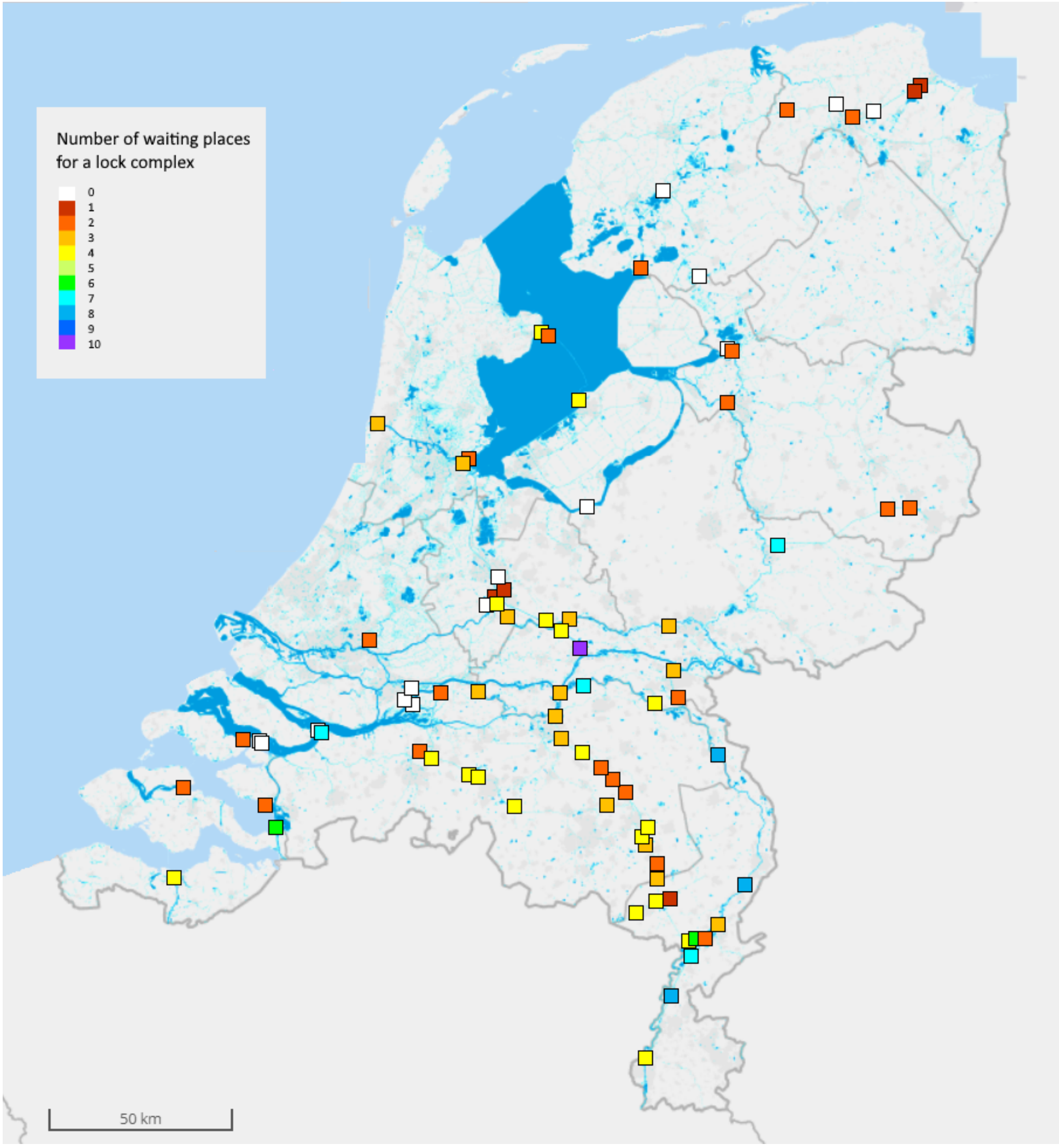


Figure 1.3: Locations and number of waiting places of (non-sea) lock complexes in the Netherlands that are managed by Rijkswaterstaat, adapted from Planbureau voor de Leefomgeving (2022)

2
Design of bed protections at waiting places

This Chapter will explain how a bed protection at a waiting place is designed. The different loads that a bed protection at a waiting place should be able to resist will be discussed, as well as the methods to calculate the governing loads. Furthermore, the relation between the expected load and both the expected scour depth and required dimensions of a bed protection are discussed. The first subquestion will thus be answered: which data are required to design bed protections at waiting places in the Netherlands?

2.1. Loads

A bed protection is necessary when the hydrodynamic forces on the bed are too big and a scour hole forms that threatens the stability of the quay wall or embankment. The critical failure modes of rip-rap protections are initiation of motion and deformation caused by hydrodynamic forces (Pilarczyk, 1995). If ships that are almost stationary manoeuvre with a lot of power in shallow water near vertical structures, e.g. at a waiting place, a bed protection may be necessary (Dienst Weg- en Waterbouwkunde, 2000). This Section discusses the loads acting on a bed protection in a waiting place.

- During levelling of the lock, the water flows through openings in the door of the lock or via special drains in the walls (Vrijburcht, 2000). Levelling causes a translatory wave or surge through the canal (Battjes & Labeur, 2017). Upstream of the lock, high flow velocities only occur right in front of the openings through where the water is extracted to fill the lock. The only high near-bed flow velocities occur downstream of the door openings and diminish quickly. At around seven times the downstream water depth, usually no significant velocities are found (Vrijburcht, 2000).

- When water needs to be sluiced through the lock, the doors are (partly) opened. This usually does not lead to significant flow velocities near the bed in the approach harbour because the flow disperses quickly (Vrijburcht, 2000). Ships are not allowed to pass through at this moment.

- When a ship navigates in a waterway, it is accompanied by a return current next to and below the ship which is opposite to the ship's direction (Elsherbiny et al., 2019). The return current increases for a higher blockage of the wet cross-section of the channel and higher navigation speed (Robijns, 2014). During berthing and deberthing the speed of a ship is almost zero. The flow rate at the bed as a result of the return flow is in most cases not decisive, unless the blockage of the waterway is extremely big; typical rates for return flows vary from 0.1 to 1.0 m/s (Dienst Weg- en Waterbouwkunde, 2000).

- Propeller jets are used to manoeuvre the ship during berthing and deberthing manoeuvres. Nowadays, vessels usually have both bow thrusters and a main propeller. Ships are only getting larger and larger and as a consequence, they use more powerful propellers to manoeuvre (Roubos & Verhagen, 2007). The near-bed velocities can reach up to 8 m/s (Verheij et al., 2010).

- Sometimes tug boats are necessary to manoeuvre a vessel into the lock chamber (Vergote et al., 2013). In order to obtain sufficient towing force, tug boats are usually equipped with high-powered engines which can lead to high near-bed flow velocities (Park et al., 2012). Tugs are however used predominantly for sea-going vessels and are not common for inland water vessels. Due to this, the hydraulic force caused by tug boats is not taken into consideration further on.
- Wind waves and primary or secondary waves can occur at a waiting place. However, neither lead to significant near-bed flow velocities (Vrijburcht, 2000).
- For impermeable types of bed protections, the suction load by the propeller should be considered as well (Hawkswood et al., 2014). The increase in water velocity results in an upward force on the bed (PIANC, 2015).

Figure 2.1 shows how the different loads act on different parts of the bed protection, implying that the loads should not be superposed. The bed protection should however always be dimensioned for the maximum load. The current thesis will only elaborate further upon the loads caused by the main propeller and bow thrusters, because these are the governing loads at waiting places. Section 2.2 explains the calculation of the near-bed flow velocities caused by these loads.

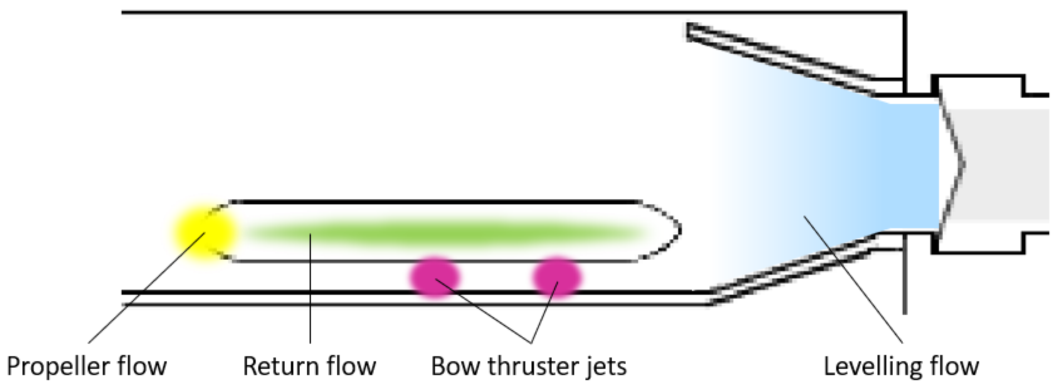


Figure 2.1: Locations of different types of loads acting on the bed protection for a ship with two bow thrusters

2.2. Calculation of flow velocity at bed

In the Netherlands, several guidelines and standards apply to the design of bed protections. In the Guidelines for Hydraulic Design (ROW), an overview of all guidelines and norms that should be used for the design of a riprap bed protection is given (RWS GPO, 2020). This document is updated regularly and is written to ensure continuity and provide clarity on more general guidelines. Where guidelines are contradicting each other, it states that the most current guideline should be followed. Important guidelines such as the PIANC report on scour caused by ships, the lock design manual, and the rock manual are mentioned here repeatedly. The guidelines for calculating the near-bed flow velocity described in this Section are up to date with the ROW of 2020.

2.2.1. Main propulsion system

The governing load can be caused by a circular jet from the main propulsion system. As shown in Figure 2.2, the flow is only confined by the bed. The flow velocity decreases as the propeller is further away from the ground due to dispersion and friction. The maximum flow velocity at the bed occurs for $h_p/x = 0.18$ (Verweij, 1983). Blaauw and van de Kaa (1987) and Verweij (1983) derived certain values that yielded equations for the flow velocity along the propeller axis and the flow distribution (PIANC, 2015). The equation for the resulting near-bed velocity is given in Equation 2.1. A scour hole can develop where the jet hits the bed. Figure 2.3 shows where the scour hole from the main propeller is located compared to the scour hole caused by a bow thruster.

$$V_{b,\max} = C2 \cdot V_0 \cdot \frac{D_p}{h_p} \tag{2.1}$$

Where:

V_0 = outflow velocity [m/s]
D_p = propeller diameter [m]
h_p = distance between propeller axis and bed [m]
C2 = coefficient to differentiate ducted from non-ducted propellers
0.216 for non-ducted propellers and 0.306 for ducted propellers

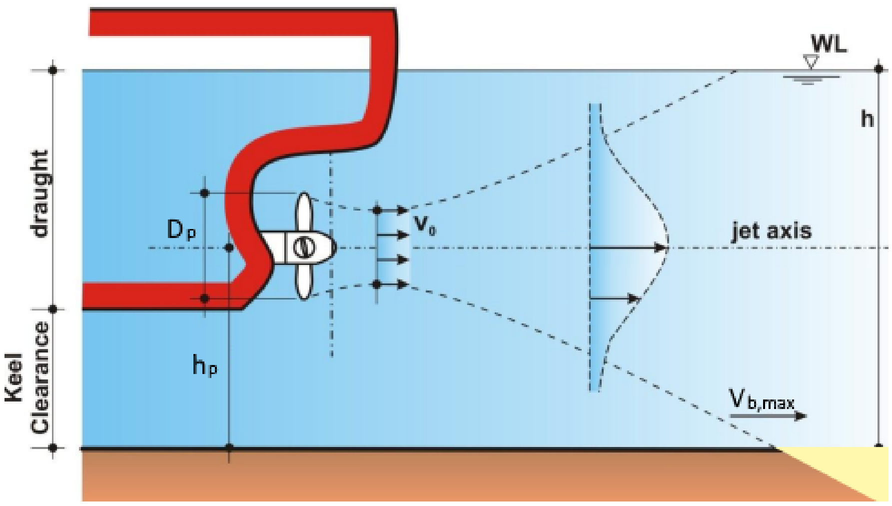


Figure 2.2: Scour of bed by main propulsion system (adapted from PIANC (2015))

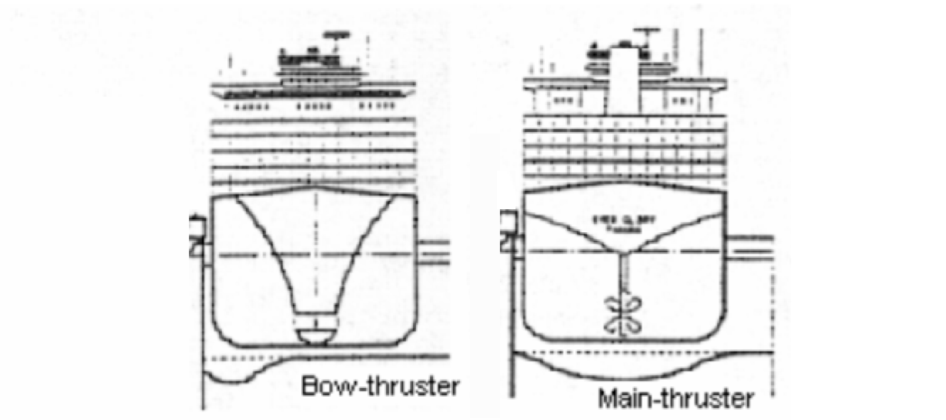


Figure 2.3: Location of scour from bow thruster (left) and main propeller (right) (Roubos & Verhagen, 2007)

2.2.2. Bow thruster

The Dutch method to determine the actual near-bed velocity caused by bow thrusters is based on research by Blaauw and van de Kaa (1987), Verweij (1983), Blokland and Smedes (1996) and Blokland (1997). The formulas for the maximum near-bed velocity caused by bow thrusters reflecting on a vertical wall are given in Equations 2.2 and 2.3. A horizontal jet propagates and expands towards the quay wall and is reflected towards both the bed and the surface, see Figure 2.4. At the bed, the flow is then diverted towards the ship again. Because the velocity is ever-decreasing during its propagation due to friction and dispersion, the maximum near-bed velocities are found at the intersection of the bed and quay wall. This relation is also expressed in Equation 2.3. The maximum flow velocity near the bed is defined as the time-averaged maximum horizontal flow velocity consisting of an x- and y-component (PIANC, 2015).

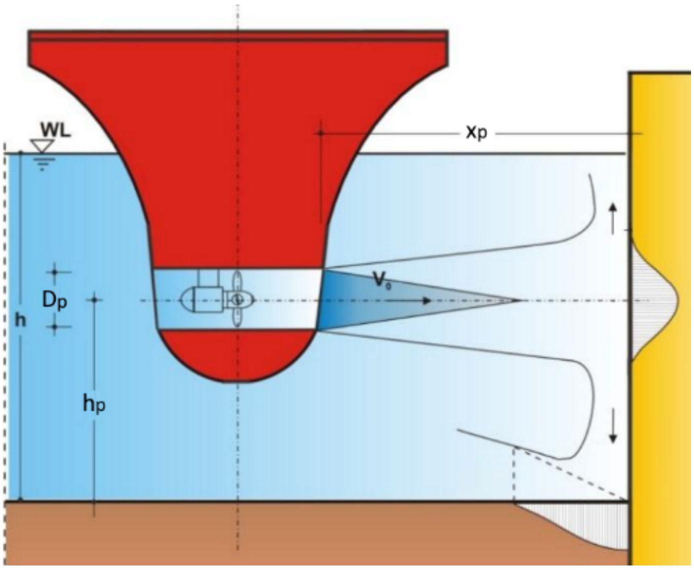


Figure 2.4: Scour of bed by bow thruster when sailing away in order to enter the lock, adapted from PIANC (2015)

$$V_{b,max} = 1.0 * V_0 * \frac{D_p}{h_p} \qquad if \quad \frac{x_p}{h_p} < 1.8 \tag{2.2}$$

$$V_{b,max} = 2.8 * V_0 * \frac{D_p}{x_p + h_p} \qquad if \quad \frac{x_p}{h_p} \geq 1.8 \tag{2.3}$$

Where:

V_0	=	outflow velocity [m/s]
D_p	=	diameter outlet bow thruster [m]
h_p	=	distance between axis thruster and bed [m]
x_p	=	distance between outflow opening and quay wall [m]

For a sloping bank, equations derived by Blokland should be used to calculate the flow velocity (PIANC, 2015). The smaller the angle, the larger the distance between the thruster and bank. More dispersion has taken place before the flow hits the slope, thus the resulting near-bed flow velocity and scour depth will be smaller, see Figure 2.5.

Outflow velocity

In the calculations of the near-bed velocities of both types of propellers, a dependence on the outflow velocity V_0 is noticed. The outflow velocity is dependent on, among other factors, the power P_D of the ship, as illustrated in Equation 2.4 (BAW, 2010).

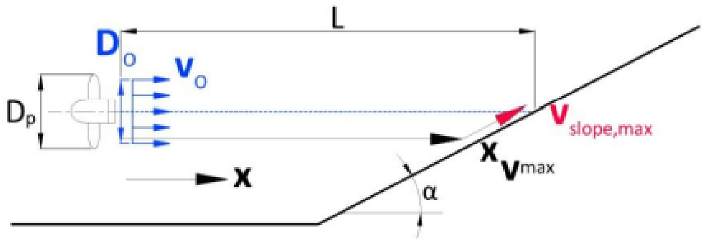


Figure 2.5: Transverse thruster jet above a slope (PIANC, 2015)

$$V_0 = C1\left(\frac{f \cdot P_D}{\rho_w D_p^2}\right)^{0.33} \tag{2.4}$$

Where:

C1	=	coefficient depending on type of propeller
P_D	=	maximum installed power [W]
f	=	percentage actual used power [-]
ρ_w	=	density water [kg/m^3]

Several values have been found for C1: according to the Rock Manual, C1 should equal 1.15 (CIRIA et al., 2007); Blokland (1997) has found a value of 1.17 and incorporates a factor f, which is usually not known and oftentimes neglected because it ranges from 1.02 to 1.05 (PIANC, 2015); PIANC (2015) uses the value of 1.17 for ducted propellers and 1.48 for non-ducted propellers.

Verheij (2010) found relations for the installed power of bow thrusters of different ship types and the main propeller. The relationships he found apply to the average values of the dimensions of a ship. Individual ships however might have considerably different dimensions.

Flow around a pile

When the ship uses its thrusters in the vicinity of piles, Equation 2.5 should be applied. In front of the pier is a downflow, which acts like a vertical jet, similar to a jet against a quay wall. Together with the accelerated flow at the sides of the pier, this jet causes erosion, see Figure 2.6 (Schiereck, 2019). In general, the flow velocity directly next to the pile is approximately twice the approach velocity (Breusers et al., 1977). Subsequently, the depth of the scour hole is also twice as (PIANC, 2015). It should be noted that this relation is based on the assumption that the flow direction of the bow thrusters is perpendicular to the pile structure. The average distance between the centre of berthing piles is 22 m (Vrijburcht, 2000). This distance is so large that the piles have no influence on each other (PIANC, 2015).

$$\mathrm{V_{pile}} \approx 2^* \, \mathrm{V_{approach}} \tag{2.5}$$

2.3. Berth types

As stated in the previous Section, the presence of piles influences the magnitude of the near-bed velocity. Whether piles are present depends on the berth type. Worldwide, there are many berth types. The choice between them depends on characteristics of the design vessel, material availability, geotechnical conditions, etc. According to Verheij et al. (2010), berth structures can be characterised in two main groups according to their relevance for the impact of both types of propellers, solid berth

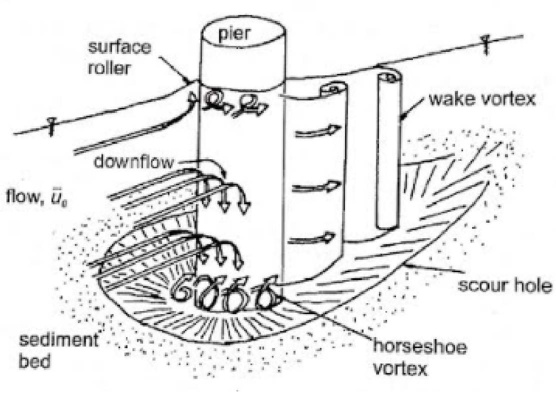


Figure 2.6: Scour along a pile (Breusers & Raudkivi, 1991)

structures and open berth structures. A vertical closed quay wall is a typical example of a solid berth structure, see Figure 2.7, whereas an open berth structure at a waiting place is characterised by piles, see Figure 2.8. It should be noted that although Figure 2.8 shows a sloped bank, in many canals and approach harbours the ground is retained by for example sheet piles. The berthing piles are then placed at some distance from the bank.

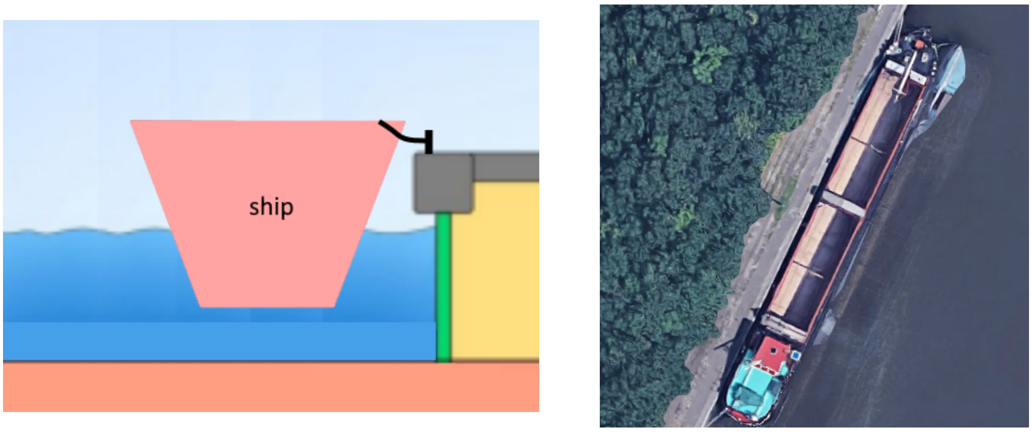


Figure 2.7: Side (left) and top (right) view of a ship berthed at a quay wall (Google, 2022b)

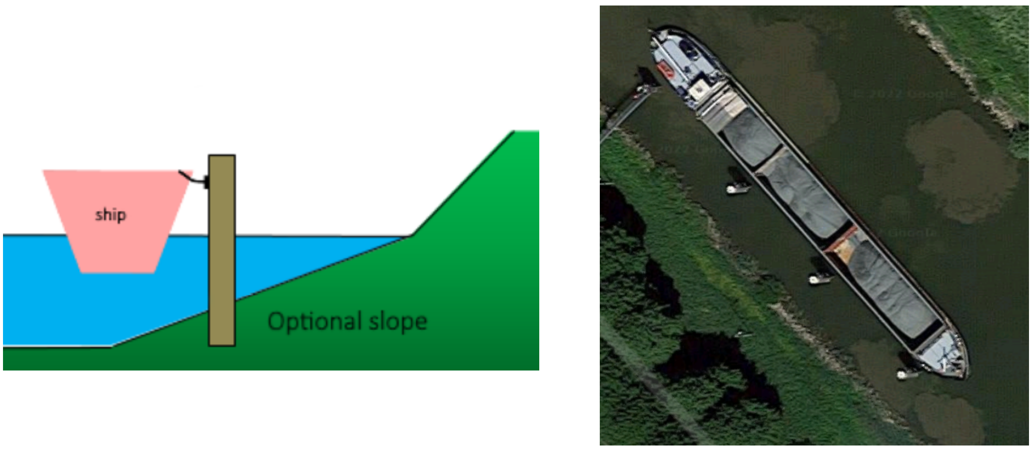


Figure 2.8: Side (left) and top (right) view of a ship berthed at piles (Google, 2022a)

2.4. Scour of bed

A scour hole develops when more particles are moved away from the bed than are settling. The flow velocities induced by a propeller may cause scour if they are higher than the threshold value, or critical velocity, of the bed material. When these holes extend towards the base of a structure, the structure may collapse. Sediment transport is a function of velocity and sediment properties. First of all, the threshold value for movement of a particle depends on the particle size. A larger and heavier particle, such as a rock, is harder to move than a sand particle and has a lower settling velocity (Bosboom & Stive, 2015). For clay in turbulent flow, a critical, or threshold value of 0.25 - 1 m/s should be assumed (PIANC, 2015). PIANC (2015) describes methods to estimate the scour depth for the specific cases of scour due to propellers. For non-cohesive soils, Römisch (2006) derived Equations 2.6 and 2.7 to determine the depth of the scour hole by a bow thruster in front of a closed quay wall. For scour by the main propeller, Römisch and Schmidt (2012) also derived similar equations. All the formulas are derived empirically and contain some degree of uncertainty. For a main propeller, the length of a scour hole is approximately 5 to 7 times the depth (Schiereck, 2019), see Figure 2.9.

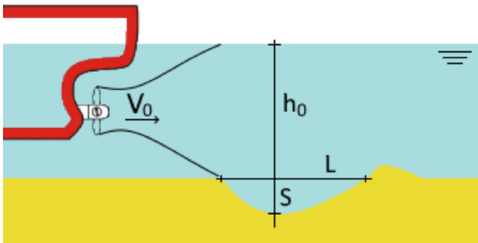


Figure 2.9: Scour due to a horizontal propeller

$$1^{\text{st}} \text{ phase: } \frac{S}{D_{85}} = C_m 0.1 \left(\frac{B}{B_{cr}}\right)^{13} \quad \text{for} \quad 1.0 \leq \frac{B}{B_{cr}} \leq 1.4 \tag{2.6}$$

$$2^{\text{nd}} \text{ phase: } \frac{S}{D_{85}} = C_m 4.6 \left(\frac{B}{B_{cr}}\right)^{2.25} \quad \text{for} \quad \frac{B}{B_{cr}} \geq 1.4 \tag{2.7}$$

$$B = \frac{V_{\text{b,max}}}{\sqrt{D_{85} g \Delta}}$$

Where:

S	=	depth of scour hole [m]
D_{85}	=	diameter of particle where 85% of total sample is smaller than this size particle [m]
C_m	=	factor for rudder angle = 0.44
B_{cr}	=	critical stability coefficient of bed material = 1.2

When inspecting a bed protection at a waiting place, Rijkswaterstaat orders a multibeam drawing to detect whether there are scour holes and what risk they pose. A multibeam drawing shows the contour lines of the bed with respective depths. A deep scour hole close to the bank poses a bigger threat than a shallow hole in the middle of the waterway. After the inspection is conducted, the expected scour depth is compared to the actual scour from the multibeam drawing to see whether there are unexpected irregularities. If very large scour holes were found where none were expected, it is an indication the calculation was not done right or that actual use deviates from the expected use. Otherwise, if no scour holes were found where large ones were expected, the calculation might have been done too conservatively. Scour holes with a depth ranging from -0.15 to +0.15 m are also regarded as stable because the dredging tolerance of waterways up to 5 m depths is 0.15 m (RWS GPO, 2020).

2.4.1. Erosion of common bed protection types

Riprap

An individual stone should be able to resist all hydraulic loads as mentioned in Section 2.1. If stones from the upper armour layer are moved, a scour hole can be created that threatens the stability of the wall or the geotextile will become exposed (PIANC, 2015). To calculate the necessary stone size, the Dutch propose the use of two stability formulas: Izbash and Pilarczyk (RWS GPO, 2020). In the Izbash approach, the forces on an individual grain are considered and a balance in forces is found. The balance of forces is illustrated in Figure 2.10. This approach is most fitting for larger rocks. For smaller grains, such as sand, it is advised to use the Shields approach (Schiereck, 2019). When the active forces, caused by the flow, become larger than the passive forces, for example gravity, the balance is lost and the grain starts to move. (Pilarczyk, 1995) uses the same principle, but takes into account more factors, which is further explained in Section 2.5.3.

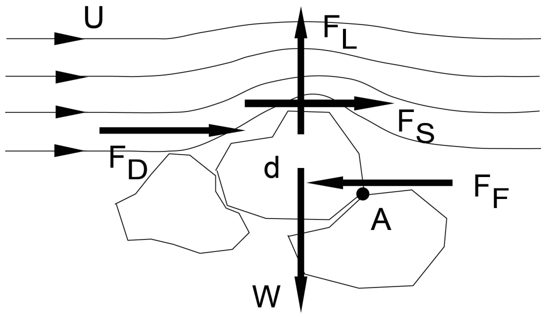


Figure 2.10: Schematic of forces on a grain by flow (Schiereck, 2019)

Composite mattresses

When large areas need to be protected, placing loose rock protections can become time-consuming and expensive. Alternatively, concrete mattresses can be used, usually constructed upon a geotextile (Schiereck, 2019). The blocks in these mattresses interlock, depending on the specific type of block. Because the blocks interlock, initial movement will occur only at higher flow velocities. First, the whole mattress will be lifted, before one block becomes loose. However, after one block has left the mattress, many blocks will follow because they lost the strength from interlocking. Also when the soil is washed away from under the mattress, the protection can fail. In Figure 2.11, a failed concrete mattress is shown, where it can be seen how large chunks of the mattress broke off after the underlying soil was washed away. Figure 2.12 also shows a mattress that has fallen apart due to instability.

Figure 2.11: Failed concrete lining (Heibaum & Trentmann, 2010)

Figure 2.12: Failure of concrete mattress (Pilarczyk & Klein Breteler, n.d.)

2.5. Calculation of dimensions of bed protection

When the critical velocity is reached, a scour hole can develop that may threaten the structural integrity of the bank. A bed protection might be necessary to prevent this. According to research by Blokland et al. (2018), from an economical perspective, bed protections should be placed only when holes deeper than 1.8 m are expected near the quay or a structure. This Section will briefly explain how the dimensions of a bed protection are determined. Where the design rules for width and length are the same for all types of bed protections, the rules for thickness differ per type. The most common types will be discussed in this Section.

2.5.1. Width

The width of the bed protection should be such that during the design life of the quay wall, no soil is lost from the passive soil wedge (RWS GPO, 2020). PIANC (2015), prescribes an equation to use to calculate the minimum required width of the protection. This equation includes an extra five meters, which is based on experience and to assure the geotechnical stability of the quay wall. The Port of Rotterdam offers a similar approach, where the total width should equal the sum of the width of the passive soil wedge and the settling strip, see Figure 2.13 (Blokland et al., 2018). Next to the bed protection, erosion can occur so that a scour hole develops. The settling strip is a strip of loose rock that will fall into the scour hole so that no soil is lost from the passive soil wedge. The width of this strip is dependent on the expected maximum depth of the scour hole. In the Port of Rotterdam, a value of 5 meters is usually assumed for $B_{settling}$. Usually, the size of the passive soil wedge is known.

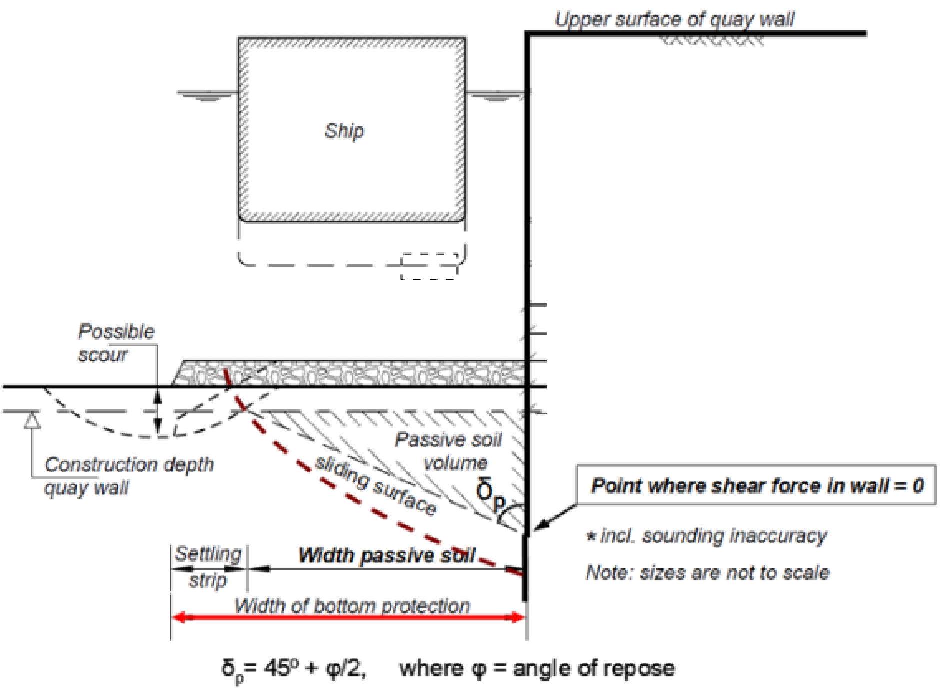


Figure 2.13: Passive soil wedge and width of the bed protection, adapted from Tipton and Krause (2013)

2.5.2. Length

According to Blokland (1997), the length of the bed protection along the quay wall should be at least be one ship's length plus fifty meters both in front of the bow and behind the stern. The exact length however depends on the berthing procedures. As can be seen in Figure 1.2, it is possible that there is both a set-up space and a waiting space. In that case, the bed protection will have to be longer to accommodate more ships. The same design rules apply.

2.5.3. Thickness

Riprap

A riprap protection consists of loose rocks that protect the bottom against scour. The armour stones in the upper layer are usually of significant size, e.g. 10-60 kg with a median nominal diameter $D_{n,50}$ of 23 cm (RWS GPO, 2020). In comparison, sand has a median diameter of 0.06 to 2.0mm. If the armour stones would be placed directly on the sand, the sand would still easily be washed away through the openings between the rocks. To prevent this, a filter layer should be in between the layers. There are several ways to construct a filter layer, of which three are discussed here. First, a granular filter is built from different layers with different size stones. From low to high the stones go from small to large so that smaller stones are blocked from moving upwards. A second possibility is a geotextile, which is a piece of cloth, originally reed, that has openings that are so small that sand cannot pass through, but water can. And lastly, concrete can be used to penetrate the stones. When a 'full and saturated' penetration is applied, no grains can escape.

The individual stone size is determined by finding the critical velocity at which a grain starts to move. The velocity in Equation 2.8 is the velocity acting on the stone defined by Izbash, but there is no definition of where on the stone. The flow is assumed to be turbulent and non-uniform (Izbash, 1932). Furthermore, in the original equation, it is not very clear how the diameter of the stone is defined. However, the ROW offers clarity by assuming the diameter to equal the median diameter D_{50} (RWS GPO, 2020).

$$D_{50} > \frac{1}{k_{sl}} \cdot \beta_{cr} \cdot \frac{V_{b,max}^2}{2g\Delta} \tag{2.8}$$

$$k_{sl} = \sqrt{1 - \left(\frac{\sin\alpha}{\sin\phi}\right)^2} \tag{2.9}$$

k_{sl}	=	side slope factor [-]
g	=	gravitational acceleration [m/s^2]
Δ	=	relative density = $\frac{\rho_s - \rho_w}{\rho_w}$ [-]
α	=	slope angle [°]
ϕ	=	angle of internal friction [°]

The value of β_{cr} depends on the frequency of the load caused by the propeller or jet: 2.5 for infrequent use and 3.0 for frequent use at one location, for example at a quay wall (Blokland & Smedes, 1996) (CUR, 1997). This value of β_{cr} includes the effect of turbulence (r ~ 0.40). The factor k_{sl} is included to incorporate the effect of the bottom slope. Pilarczyk combined several design formulas and added extra coefficients to the Shields and Izbash equations to arrive at Equation 2.10 (CIRIA et al., 2007). The extra coefficients take the following factors into account: turbulence, slope angle of the bed, vertical velocity profile and geometrical characteristics of the protection layer (Pilarczyk, 1995).

$$D_{n50} = \frac{\phi_{sc}}{\Delta}\frac{0.035}{\Psi_{cr}} k_h k_{sl}^{-1} k_t^2 \frac{V_{b,max}^2}{2g} \tag{2.10}$$

Where:

ϕ_{sc}	=	stability correction factor for the geometry of transitions [-]
Ψ_{cr}	=	critical Shields stability parameter [-]
k_h	=	velocity profile factor [-]
k_t	=	turbulence factor [-]

When filling in the Pilarczyk equation for a rock bed protection, $D_{n,50}$ equals ~ 2.89 $\cdot \frac{U_b^2}{2g\Delta}$. The used parameters apply to riprap and have been retrieved from the guidelines (RWS GPO, 2020): ϕ_{sc} = 0.75,

Ψ_{cr} = 0.035, k$_h$ = 1, k$_t$ = 1.8, k$_{sl}$ = 1. This is only slightly lower than the value for β_{cr} that has been found by Izbash. The formula from Izbash is used most commonly in the Netherlands, because it is less complicated than the formula from Pilarczyk and experience proved that it yields sufficient stable results.

As explained, a bed protection might consist of multiple layers of rock. Wörman (1989) found a sensible thickness-to-diameter ratio. Generally, the minimum thickness of any layer is 2 $\cdot D_{n,50}$ (Schiereck, 2019). For smaller stones, a minimum thickness of 250 cm is maintained for constructability.

Riprap can be penetrated with colloidal concrete to improve its strength. Grouting binds smaller stones and grains together; the cohesion between the stones makes the armour layer more resistant against the flow (RWS BD & Vrijburcht, 2000). Stone sizes or other elements may therefore be reduced, thus making more economic use of available materials. Colloidal concrete is cement-based and is used most commonly for riprap penetration in the Netherlands. The amount of concrete can differ, but 'full and saturated' grouting is the most common. Limited theoretical knowledge is available for the sizing of grouted stones (CIRIA et al., 2007). Sometimes, the concrete is only used as a binder and the armour stones are dimensioned with the rules for loose rock. Using this method, the economic advantage of using less rock is lost. According to the Rock Manual, grouted rock can resist current velocities up to 10 m/s (CIRIA et al., 2007).

Composite mattresses

The minimal thickness of a mattress is, similar to rocks, proportional to the squared bottom velocity, see Equation 2.11. To include turbulence, the factor K_t can be introduced as done by Pilarczyk for rock protections (PIANC, 2015).

$$D_{mattress} \geq \frac{C_L}{2 \cdot \Delta \cdot g} \cdot V_{\mathrm{b,max}}^2 \tag{2.11}$$

Where D$_{mattress}$ is the mattress thickness and C$_L$ is the lift factor. Mattresses can cope with high propeller velocities, with a relatively low thickness compared to rock protections. A thickness of 150-300 mm is most commonly used, but thicknesses from 100 mm to 600 mm are also readily available (Hawkswood & Assinder, 2013). Where berths are dredged by large maintenance dredging vessels, a minimum thickness of 200 mm is advised. Figure 2.14 shows an example of the placement of concrete block mattresses.

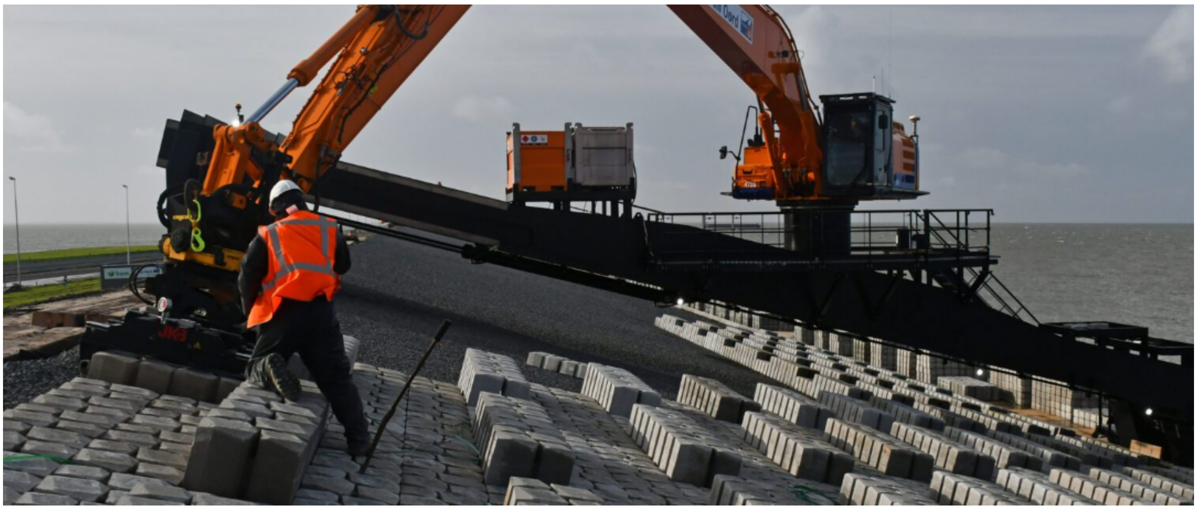


Figure 2.14: Placement of interlocking concrete blocks on the Afsluitdijk (deafsluitdijk.nl, 2021)

2.6. Which parameters are required to design a bed protection at a waiting place?

The bed at a waiting place should be protected when scour holes might occur that threaten the structural stability of the bank. These can be created when the near-bed flow velocity exceeds the critical velocity of the particles in the bed. The governing loads on a bed protection located at a waiting place are the near-bed flow velocities caused by the main propulsion system and bow thrusters. The type of berth influences the near-bed flow velocity because the possible presence of piles affects the flow pattern and thus increases the velocity. The width of a bed protection depends mostly on the beam of the design ship; the length depends on both the length of the design ship and the number of ships that the waiting place can accommodate at the same time. The thickness however depends on the type of bed protection. The most common bed protections are made of riprap or composite mattresses with a geotextile to ensure no sand is washed from under the protection. For loose rock, individual stone dimensions have been calculated most commonly with the Izbash formula or a variation on it, such as the Pilarczyk formula.

Table 2.1 concludes all data that is required to design a bed protection at a waiting place. Rijkswaterstaat also uses bed elevation measurements from multibeam drawings to estimate the actual erosion and to compare this with the expected load. This thesis will therefore also collect data on scour holes at the location of the waiting places. Because of the different scour processes for varying bed protection types, only the waiting places, where the most common type is expected, will be taken into consideration. In the next Chapter, it will be discussed how the data of these waiting places are gathered and an overview of the available data will be presented.

Table 2.1: Required data for designing a bed protection at a waiting place

Ship dimensions	Unit
Beam	m
Design draught	m
Propeller characteristics (main and bow)	
Type	-
Number of thrusters	-
Used power	kW
Diameter	m
Distance propeller axis to bed	m
Distance propeller axis to quay	m
Hydraulic boundary conditions	
Design water depth	m
Berth properties	
Berth type	-
Slope angle	°
Bed material	-

3 Materials

This Chapter will answer a set of three sub-questions: a) What types of bed protections are expected in the approach harbours of inland ship locks in the Netherlands and which type is most common? and b) For this most common type, what data are available and how can they be collected? and c) For this most common type, what is the state of each bed and are the expected bed protections present? First, the most commonly expected type of bed protection is determined. Next, all used sources for the data collection are discussed. This is followed by a discussion on the availability of the data per waiting place, because not for all waiting places, data is obtainable. The collected data are presented in Section 3.4, where also the state of each bed and presence of expected bed protections is discussed.

3.1. Most common bed protection

To provide necessary protection for a bed against current attack, many solutions have been developed. The current research considers only the most common type of protection for waiting places in the Netherlands. The most commonly used type of protection is derived from a data analysis of the approach harbours of all the locks maintained by Rijkswaterstaat in the Netherlands as done by De Kat (2021). Because a waiting place is usually located within the approach harbour of a lock, it is expected to have the same type of bed protection as the protection of the approach harbour. The full research data with type of bed protection per individual lock are provided in Appendix A. No distinction was made between riprap and riprap penetrated with colloidal concrete. For this thesis, the waiting places of locks destined for sea-going vessels were neglected. Also the data from the locks with zero waiting places are not used. For three lock complexes, the research by De Kat (2021) states multiple types of bed protection are used in the approach harbour. For the waiting places of these locks, it is assumed that the different types are all equally present. For example, lock Empel has three waiting places and both riprap and concrete are expected in the approach harbour. It is then assumed that 1.5 waiting place has a riprap protection and 1.5 waiting place has a concrete protection. The exact distribution of bed protections of each waiting place is not known. Table 3.1 concludes this analysis.

Table 3.1: Number of waiting places with a specific bed protection type found in the approach harbour

Type	# waiting places	% waiting places
Riprap	162	69
Concrete	25	11
Set stone	3	1
Unknown	46	19
Total	236	100

From Table 3.1, it can be concluded that riprap is the most commonly used type of bed protection in approach harbours of ship locks. These findings are consistent with literature data. Rock is relatively easy to construct, has a long design life, is relatively cheap, can follow settlements in the soil, and can be reused (Dienst Weg- en Waterbouwkunde, 2000). As explained in the Introduction, loose rock is preferred over concrete from a sustainability perspective. The ROW mentions and acknowledges the use of concrete and other types of bed protections, but covers only the application of rock because it is the most common material (RWS GPO, 2020). Furthermore, it is remarkable that for almost one-fifth of the waiting places, it is not known whether there is a bed protection or which type of bed protection it is.

Henceforward, only the waiting places of locks where riprap is expected in the approach harbour will be analysed. This includes also the waiting places where multiple types of bed protections were expected in the approach harbour. The total number of waiting places that will be analysed is 168, which belong to 46 lock complexes.

3.2. Used sources for data collection

To design a bed protection at a waiting place, the design parameters from Table 2.1 should be known. This Section will discuss what sources were used to find and collect the data. The different types of sources that were used are databases from Rijkswaterstaat, lock managers, and the physical archive of Rijkswaterstaat.

3.2.1. Databases of Rijkswaterstaat

Rijkswaterstaat gathers and stores enormous amounts of data, of which a big part is open to the public (Rijkswaterstaat, 2022e). This Section discusses the consulted databases with regard to the type of information they contain and what information is obtained. The consulted databases are shown below. Appendix B further explains how the databases can be accessed. Per region, data is stored differently. Appendix B also shows the different regions in the Netherlands.

- DISK
- RINK-database
- Meridian UIM
- Geoweb
- Ultimo RWS
- Vaarweginformatie.nl

DISK

All locks considered in this thesis can be found in DISK. DISK provides an overview of complexes of structures which consists of multiple objects with each their own components. Using the DISK code of an object or structure, its passport can be found in the database. Also inspection reports and small risk assessments can be found in DISK. Appendix B explains the use of DISK-codes further. The information on components was used by De Kat (2021) to estimate which type of bed protection is present in the approach harbour of a lock, see Section 3.1. No further data relevant to this thesis have been acquired using DISK.

RINK-database

In RINK reports, different components of a lock are analysed and assessed. Control calculations were explained regarding the strength of the structures and inspection results were attached. Based on the analyses, measures to improve performance are recommended for each object (Movares & Gerdessen, 2013). Not for all locks, a RINK report was made. The reports that however were available, have been used extensively to collect data on design parameters, near-bed flow velocities, and erosion.

Meridian UIM

In Meridian UIM, technical documentation is stored per region, e.g. as-built drawings, certificates, etc. Design documents of the Zandkreeksluis and Grevelingensluis were obtained through Meridian.

Geoweb

Geoweb contains several maps where data on a lock can be found at its geographic location. Meridian UIM can also be accessed through the Geoweb viewer. For the region Southern Netherlands, a profile tool is available to determine the slope of the bank and bed level at waiting places of locks. No further documents have been acquired with Geoweb.

Ultimo RWS

In Ultimo, mostly qualitative information is stored, such as general information and the configuration manager. Lots of documents can be acquired, for example manuals for the use of a bridge, or warranties for components. Only for two lock complexes, Hintham and Empel, relevant data has been acquired using Ultimo.

Vaarweginformatie.nl

On the website Vaarweginformatie.nl, up-to-date information can be acquired on the availability of a waterway, next to real-time information on a multitude of waterways, waiting places, and locks (RWS Dienst VenW, 2022). Information was retrieved on the location of all locks and waiting places. Furthermore, the sizes of the waterways were identified using this website.

3.2.2. Lock and regional information managers

To obtain technical drawings, maintenance histories, and design documents, many locks and regional information managers should be contacted. Their contact information can be obtained through the regional managers, whose contact information can be found on the intranet of Rijkswaterstaat. For several regions, the request for data can only go through a datadesk (NL: dataloket). The necessary data is expected to be documented within the following type of documents:

- Maintenance history, for state of bed and extent of erosion
- Inspection results, for state of bed and extent of erosion
- Design documents, for assumed parameters, expected loads, and dimensions
- As-built drawings, for dimensions
- Hydraulic conditions, for water levels

Only in the region Sea and Delta, the lock manager has the design documents of some waiting places of locks available. Regional information managers are not able to provide the correct data, but can refer to possibly useful databases. Moreover, they can provide help in accessing and navigating the previously mentioned databases.

3.2.3. Archive

Several lock and regional information managers indicated that the original design documents of bed protections of locks might be stored in regional archives. A nationwide request was put in to search for these documents. Furthermore, design documents and technical drawings were requested at the main Technical Archive at the headquarters in Utrecht. No documents relevant to this thesis are available.

3.3. For which waiting places can data be acquired?

The total number of waiting places that will be analysed is 168, which belong to 46 lock complexes. This Section will discuss which data are available per lock complex and waiting place. First, the available data on the required design parameters as listed in Section 2.6 is shown. Furthermore, the availability of data on flow velocities and erosion is discussed.

3.3.1. Availability of data on design parameters

In the RINK reports, strength calculations were made for the bed protections. From these reports, the design parameters used to calculate the expected near-bed flow velocity and required bed protection were obtained. For 55% of the waiting places, a RINK report was acquired. For two lock complexes (= 3.5% of the waiting places), Hintham and Empel, other documents were acquired in which some relevant data was found. Not for every design parameter, the correct data could be retrieved from the reports. Table 3.2 shows for each design parameter how much data was acquired.

Only for the Grevelingen lock complex, a design document was acquired which also includes the required design parameters. This document was drafted in 1980 and uses different relations and assumptions to calculate the expected load than the calculations done in RINK reports. Comparison between waiting places based on the original design is not possible due to a lack of available data. For consistency, only the design parameters used for the strength calculation in RINK reports are used for the comparison between waiting places. The data from the design documents of the Grevelingen lock complex are not taken into consideration any further.

Table 3.2: Percentage of waiting places for each design parameter where data could be retrieved from RINK reports

Ship dimensions	% available
Beam	59
Design draught	59
Propeller characteristics (main and bow)	
Type	59
Number of thrusters	59
Used power	59
Diameter	59
Distance propeller axis to bed	59
Distance propeller axis to quay	52
Hydraulic boundary conditions	
Design water depth	59
Berth properties	
Berth type	59
Slope angle	41
Bed material	59

For most waiting places, the RINK reports provide all design parameters. For 11 waiting places where a RINK report was available, the horizontal distance between the bank and bow thruster was not given. This does not include the number of waiting places where no bow thrusters were assumed. For 38 waiting places, the slope of the bank could not be found in a RINK report. However, for 8 waiting places in the region Southern Netherlands, the slope of the bank could be acquired by making a bed profile with the GeoWeb profile tool. Figure 3.1 shows an overview of the availability of RINK reports and whether all design parameters were acquired.

Figure 3.1: Availability and completeness of design parameters for all 46 lock complexes

3.3.2. Availability of data on flow velocities

Next to the parameters required to design a bed protection, also the expected flow velocities caused by propellers were retrieved from the RINK reports. In the reports, the flow velocities were calculated at the bed near the lock. Where the water depth near the lock is equal to the water depth at the waiting place, the velocities are equal as well. However, this is not the case for all waiting places. Table 3.3 gives an overview of how much data was acquired on flow velocities. For 90 waiting places (=45%), a RINK report was available and the water depth near the lock and at the waiting place is equal. For 21 waiting places (=13%), the water depths are not equal, but the flow velocities caused by the propellers are known near the lock. Figure 3.2 shows for all 46 lock complexes at how many waiting places, the near-bed velocity can be obtained directly from the reports in orange. In turquoise, the number of waiting places per lock is shown where the expected near-bed flow velocity is given only near the lock. The water depth of the waiting place can differ from the water depth at the lock. When the water depths at both the waiting places and locks are known, the expected near-bed flow velocity at the waiting place can also be calculated. This is the case for all waiting places where the water depth at the waiting place differs from the water depth near the lock.

Table 3.3: Percentage available data on flow velocities

Type of data	% available
No data	39.9
V_{bed} at waiting place	47.6
V_{bed} near lock	12.5
Total	100

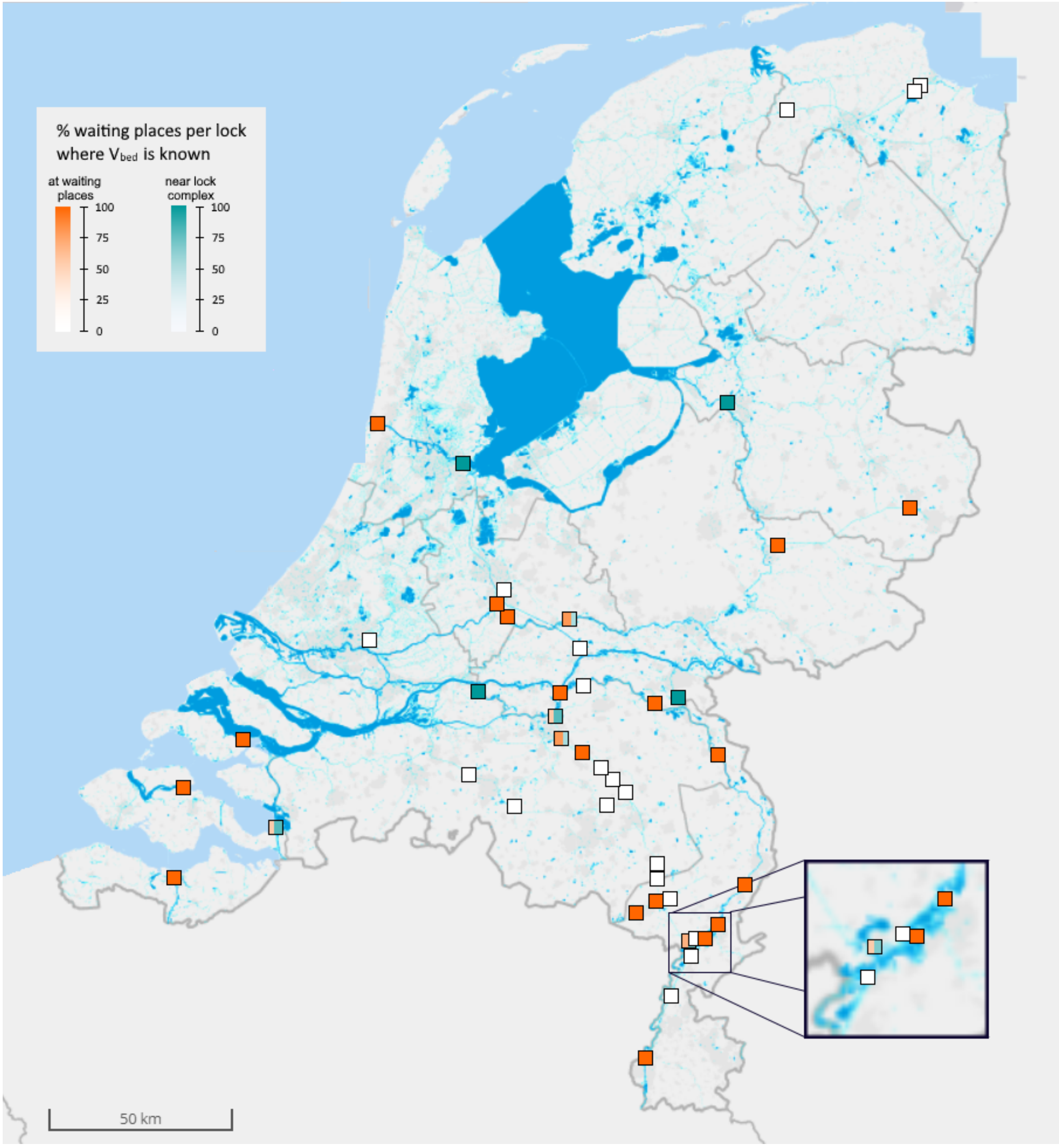


Figure 3.2: Percentage waiting places per lock complex where the near-bed velocity is known at the waiting places in orange, or near waiting places in turquoise

3.3.3. Availability of data on erosion

In Section 2.4, it was explained that Rijkswaterstaat uses multibeam drawings to detect scour holes. The expected scour hole depths, calculated with the assumed design parameters, are then compared to the actual scour holes as seen on the multibeam drawing. All multibeam drawings were obtained from the RINK database. For 99 waiting places, RINK reports have been acquired. However, not all RINK reports contain multibeam drawings. Furthermore, some multibeam drawings contain information only close to the lock and do not cover all waiting places. For 68 waiting places, a multibeam drawing has been obtained. Figure 3.3 shows for each lock complex at how many waiting places multibeam drawings can be acquired. No documents with xyz-coordinates of the bed have been found.

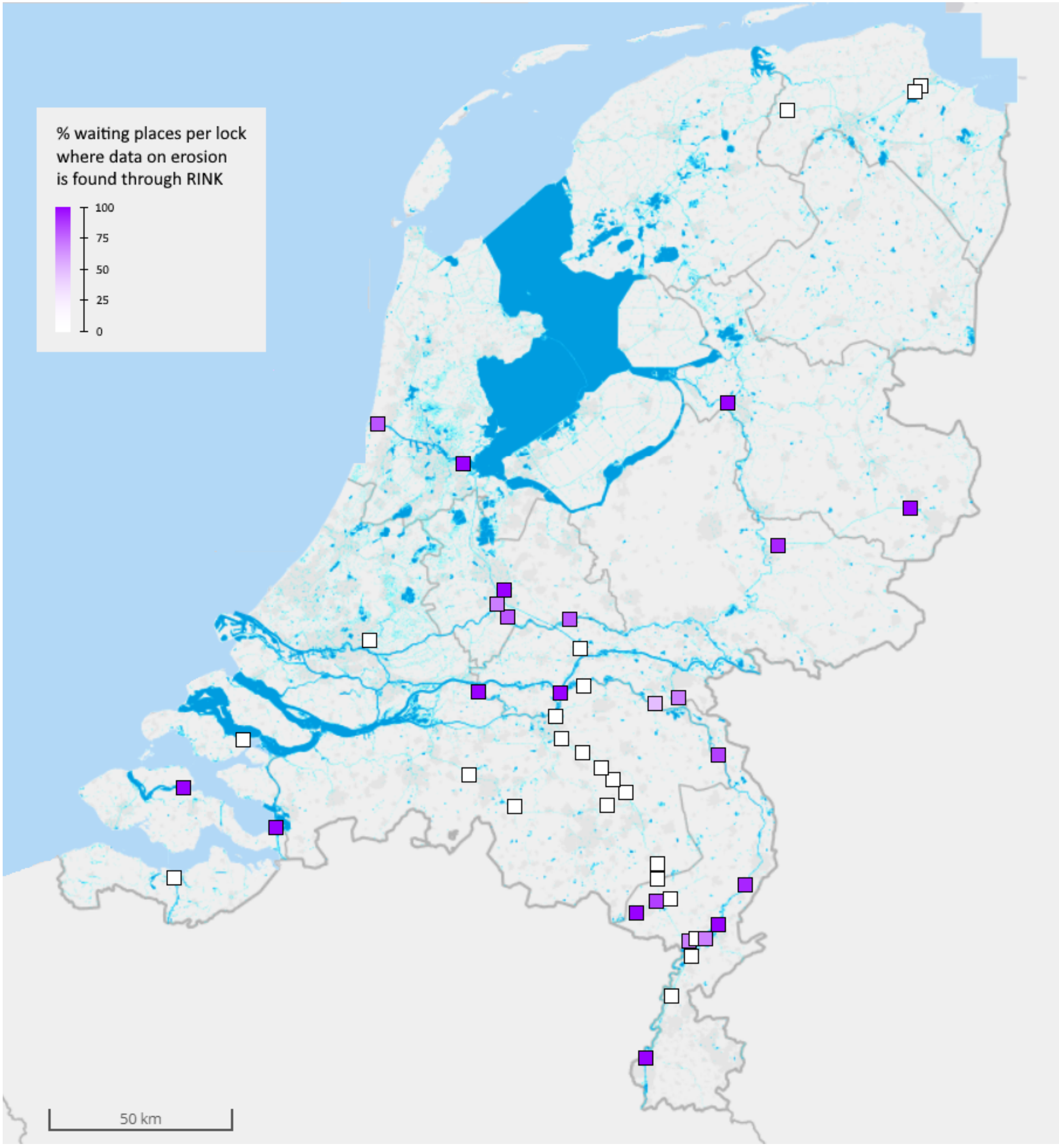


Figure 3.3: Percentage waiting places per lock complex where data on erosion is available in RINK reports

3.4. Collected data

This Section will provide an overview of all found design parameters as discussed in Section 2.6. Furthermore, near-bed flow velocities and data on erosion are given. The collected data are shown in bar charts and histograms. The number of bins is chosen so that the histograms are representative of the data they show. As Scott (1979) notes, multiple scientists advise that for real data sets histograms based on 5-20 bins usually suffice. Because of the large variation in most parameters, most times 20 bins are used to represent the data in this Section. This Section does not include the waiting places where no data was acquired. All data per waiting place can be found in Appendix D.

3.4.1. Ship dimensions

Ships are designed to be able to navigate a certain shipping route. CEMT (1992) has described certain classes in which waterways and ships are divided, called CEMT-classes. Appendix C shows which size design vessel falls into which class. Tables 3.4 and 3.5 show the distribution of the design vessels' beams and draughts.

Table 3.4: Distribution of ship beams

Min [m]	Max [m]	CEMT	Number of ships [-]
0	5.05	I	0
5.05	6.6	II	0
6.6	8.2	III	8
8.2	9.5	IV	20
9.5	11.5	V	51
11.5	23.0	VI	20
Total			99

Table 3.5: Distribution of ship draughts

Min [m]	Max [m]	CEMT	Number of ships [-]
0	2.2	I	13
2.2	2.5	II,III,IV	4
2.5	2.8	Va	16
2.8	4.5	Vb,VI	63
4.5		>VI	3
Total			99

No ships with a beam belonging to CEMT-class I are observed, since such small ships are not decisive for the design. However, there are 13 ships with a small draught that fall into CEMT-class I. This difference is caused by the limited water depths of several shallow waterways. The assumed beam and draught of the design vessel are not always in accordance with the CEMT-class of the waterway. This can be explained by the fact that in practice, sometimes wider ships are allowed. Next to a design beam, the CEMT-class also prescribes a design depth and length, see Appendix C. When the waterway is built for a ship with a limited length, its CEMT-class will also be lower. However, it is possible that the width of the waterway allows for wider ships. Then, it is more logical to assume the design vessel to have these different dimensions.

3.4.2. Propeller characteristics

Propeller type

Per propeller type, a different factor should be used to account for a decrease in effective power, see Table 3.6. The relation between the effective diameter and actual propeller diameter equals $D_0 = D_p * C1$. The values for C1 correspond to the three types described in the manual for design of a ship lock (Vrijburcht, 2000). Figure 3.4 shows for both the main propulsion system and bow thrusters what factor was assumed in the strength calculation in RINK reports.

Table 3.6: Factor $C1$ for different screw placements in nozzle

Type	Factor [-]
Screw without nozzle	0.71
Screw in nozzle	1
Screw/nozzle combination	0.85

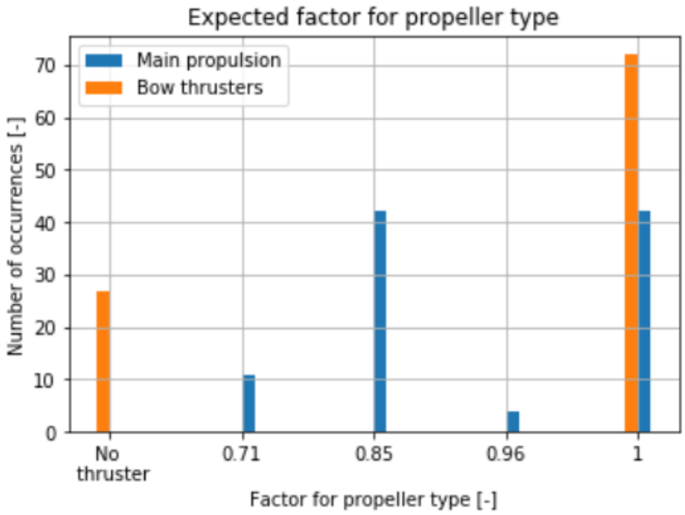


Figure 3.4: Bar chart of factors for propeller type

From Figure 3.4, it can be concluded that for 27 waiting places, it is assumed that the ships that use the waiting places either don't have or don't use bow thrusters. At the other 72 waiting places, the screw is always assumed to be placed in the nozzle. For the main propulsion system, either a screw/nozzle combination or a screw in nozzle system is usually assumed. At four waiting places, a value of 0.96 was used. Here, it can be assumed that the screw is also placed in the nozzle because the difference in factors is minimal.

Number of thrusters

Figure 3.5 shows the distribution of number of thrusters of the design vessel. Again, for 27 waiting places, no bow thruster is expected. The maximum number of bow thrusters is two, but one bow thruster is used most commonly. For the main propulsion system, having two main propellers is typical. Only for a small number of waiting places, the design vessel is assumed to have three propellers.

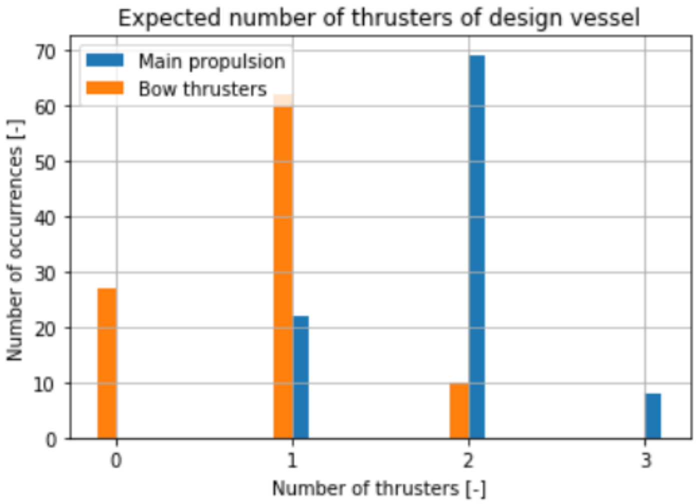


Figure 3.5: Bar chart of number of design vessels with a certain number of thrusters

Used power per thruster

Figure 3.6 shows a histogram of the expected used power at waiting places for both the main propulsion system and bow thrusters. The power shown is the power per individual propeller of the design vessel. It can be concluded that generally, the power of the main propeller is higher than the power of a bow thruster. The variation is however larger for the power of bow thrusters.

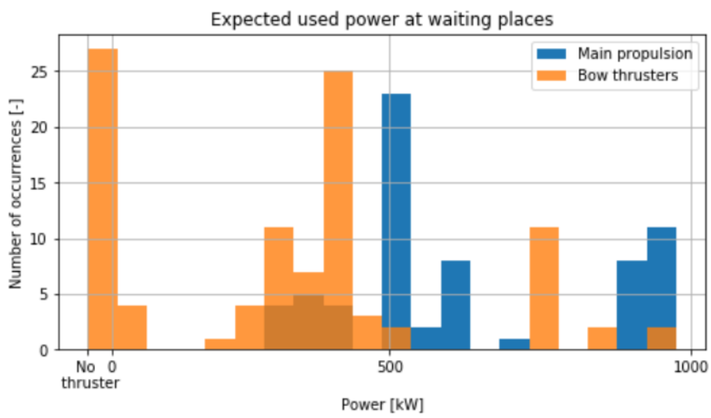


Figure 3.6: Histogram with 20 bins of the used power per propeller of both the main propellers and bow thrusters at waiting places

Diameter

Figure 3.7 shows the histogram of the diameters of the propellers. The diameter of the main propeller is almost always larger than the diameter of the bow thrusters. The variation of the diameters is small; two outliers are detected: at the southern locks of IJmuiden, the diameter of the main propeller is assumed to be 3.4 m; at lock complex Roermond, the diameter of the bow propeller is assumed to be 2 m.

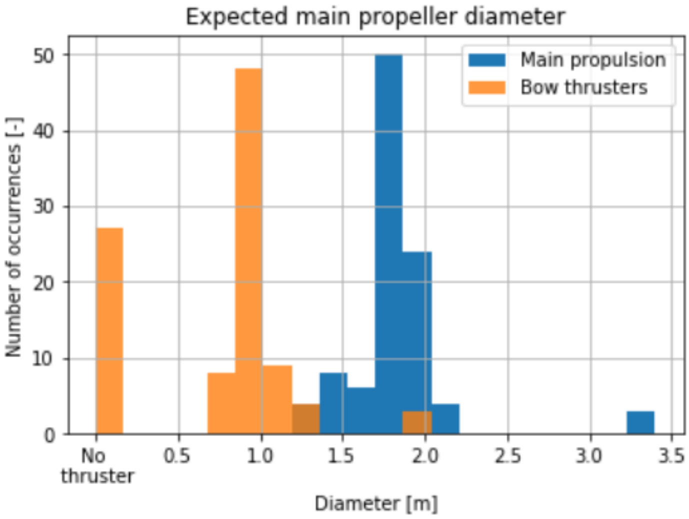


Figure 3.7: Histogram with 20 bins of the propeller diameters of both the main propellers and bow thrusters of the design vessel

Distance axis to bed

Figure 3.8 shows the distribution of vertical distances between the axis of a propeller and the bed. There is a lot of variation for both the distance from the main propellers to the bed and from the bow thrusters. For seven waiting places, the distances from the main propeller and bed and from bow thruster to bed are equal.

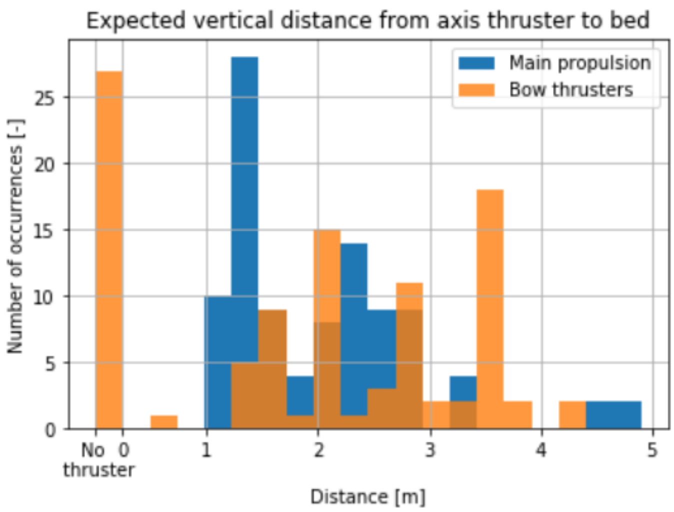


Figure 3.8: Histogram with 20 bins of the vertical distances between the axis of the propeller and the bed

Distance axis to quay

Figure 3.9 shows the distribution of horizontal distances between the axis of the bow thruster and the bank. For twelve waiting places, the distance between the bow thruster and bank is unknown. There is a significant difference in distance to the bank. When a ship is berthed at a quay wall, it lies very close to the quay, whereas piles could be placed at a distance from the bank. See for example Figure 3.10, where two waiting places upstream of the Bosscherveld lock are shown. At the waiting place nearest to the lock, ships berth at a quay wall, so directly to the bank. At the waiting place further away, ships berth at piles that are right in the middle of the waterway.

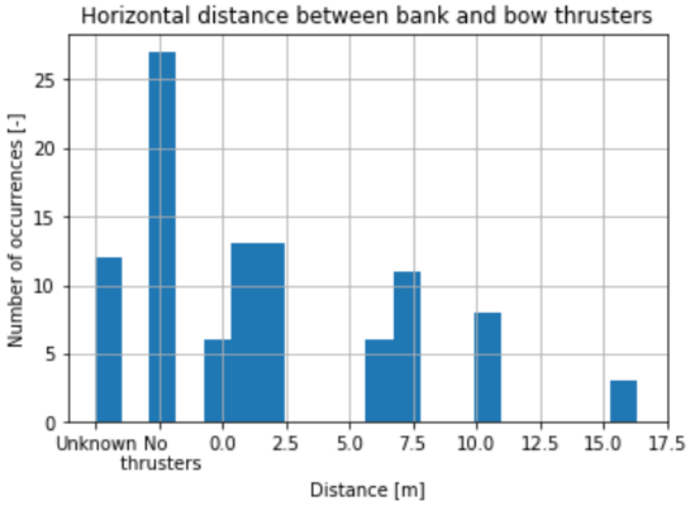


Figure 3.9: Histogram with 20 bins of the horizontal distances between the axis of the bow thruster and the bank

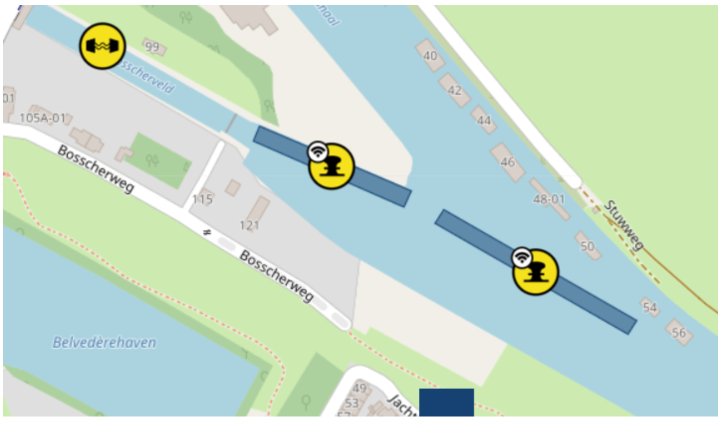


Figure 3.10: Top view of the Bosscherveld lock with two waiting places (dark blue) upstream of the lock (RWS Dienst VenW, 2022)

3.4.3. Hydraulic boundary conditions

Water depth

Figure 3.11 shows the histogram of the expected water depths. At most waiting places, the water depth is approximately 4 meters.

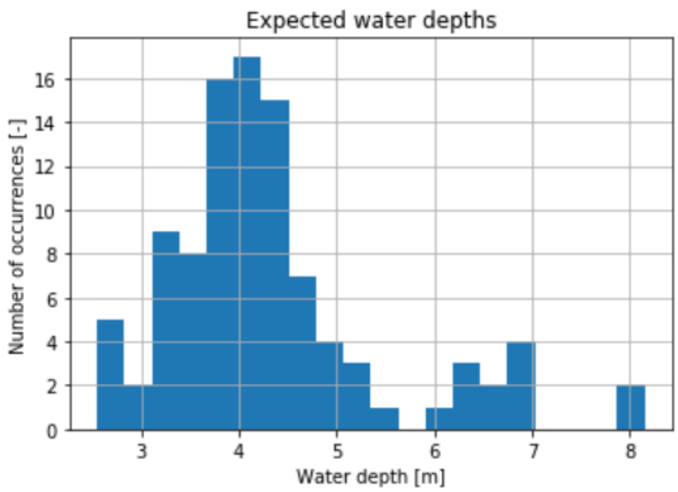


Figure 3.11: Histogram with 20 bins of expected water depths

3.4.4. Berth properties and the presence of bed protections

Berth type

Figure 3.12 shows how common the two berth types are. Although piles are the most common, there is still a significant number of quay walls present. One waiting place, at lock Hengelo, is a combination of the two berth types. In Figure 3.13, it can be seen how close to the lock, at the left side, the berth is a quay wall, whilst further away, the ship berths at piles.

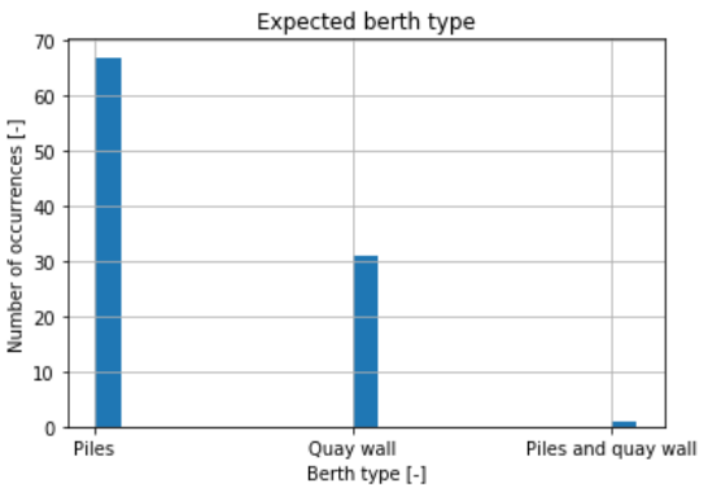


Figure 3.12: Bar chart of berth types

Figure 3.13: Waiting place upstream of lock Hengelo. The lock is to the left of the picture. (Google, 2022c)

Slope angle

Figure 3.14 shows the distribution of the angles of the slopes of the banks at the waiting places. It is very clear that most angles are (close to) 90 degrees, indicating that most banks are vertical walls. As stated in Section 3.3.1, for eight waiting places in the Southern Netherlands, the angle of the slope was obtained with the RWS Southern Netherlands GeoWeb tool. Figures 3.15 and 3.16 show how a cross-section at a waiting place can be obtained. From Figure 3.16, the angle of the slope can be calculated.

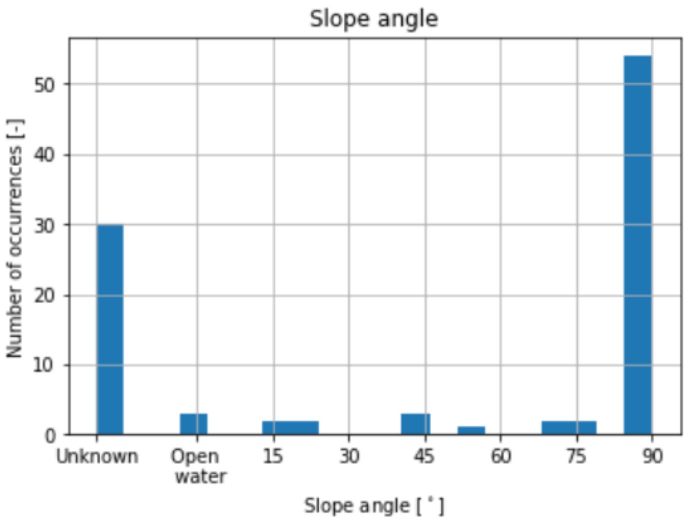


Figure 3.14: Histogram with 20 bins of the angle of the slope of the banks at the waiting places

Figure 3.15: Location of cross section; top view of lock Linne using the RWS ZN profile tool (Rijkswaterstaat & GeoWeb, 2022)

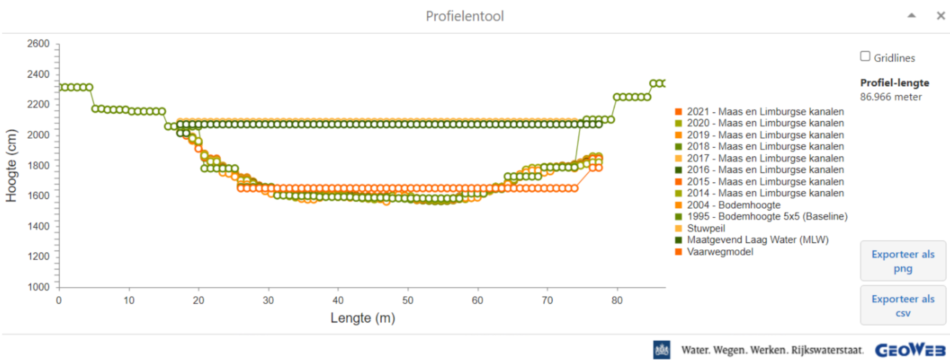


Figure 3.16: Cross section of waterway at location as shown in Figure 3.15 (Rijkswaterstaat & GeoWeb, 2022)

Bed material

All RINK reports make some note of the bed material; sometimes it is described qualitatively, sometimes quantitatively with exact grain sizes. Using Table 3.7, all bed materials were described qualitatively in Table D.5. Figure 3.17 shows how common different bed materials are. At most waiting places, the upper layer of the bed consists of sand.

Table 3.7: Standard to determine bed material type based on grain diameters, translated from Normcommissie 351006 'Geotechniek' (2020)

Category	Grain size fraction (abbreviation)	Grain size range [mm]
Very coarse ground	Large blocks (Lbo)	> 630
	Boulders (Bo)	> 200 tot ≤ 630
	Cobbles (Co)	> 63 tot ≤ 200
Coarse ground	Gravel (Gr)	> 2.0 tot ≤ 63
	Coarse gravel (cGr)	> 20 tot ≤ 63
	Middle coarse gravel (mGr)	> 6.3 tot ≤ 20
	Fine gravel (fGr)	> 2.0 tot ≤ 6.3
	Sand (Sa)	> 0.063 tot ≤ 2.0
	Coarse-grained sand (cSa)	> 0.63 tot ≤ 2.0
	Middle coarse-grained sand (mSa)	> 0.2 tot ≤ 0.63
	Fine-grained sand (fSa)	> 0.063 tot ≤ 0.2
Fine ground	Silt (Si)	> 0.002 tot ≤ 0.063
	Coarse silt (cSi)	> 0.02 tot ≤ 0.063
	Middle coarse silt (mSi)	> 0.0063 tot ≤ 0.02
	Fine silt (fSi)	> 0.002 tot ≤ 0.0063
	Clay (Cl)	≤ 0.002

Presence of the expected bed protections

For 33 out of the 99 waiting places, there is no doubt about whether either rocks or gravel have been placed on top of the bed. At 15 waiting places, a riprap or gravel protection has been found. For 55 of the remaining 66 waiting places, a discussion on the bed is included in the RINK report. Here the state of the bed is discussed, e.g. possible scour holes in a sandy bed are mentioned. For none of those 55 waiting places, a bed protection at a waiting place is mentioned. Therefore, it is assumed no bed protection is placed on top of the bed. For the remaining 11 waiting places, which fall outside of the multibeam survey scopes, the same assumption is made. For 81 waiting places where a riprap bed protection was expected, the expectation was inaccurate.

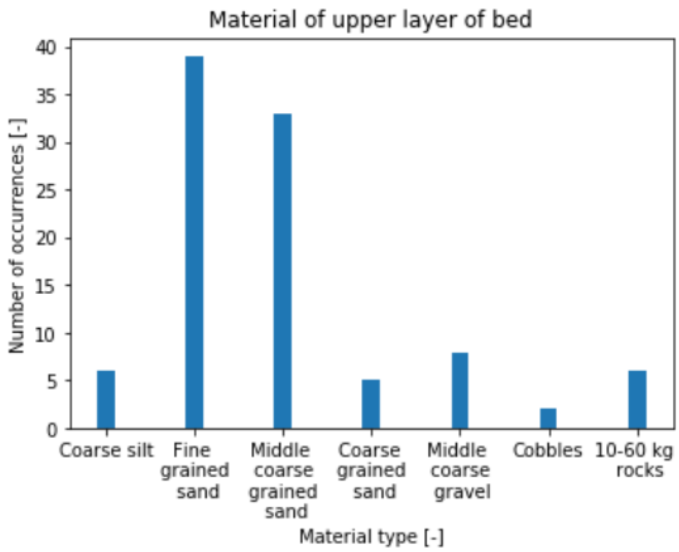


Figure 3.17: Bar chart of materials found in the upper layer of the bed at the waiting places

3.4.5. Near-bed flow velocities

Figure 3.18 shows the distribution of the near-bed flow velocities caused by either the main propulsion system or the bow thrusters. Whereas the used power in Figure 3.6 was portrayed as the power per individual propeller, the near-bed flow velocities are caused by all main (or bow) propellers of the design vessel together. Due to the difference in use and locations of the load, it is assumed that the near-bed flow velocities do not interfere with each other, see Section 2.1. For many locks, the near-bed flow velocities cannot be directly read from the RINK reports. RINK reports calculate the near-bed flow velocity near the lock and at some waiting places, the local water depth differs from the depth at the lock. In this case, the near-bed flow velocity from the lock should be multiplied with $\frac{h_{waitingplace}}{h_{nearlock}}$. In case the water depth of the lock is equal to the water depth at the waiting place, the near-bed flow velocity is equal as well. The obtained data per waiting place is shown in Appendix D.5.

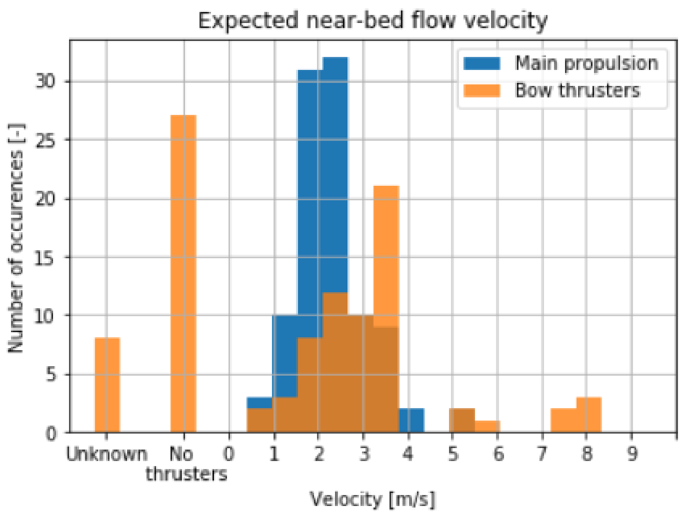


Figure 3.18: Histogram with 20 bins of the expected near-bed flow velocities caused by either the main propulsion system or bow thrusters

3.4.6. State of the bed

Information regarding the state of the bed can be retrieved from multibeam drawings. 3D multibeam measurements are taken with a multibeam sonar which maps the bed of a waterway, see Figure 3.19. These measurements are then visualised in a technical drawing. Figure 3.20 shows a multibeam drawing near the Zandkreek lock with several highlighted scour holes. The drawing contains both a colour scale and contour lines to illustrate differences in bed level. To compare the erosion at waiting places, both the location and depth of the scour holes are researched. To find the locations of waiting places in the multibeam drawings, the website Vaarweginformatie.nl from RWS Dienst VenW (2022) is used, see Figure 3.21.

The location of the scour hole indicates which propeller is responsible for the erosion: a scour hole at the rear indicates erosion by the main thruster, while erosion at the front is more likely to indicate erosion by the bow thruster, as shown in Figure 2.1. Furthermore, when the ship berths at piles, scour holes around the piles are expected, because the near-bed flow velocities are higher near the pile, see Section 2.2.2. On the contrary, a singular pit is predicted when the ships berth at a quay wall. Also the distance to the bank or another structure is important: the closer the hole, the greater the risk of collapse.

To find the depth of a scour hole, the bed level is compared to a point at the same distance from the bank where the bed shows little to no irregularities, i.e. a similar point where no erosion occurs. The depth of the scour hole is equal to the difference between the bed levels.

For 68 waiting places, a multibeam drawing has been acquired. These drawings show a snapshot of the bed profile, i.e. they show the bed profile at only one moment in time. It is possible that if the inspection was carried out at a different moment, the bed profile would have been different. This is more likely for smaller scour holes than for larger ones, because large scour holes develop over a longer time period. Therefore, the conclusions drawn from these data contain uncertainty.

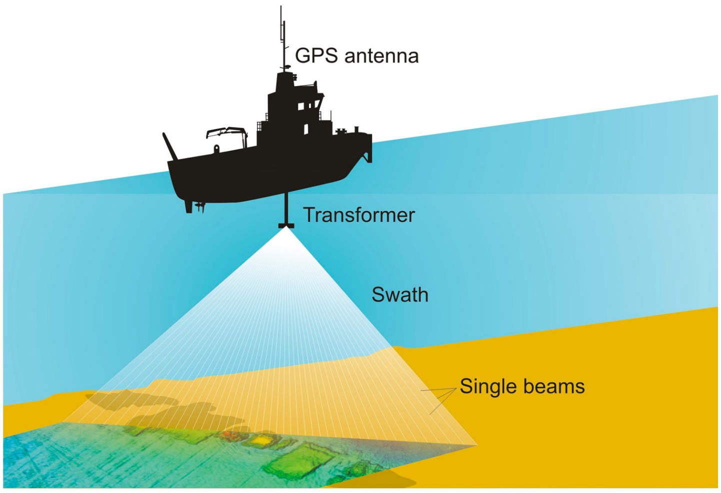


Figure 3.19: Scanning with Multibeam Bathymetry (Wessex Archeology, 2010)

There is a lot of difference in how the data from the multibeam are presented. First of all in the use of colours and contour lines. Most drawings are similar to Figure 3.20, but some are made with a more practical purpose in mind, see Figure 3.22. Also the quality of the images varies greatly. Whilst most images are of high quality with legible bed levels, there are multiple waiting places where the bed levels are hard to decipher. Lastly, different reference levels are used, such as NAP (Dutch reference level) or the local bank level. Attention should be paid to whether the difference in bed level is positive, indicating a hole, or negative, indicating accumulation.

Figure 3.23 shows the spread of the depths of the scour holes per longitudinal location, i.e. at the rear or mid-front. The distance from the scour hole to the bank on the x-axis is the shortest horizontal distance

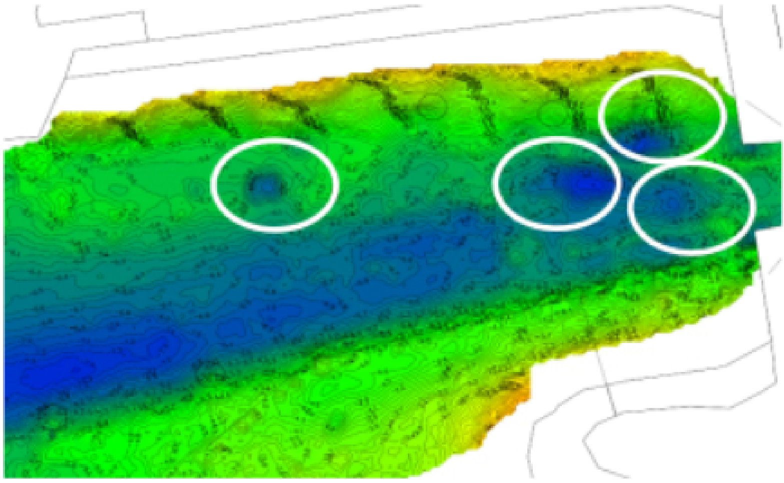


Figure 3.20: Multibeam drawing of the bed at the Zandkreek lock, where several scour holes are pointed out with white circles. Adapted from RWS Dienst Infrastructuur (2013)

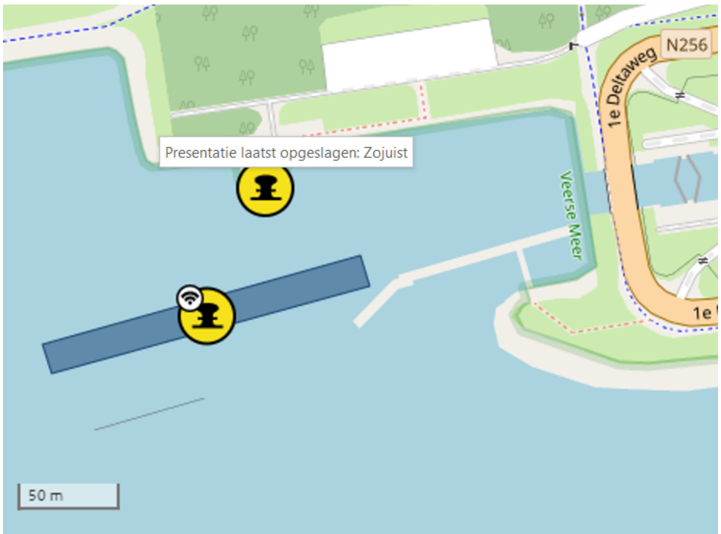


Figure 3.21: Top view of the Zandkreek lock with its waiting place in dark blue (RWS Dienst VenW, 2022)

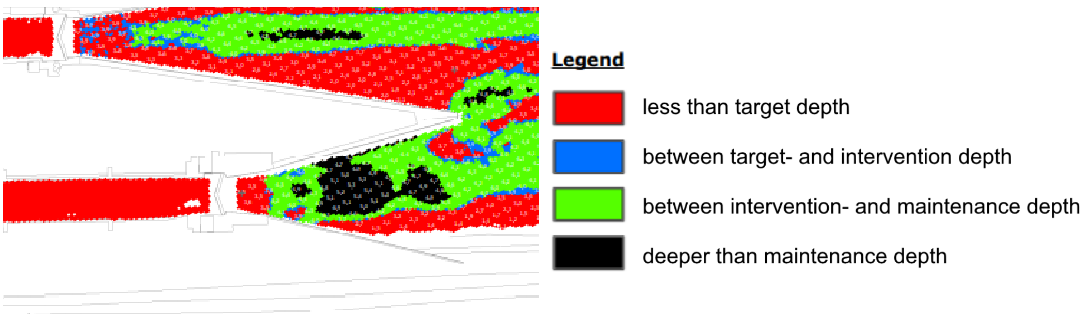


Figure 3.22: Multibeam drawing of Belfeld, translated from RWS Dienst Infrastructuur and Iv-Infra B.V. (2010)

to a bank or pile. The closer the hole is to a structure, the higher the risk of collapse. The horizontal distance is not the exact distance; an estimation has been made and the exact distance can differ by a few meters. 84 scour holes have been found. Most waiting places have one pronounced scour hole; only few waiting places have two holes that are worth mentioning. In Table D.7, the erosion information can be found per waiting place. At four waiting places, a negative depth was found. At those waiting places, not erosion but accretion occurred. At 8 waiting places, neither erosion nor accretion has been caused by ships (de)berthing at the waiting place. Accretion is not a risk for the stability of the quay wall, but may cause problems for navigation due to a locally reduced water depth.

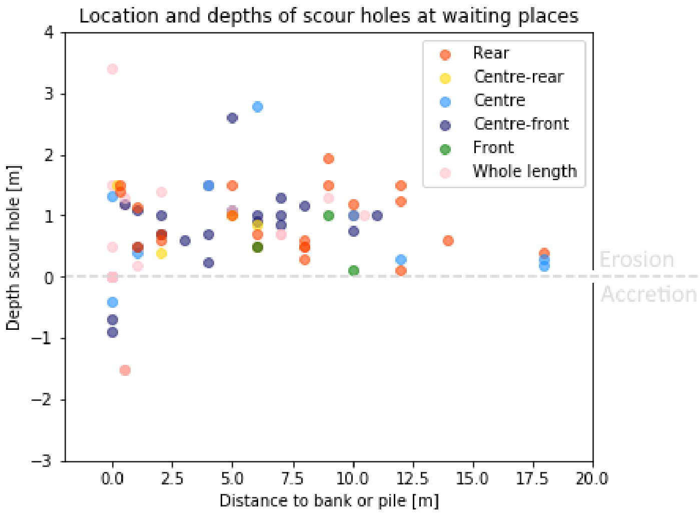


Figure 3.23: Visualisation of the location and depth of scour holes, where a negative scour hole depth equals accretion and a positive depth erosion

The deepest scour hole is 3.4 meters and is located at the Zandkreeksluis. To assess the bed protection at this location, a near-bed flow velocity of the main propeller of 2.1 m/s was assumed. No bow thruster is assumed in the strength calculation of the bed. However, there are multiple deep holes found near the piles, which makes it unlikely that the scour is caused by only the main propeller. It is however very likely that the ships that berth at this waiting place do use a bow propeller, which might be the cause for the large scour hole. This shows that actual use may deviate from the assumed use.

4

Method used for comparison of waiting places

This Chapter will explain the method that is used to compare the waiting places methodically using the data that was collected in Chapter 3.

4.1. Classification analysis

The locks have to be compared methodically, which is difficult because of the many different design parameters. To group similar bed protections together, classification analysis is applied. Classification is useful because it makes it possible to identify, group, and correctly recognise design parameters through a standardised system (De Smith et al., 2018). Using classification analysis, ratio data (numerical data with a true zero) are converted into nominal, or categorised, data. The used design parameters which were analysed for each waiting place in Section 3.4 are the ratio data to be categorised.

With a classification analysis, waiting places that are similar can be grouped together in a class to make the comparison between waiting places easier. To determine which waiting places fall in which class, each parameter should first be divided into a number of ranges, k. When two waiting places fall into the same range for every parameter, they fall into the same class. In this thesis, each range will be assigned a letter, so that the class become a string of letters. Waiting places where design parameters fit within the same ranges will have identical strings and are grouped together in a class.

Both the number of ranges and the number of parameters included in the classification analysis have to be determined carefully. If the number of parameters is too large, the analysis will result in too many classes. Waiting places that are almost identical will fall into different classes, which defeats the purpose of the classification. However, all parameters that significantly influence the design of a bed protection at a waiting should be included, see Section 4.1.1. Also the number of ranges into which each parameter is divided into shouldn't be too large. This results in small ranges and consequently many classes, which again defeats the purpose of classification. However, if the number of ranges is too small, the ranges are larger. With a larger range, the likelihood of a bigger variety within a class increases as well. If the variation within a class becomes too great, no meaningful conclusion can be drawn from a comparison between classes. The determination of the number of ranges per parameter is discussed in Section 4.2.

4.1.1. Which parameters are included in the classification analysis?

As explained in the previous Section, not too many parameters should be included in the classification analysis for it to be meaningful. Therefore, not all parameters from Table 2.1 should be considered. Using the formulas from Chapter 2, the number of parameters can be condensed so that only three remain, see Table 4.1. The bed material and berth type represent the constructive side, i.e. the berth properties, whereas the maximum near-bed flow velocity represents the load for which the bed protection is dimensioned. Next to these design parameters, the waiting places will also be compared on erosion. Furthermore, a comparison per vessel class and per waterway is done for waiting places in CEMT-class V waterways. Figure 4.1 shows the classification analysis for an example waiting place. It also shows the process of condensation of the design parameters into the final three parameters.

During condensation of the parameters, a lot of detail is lost. Section 6.1.4 discusses the impact of this in further detail.

Table 4.1: Condensed set of parameters required to design a bed protection at a waiting place

Parameter	Unit
Bed material	-
Berth type	-
Maximum near-bed flow velocity	m/s

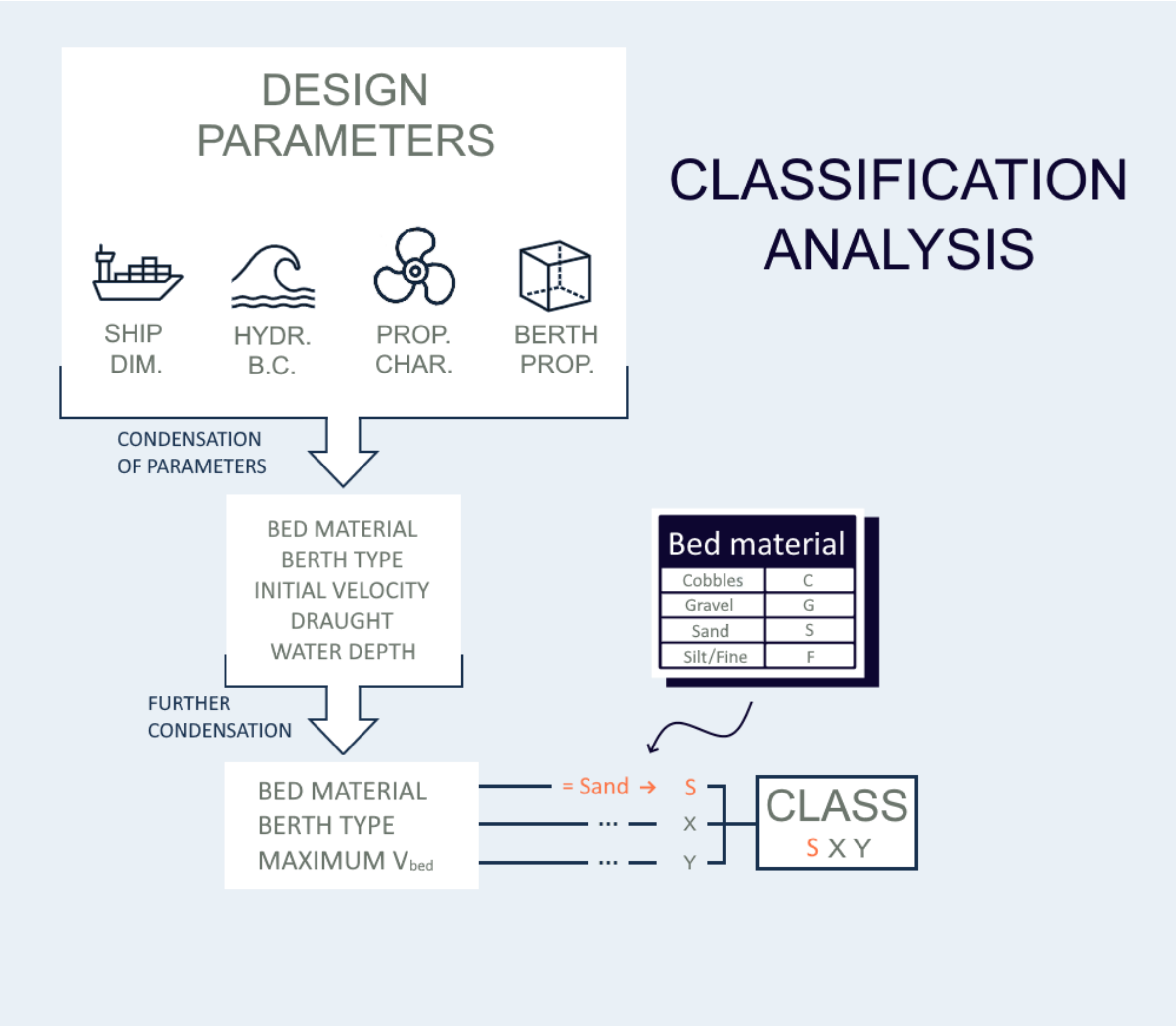


Figure 4.1: A schematic visualisation of the conducted classification analysis of a waiting place

4.2. Defining range boundaries

This Section will define the range boundaries of each parameter in Table 4.1. As discussed in the above Section, the number of ranges per parameter should be neither too big nor too small.

4.2.1. Bed material

For the type of material in the upper layer of the bed, again categories are discerned. The categorisation roughly follows the standard from Table 3.7: cobbles and 10-60 kg rocks fall into the category 'very coarse ground'; sand and gravel fall into the category 'coarse ground'; silt falls into the category 'fine ground'. Cobbles or larger rocks are always a bed protection and do not occur naturally in the bed of Dutch waterways. Sand and silt are never used as protection since they offer no more stability than naturally occurring sand. Gravel may occur naturally in the Meuse, south of Roermond, but can be used as a protection at other places where the bed is finer. In the Meuse, upstream of Roermond, gravel is observed at lock Bosscherveld and lock complex Belfeld. It is not certain whether these gravel beds are placed or naturally occurring.

Table 4.2: Categorised ranges for the material in the upper layer of the bed

Material type	Letter	Protection
Silt / Fine ground	F	No
Sand	S	No
Gravel	G	Sometimes
Cobbles	C	Yes
10-60 kg rocks	R	Yes

4.2.2. Berth type

For the berth type, three options have been distinguished in Section 3.4.4: piles, quay wall, or a combination of the two, see Table 4.3.

Table 4.3: Categorised ranges for the berth type

Berth type	Letter
Piles	P
Quay wall	Q
Combination	C

4.2.3. Maximum near-bed flow velocities

The categorisation of the near-bed flow velocities is based on the critical near-bed flow velocities of different bed materials. As explained in Section 2.4, the threshold value for cohesive material, e.g. silt, is 1 m/s. At 4 m/s, a boundary is placed to differentiate the extreme flow velocities. The difference between 1 and 4 m/s is too great to lump together all waiting places that fall in that interval. Therefore, an extra range boundary is placed at 2.5 m/s. The range boundaries are shown in Figure 4.2 and Table 4.4.

4.3. Result of classification analysis

Using these range boundaries, there are 60 possible classes. In total, 19 classes have been found. A full overview of which waiting place belongs in which class can be found in Appendix E, of which an excerpt is shown in Table 4.5. The waiting places of the Spooldersluis fall into the same range for every parameter and are thus grouped in the same class. The waiting place of IJmuiden has the same berth type as the waiting places of the Spooldersluis, but the top layer of the bed and the maximum near-bed flow velocity are very different. Therefore, the waiting place of IJmuiden falls into a different class.

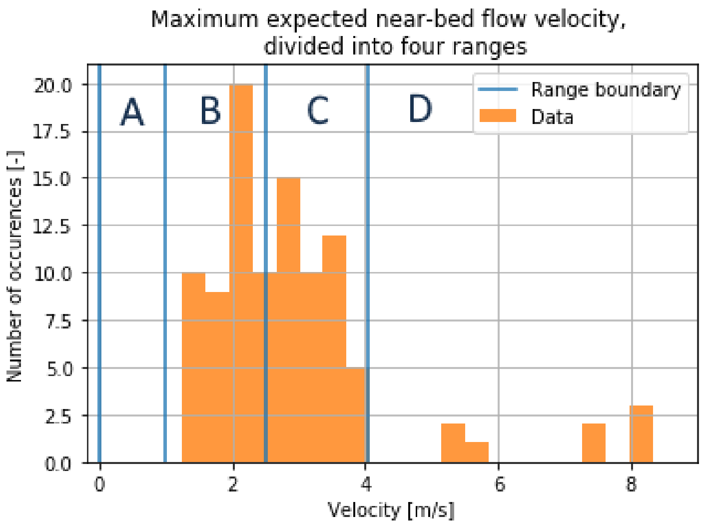


Figure 4.2: Range boundaries for the maximum near-bed flow velocity

Table 4.4: Categorised ranges for the maximum near-bed flow velocity

Min [m/s]	Max [m/s]	Letter
0	1	A
1	2.5	B
2.5	4.5	C
4.5	-	D

Table 4.5: Classification of waiting places, excerpt from Table E.2

Complex	Name waiting place	CEMT-class	Bed material	Berth type	Max. V_{bed}	Total string
Spooldersluis	Binnenkant 1	Va	S	P	D	SPD
	Buitenkant 1	Va	S	P	D	SPD
Ijmuiden zuidersluizen (kleine sluis + zuidersluis)	WachtPiles sluis west	Va	R	P	C	RPC

5

Result of comparison of waiting places

In the previous Chapter, similar waiting places have been grouped together in classes. This results in Figure 5.1. This Chapter will look into the degree of variation of waiting places in a CEMT-class and corridor. For a CEMT-class, it is expected that the design vessels and water depths are similar, which should result in a similar maximum near-bed velocity. For the waiting places in a specific corridor, it is expected that the design vessel and berth properties are even more similar. The state of the bed is also discussed. In this thesis, the potential for standardisation is measured by the variation in assumptions made in the assessment of the bed protections, variation in the state of the beds, and whether the beds are behaving in accordance with literature. If indeed the waiting places are alike, standardisation would be beneficial. If either a lot of variation or unexpected erosion is found, it is more beneficial to optimise the bed protection per waiting place.

No waiting places occur in CEMT-class III waterways. For CEMT-class I, there are two waiting places at the Groevesluis. However, no data on design parameters are available. Therefore, CEMT-class I and III are not shown in the Figure. Figure 5.1 shows how many waiting places fall into each class. Class 'SPB' and 'SPC' are the prevailing classes. 'SPB' represents a waiting place with a sandy top layer, piles, and a moderate near-bed flow velocity. Class 'SPC' also represents a waiting place with a sandy bed and piles, but with a higher flow velocity. Next to these two most common classes, there are seventeen other classes with a lower number of waiting places in them.

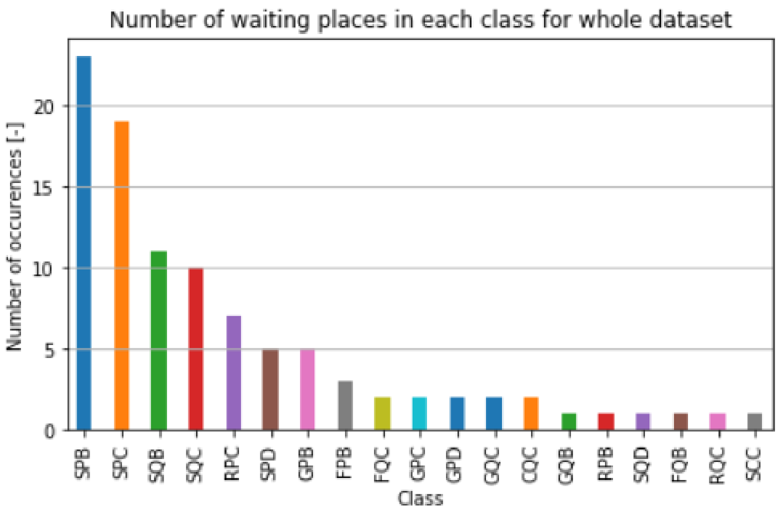


Figure 5.1: Number of waiting places in each class for the whole dataset

5.1. Comparison over CEMT-class

In the following Subsections, the result of the classification analysis is shown per CEMT-class, complemented by a discussion on the state of the bed and erosion. It is expected that deeper scour holes are found where the bed is unprotected and made of finer material or where higher near-bed flow velocities occur.

Figure 5.2 shows the distribution of berth properties and maximum near-bed flow velocity per CEMT-class. First of all, the number of waiting places per CEMT-class can be obtained. In Table E.1, an overview of the CEMT-class of the waterway of each waiting place is given. It is clear that most waiting places are located in a CEMT-class V waterway. In the left graph of Figure 5.2, the distribution of berth properties is shown. At most waiting places, a sandy top layer and piles have been observed. In the right graph, the distribution of maximum near-bed flow velocities is shown per CEMT-class. Moderate and high velocities are distributed quite evenly; only in CEMT-class V, extreme flow velocities are expected. In CEMT-class II, all waiting places have a sandy top layer and quay walls. However, from the right chart, it can be concluded that there is variation in the distribution of maximum near-bed flow velocities. So for CEMT-class II, the classification analysis results in two different classes. For CEMT-class V however, many different classes are expected because of the variety in berth properties and flow velocity. In CEMT-class V, also a few waiting places are protected. Where a bed protection has been placed, a larger flow velocity is expected and vice versa. All waiting places in CEMT-class IV of which data have been acquired are protected with 10-60 kg rocks.

Figure 5.3 shows the distribution of the scour depths per CEMT-class in box plots. The median depth becomes higher for higher CEMT-classes, indicating deeper scour holes for higher CEMT-classes. For CEMT-class II and V, accretion, or a negative scour hole, is observed. For waiting places in CEMT-class IV waterways, no data on the state of the bed has been acquired.

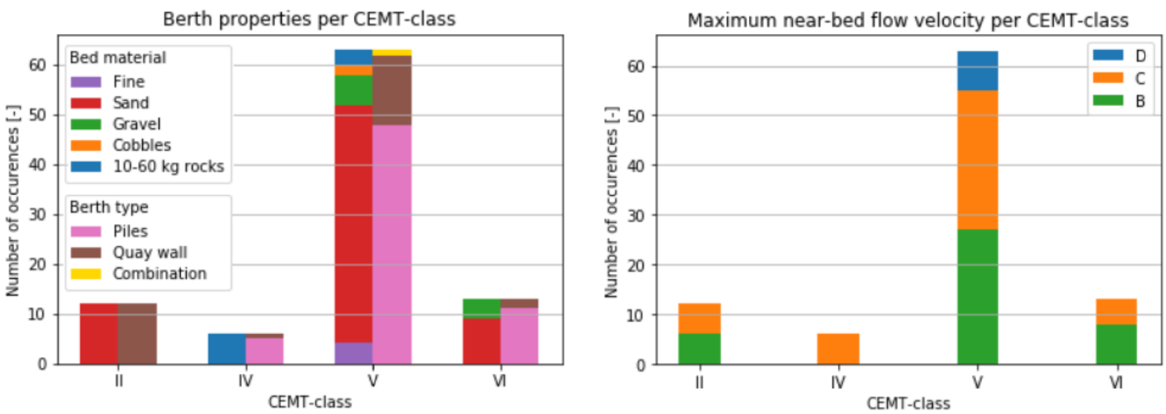


Figure 5.2: Distribution of berth properties (left) and near-bed flow velocities (right) of waiting places per CEMT-class

5.1.1. CEMT-class II

Three lock complexes are located in a class II waterway. Together they hold 12 waiting places. Half of the waiting places fall into class 'SQB', half fall into class 'SQC'. Both waiting places thus have a sandy top layer and a quay wall where only the load differs. This difference is caused because at lock Panheel, it was assumed there are bow thrusters, whereas at locks 15 and 16, no bow thrusters were assumed. Where bow thrusters were assumed, the near-bed flow velocity is slightly higher. In reality, bow thrusters are used at all waiting places. These differences in assumptions show there is room for uniformity in the design or assessment of the bed protections.

Figure 5.4 shows how many waiting places are in each class (blue + grey) and for how many of these waiting places data on erosion is known (blue). In the right bar, the number of scour holes or stable beds is shown. Scour holes with a depth ranging from -0.15 to +0.15 m are also regarded as stable

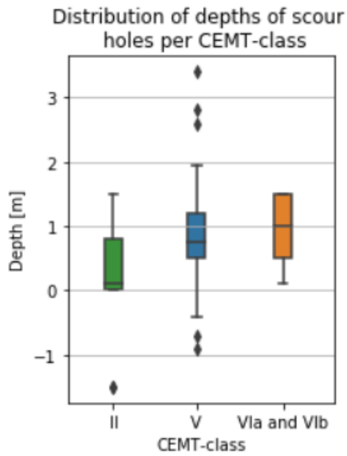


Figure 5.3: Distribution of depths of scour holes per CEMT-class

because the dredging tolerance is 0.15 m for waterways up to 5 m depths (RWS GPO, 2020). The number of scour holes can be higher than the number of waiting places where data on erosion is known, because some waiting places have two separate noteworthy scour holes. CEMT-class II waterways contain relatively many stable beds and waiting places with accretion compared to waterways of higher CEMT-classes.

Figure 5.5 shows the distribution of the scour hole depths, where a negative depth indicates accretion. At two waiting places of lock complex 16, 1.5 m sand has accumulated on top of the bed over a large area from the centre to the rear of the waiting places. Furthermore, it can be concluded that scour holes of class 'SQC' are on average deeper. The difference in near-bed flow velocities is caused by the fact that not for all waiting places of CEMT-class II, a load from a bow thruster was expected. At lock complex Panheel, the near-bed flow velocities from the bow thrusters are larger than the load from the main propellers.

Figure 5.6 shows the location and depth of the scour holes. The distance to the bank is the shortest distance from the deepest point in the pit to the closest bank. There are two holes close to a bank, both 1.5 m deep. This is below the limit where placing a protection would be preferred. The other holes are smaller and further away and thus do not pose a great risk for the collapse of the quay walls. The variation between the two classes regarding location and depth of the scour holes is small. Furthermore, no hole is so large that a bed protection is required. Due to little variation in berth properties and bed-load and actual erosion, there is a potential for standardisation for waiting places in CEMT-class II waterways.

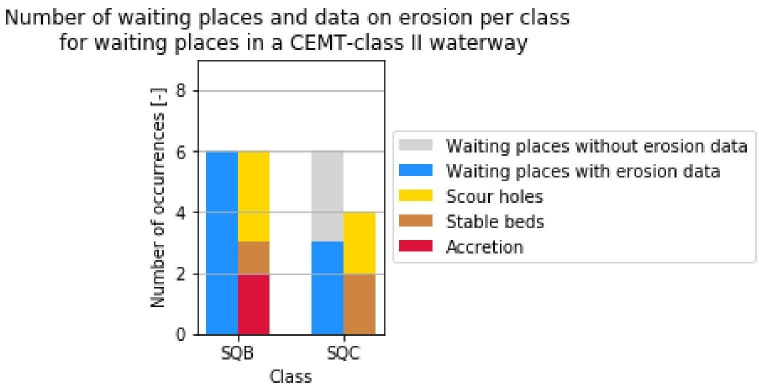


Figure 5.4: Number of waiting places, availability of erosion data, and scour holes in each class for waiting places in a CEMT-class II waterway

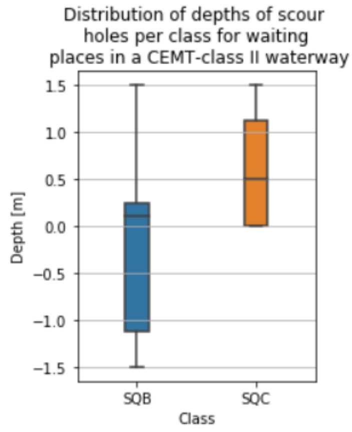


Figure 5.5: Distribution of depths of scour holes per class for waiting places in a CEMT-class II waterway

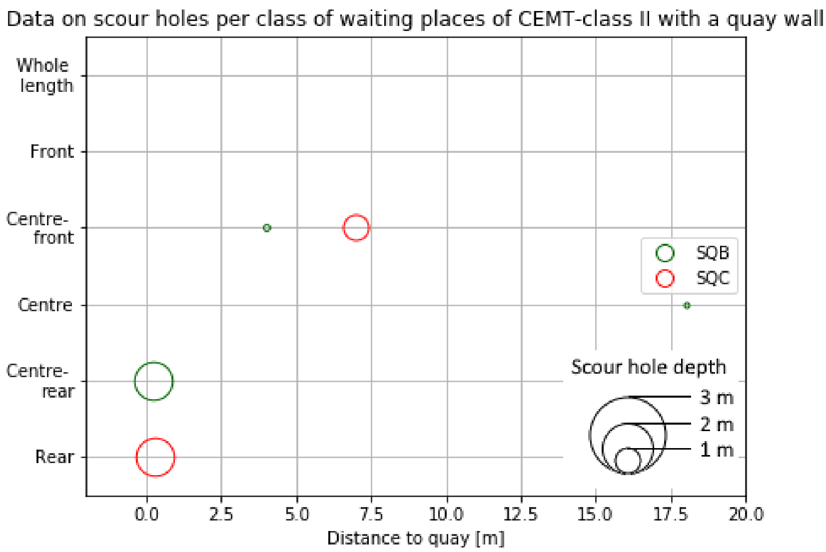


Figure 5.6: Location and depth of scour holes per class of waiting places in CEMT-class II waterways

5.1.2. CEMT-class IV

Two lock complexes are located in a class IV waterway, holding six waiting places in total, see Figure 5.7. Two different classes have been found, where the berth type is the only difference. At all six waiting places, 10-60 kg rocks have been placed on the bed to protect it. At none of these waiting places, measurements or information on the state of the bed have been found. The maximum expected near-bed flow velocities and actual bed protections fall into the same range, indicating that standardisation is beneficial. Information on the state of the bed could either validate or discredit this statement.

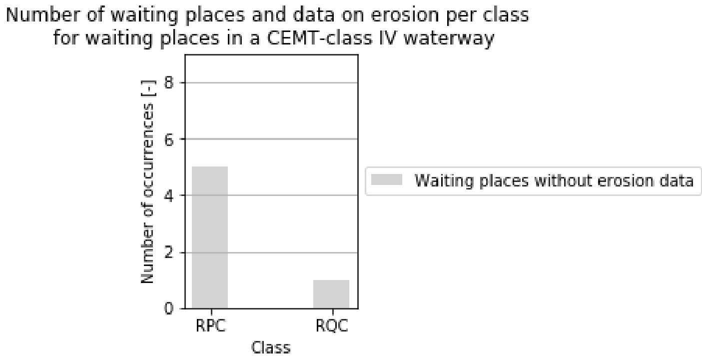


Figure 5.7: Number of waiting places and scour holes in each class for waiting places in a CEMT-class IV waterway

5.1.3. CEMT-class V

Most waiting places (68 out of 99) are located in a CEMT-class V waterway. They fall into 16 different classes, which are shown in Figure 5.8. Most waiting places are in class 'SPB' or 'SPC', meaning in a sandy waiting place with piles and a lower or medium near-bed flow velocity. These classes show the most potential for standardisation because they contain the most waiting places. Figure 5.9 shows the distribution of the scour hole depths for all classes. Several subsets of this Figure are shown in Figure 5.10.

For two classes, 'SPC' and 'SPD', multiple scour holes have been found at many waiting places. These two classes have their berth properties in common and are expected to have high to extreme near-bed flow velocities. Thus, more and deeper scour holes are expected than at class 'SPB'. However when looking at Figure 5.10a, it can be observed how the depths of the scour holes for sandy berths with piles don't differ significantly depending on their expected near-bed flow velocity.

For piles, the scour holes are expected to be deeper. However, Figure 5.10b does not confirm this expectation. Scour holes of classes SQC', 'SQB', and 'GQB' are deeper than their respective counterparts SPC', 'SPB', and 'GPB'.

Figure 5.10c shows the distribution of scour hole depths per class for waiting places with a protected bed, where a negative depth indicates accretion. The bed is stable in classes 'GPB' and 'RPC', where the scour hole depth is equal to zero, probably because the beds are protected. Most waiting places that are protected don't have deep scour holes, except for class 'CQC'. At Schijndel, the bed is protected with cobbles, but a scour hole of 1.5 m has been measured.

Also for finer beds, deeper scour holes are expected. As shown in Figure 5.10d, there are quite deep scour holes for class 'FPB', so near piles and with a moderate flow velocity. Only one waiting place has a fine bed with a quay wall. There, the scour depth is the same as the median depth of waiting places with a fine bed with piles.

At locks Eefde and Roermond, accretion has been found, which might cause problems for ships wanting to (de)berth. At Eefde however, the biggest heap of sand has accumulated mostly under a walkway between the bank and the piles, where ships cannot go. At Roermond, the largest heap is located at the front of the waiting place and is very concentrated in one location. The smaller heap is less steep and located more at the centre of the waiting place. The piles are at such distance from the bank, that the heap at the front does disturb any ships in the waiting place because of its steepness, whereas the heap in the centre does due to its smaller slope.

Figure 5.11 shows the location and depth of the scour holes. For berths with piles, it shows the distance from the deepest point of the scour hole to a pile; for berths with quay walls, it shows the distance from the deepest point to the closest quay. Most holes are located at the centre-front or rear of the waiting place, which is where the bow thrusters and main propellers are located. Holes caused by

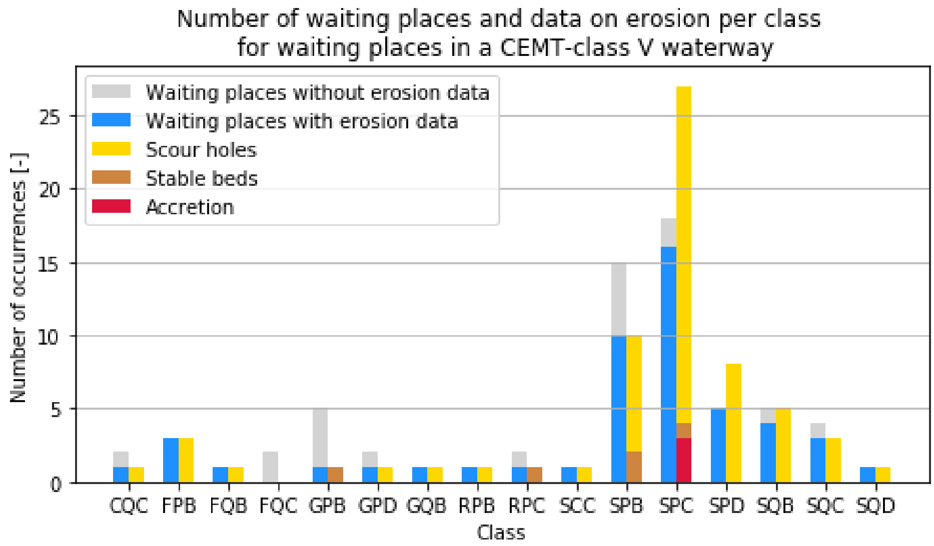


Figure 5.8: Number of waiting places and scour holes in each class for waiting places in a CEMT-class V waterway

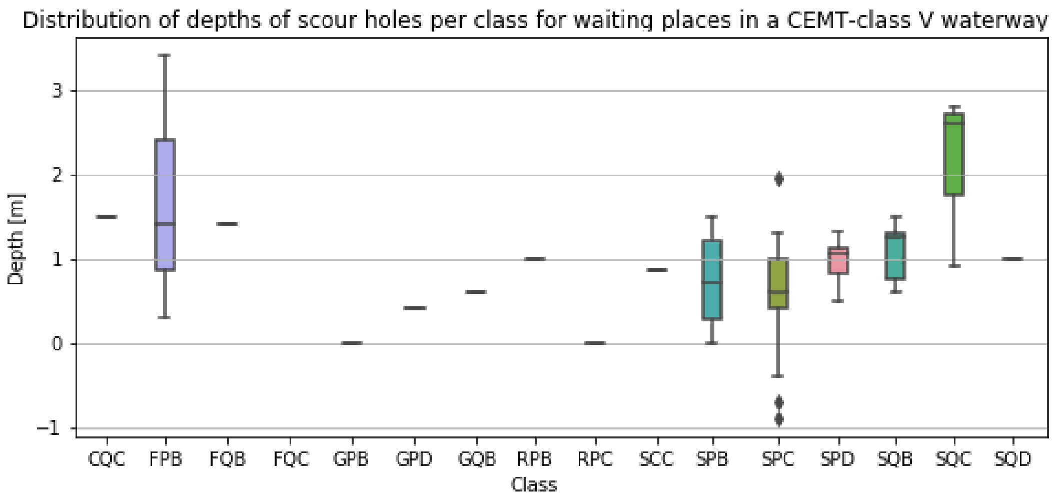
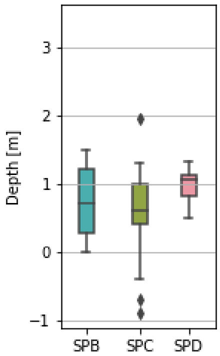


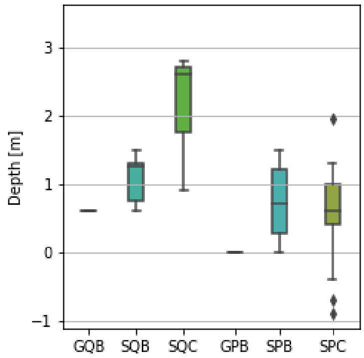
Figure 5.9: Distribution of depths of scour holes per class for waiting places in a CEMT-class V waterway

bow thrusters are located closer to the piles or bank than holes caused by the main propeller, which corresponds with Figure 2.3.

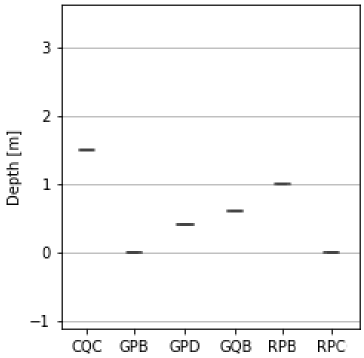
Within the two largest classes ('SPB' in pink and 'SPC' in yellow), there is not a lot of variation in scour hole depth. The largest hole from these classes is 1.94 m deep and is found in Hengelo. This hole was already detected some time ago during the inventorying of locks for RINK. At this moment, the waterway of lock Hengelo is being upgraded and deepened, so less scour is expected to occur in the future. All other scour holes are less than 1.8 deep and would thus suffice without a bed protection. This limit has been determined by the Blokland et al. (2018), where for holes with a depth under 1.8 m, it is not economically attractive to add a bed protection. A deeper quay wall or regular maintenance should suffice. Because the beds of classes SPB' and 'SPC' show similar erosion holes without extremes, there is a potential for standardisation. For example, the assumed used power and distance from the bow thruster to the quay wall vary per lock complex. Using standardised assumptions would result in equal expected bed loads without changing the actual erosion. However, the complexity of the strength calculation and comparison of waiting places would decrease. The larger holes are found in the classes containing fewer waiting places. Therefore, standardising the design of the bed protection for all classes would not be beneficial. Because the variety between the waiting places is still very



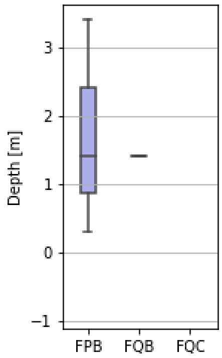
(a) Distribution of scour depths for increasing V_{bed}



(b) Distribution of scour depths for three sets of classes where only the berth type (quay vs. piles) differs



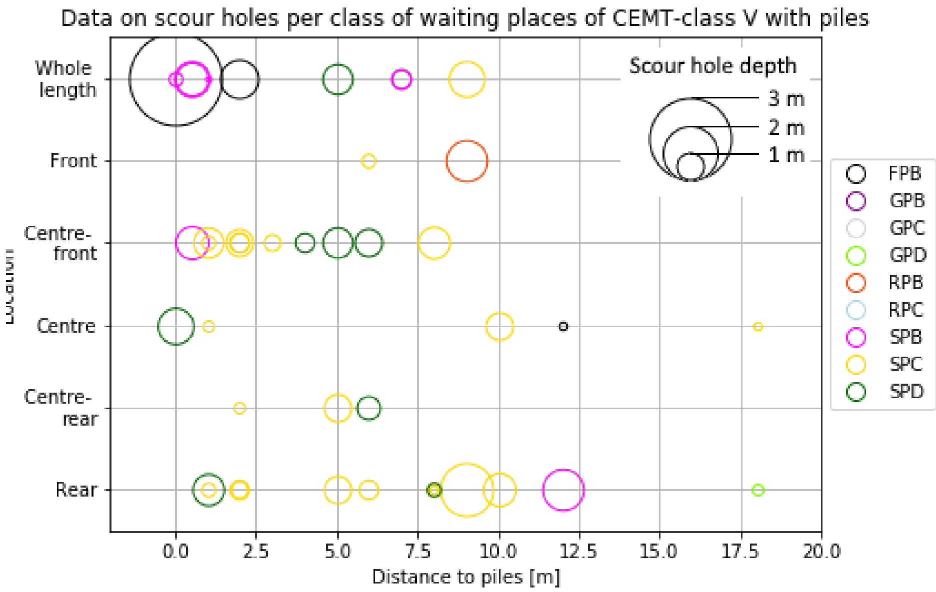
(c) Distribution of scour depths for protected beds



(d) Distribution of scour depths for fine beds

Figure 5.10: Distributions of scour depths

large, they are further divided into the corridors they are located in, see Section 5.2. In that Section, the differences between the waiting places and corridors are discussed in more detail.



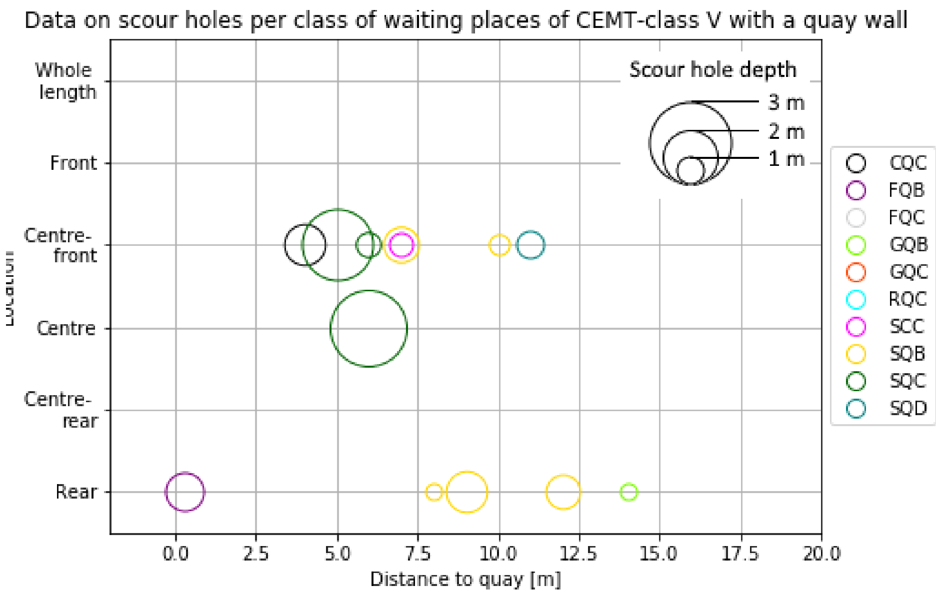


Figure 5.11: Location and depth of scour holes per class of waiting places in CEMT-class V waterways for waiting places with piles (top) and quay walls (bottom)

5.1.4. CEMT-class VI

Three locks are located in a waterway of class VI. Together they hold thirteen waiting places, see Figure 5.12. Four different classes have been found. Most waiting places fall into class 'SPB', so a sandy bed with piles and a moderate maximum near-bed flow velocity. One waiting place in the Prins Willem-Alexander lock has a deeper scour hole because the water depth is slightly smaller, 'Remmingwerk Buiten IJ'. For each waiting place where data on erosion was acquired, a scour hole has been found. No accretion or stable beds have been observed. Figures 5.13 and 5.14 shows the location and depths of the scour holes. Standardisation of the design of the bed protections shows some potential, because based on the multibeam drawings, no waiting places require a bed protection. Furthermore, the berth properties and expected load on the bed are very similar. However, for four waiting places, no multibeam was found. At these waiting places, a bed protection has been placed, probably because more scour was expected. It is unknown whether these waiting places would also have sufficed without a bed protection.

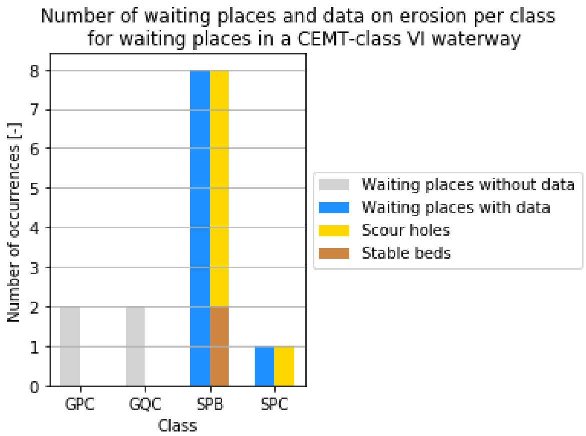


Figure 5.12: Number of waiting places, availability of erosion data, and scour holes in each class for waiting places in a CEMT-class VI waterway

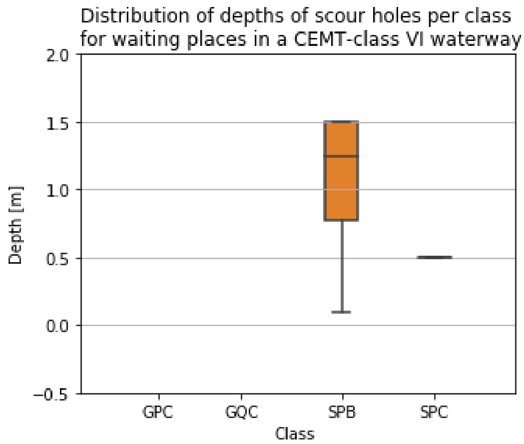


Figure 5.13: Distribution of depths of scour holes per class for waiting places in a CEMT-class VI waterway

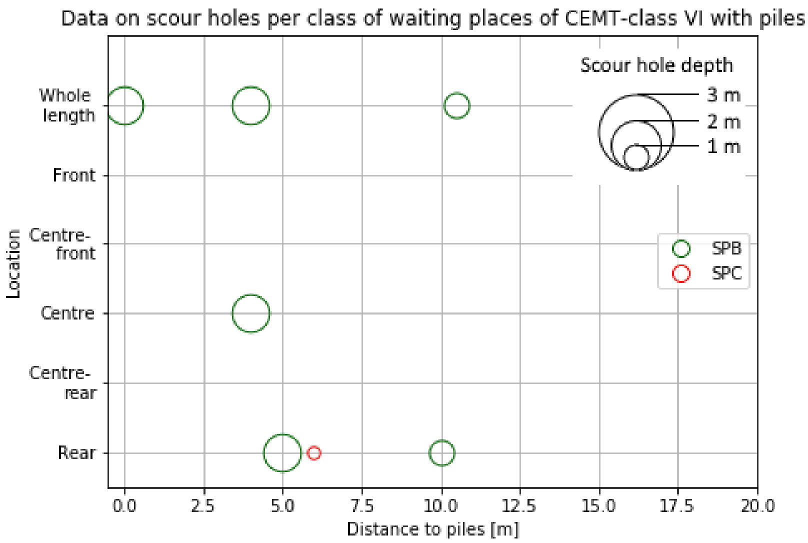


Figure 5.14: Location and depth of scour holes per class of waiting places in CEMT-class VI waterways for waiting places with piles

5.2. Comparison over corridors of CEMT-class V

Most waiting places are located in CEMT-class V, divided into 16 classes. The variation is too large for standardisation of all waiting places. This section will divide the waiting places into corridors. Both differences between corridors and more similarities within each corridor are expected because the design ship should be able to pass all locks in the corridor. Appendix F shows the corridors in which the lock complexes are situated, as retrieved from Rijkswaterstaat (2022c), these are visualised in Figure 5.15. Only waiting places in CEMT-class V are taken into further consideration, because only for this CEMT-class there is a significant number of waiting places. Figure 5.16 shows firstly the number of waiting places per corridor. Most waiting places are located in the Meuse corridor. As shown in Figure 1.3, the average number of waiting places per lock complexes in the Meuse corridor is high relative to other corridors.

Figure 5.17 shows the distribution of berth properties per corridor on the left and the distribution of maximum near-bed flow velocities on the right. Most waiting places have a sandy unprotected bed with piles. Most corridors contain too few waiting places to be of interest for standardisation. The Meuse, Nederrijn-Lek, and Twente channels are further discussed in the Subsections below. From

Figure 5.15: Corridors with lock complexes visualised by geographical location

Figure 5.17, a clear difference between these waiting places can already be seen in the expected loads: in the Meuse, there is much variation in near-bed flow velocities; in the Twente channels, the loads are on average higher than in the Nederrijn-Lek. This is because of a smaller depth. The Twente channels are being deepened, which will mean the near-bed flow velocities will decrease. The waiting places of lock IJmuiden in the North sea channel are noteworthy because they are protected with 10-60 kg rocks. However, the expected maximum near-bed flow velocities are not extreme.

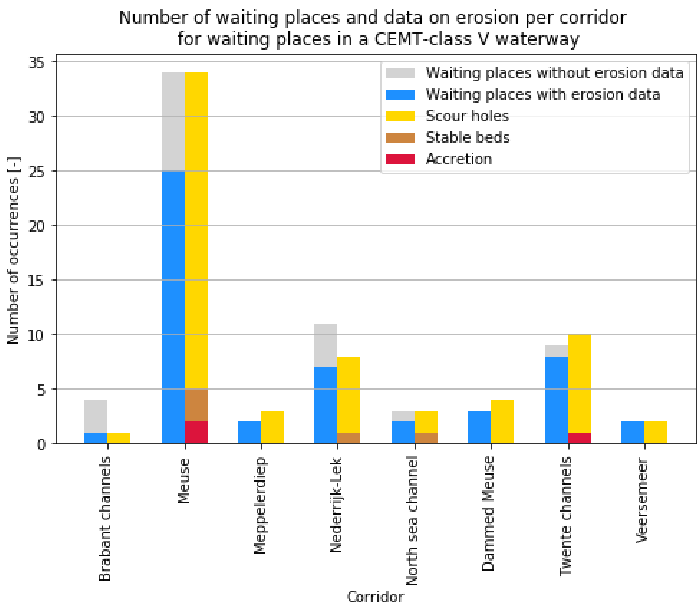


Figure 5.16: Number of waiting places, availability of erosion data, and scour holes per corridor for waiting places in a CEMT-class V waterway

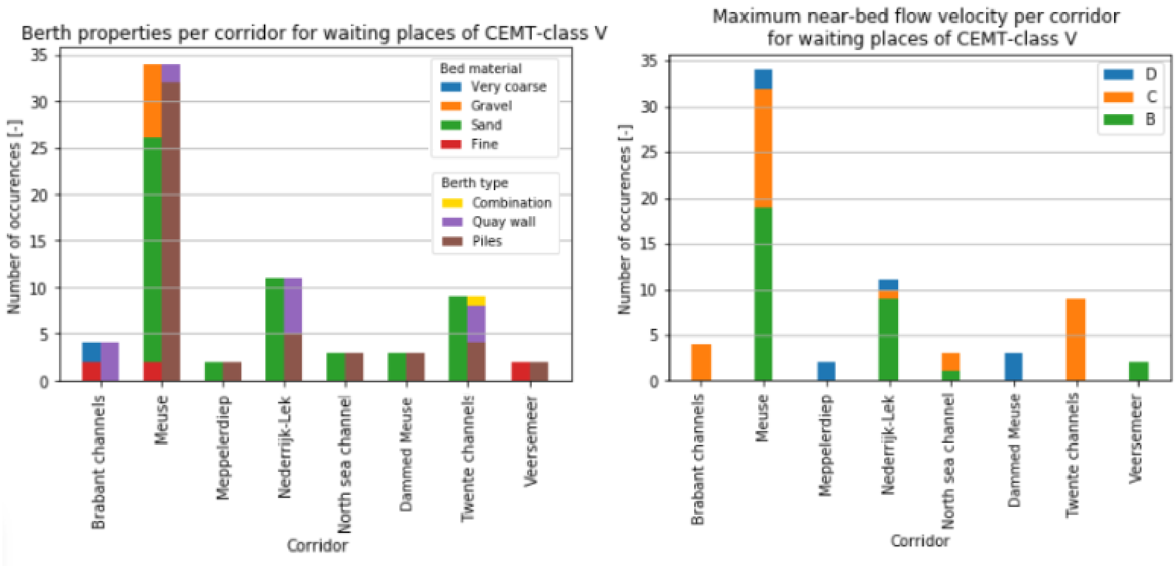


Figure 5.17: Distribution of berth properties (left) and near-bed flow velocities (right) of waiting places per corridor for waiting places in a CEMT-class V waterway

5.2.1. Meuse

In the Meuse, 34 waiting places are located where the expected flow velocities and berth properties are known, of which at 25 waiting places the state of the bed is known, see Figure 5.18. For only a few waiting places, an extreme near-bed flow velocity is expected. These velocities occur at lock Heumen, where the bed is protected with gravel. The distance from the bow thruster to the bank is smaller than at other waiting places, which is why the calculated near-bed flow velocity is higher. At lock Grave, which is the closest lock to lock Heumen, the bed is also protected with gravel. Contrariwise, the expected flow velocities at Grave are of category 'B', so moderate. For the waiting places with a higher near-bed flow velocity of range 'C' or 'D', e.g. Roermond, Belfeld, and Heumen, the used power that was assumed in the strength calculation of the RINK report is higher, which causes the higher flow velocity. Only at two waiting places, a finer bed material has been found, in Bosscherveld, which lies in Maastricht, far away from other locks.

Figure 5.19 shows the distribution of scour hole depths per class. It is remarkable that holes from class 'SPB' and 'SPC' are very similar, because the flow velocity of the second class is higher. A reason could be that although different assumptions were made in the RINK assessment, the actual load on the bed is similar. Furthermore, it is unexpected that there is accretion in class 'SPC', where the expected maximum near-bed flow velocity is larger. At most waiting places where the bed is finer, the observed scour holes are larger, which is in line with the expectation. The little variation in erosion indicates that there is potential for standardisation.

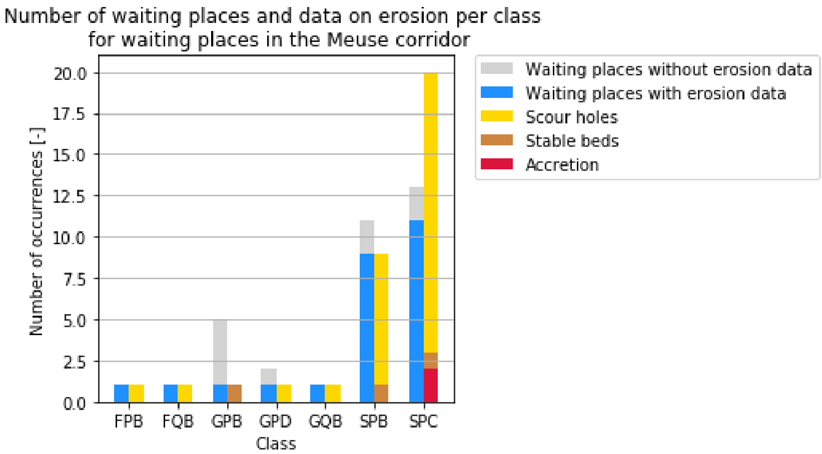


Figure 5.18: Number of waiting places, availability of erosion data, and state of bed for waiting places in the Meuse corridor

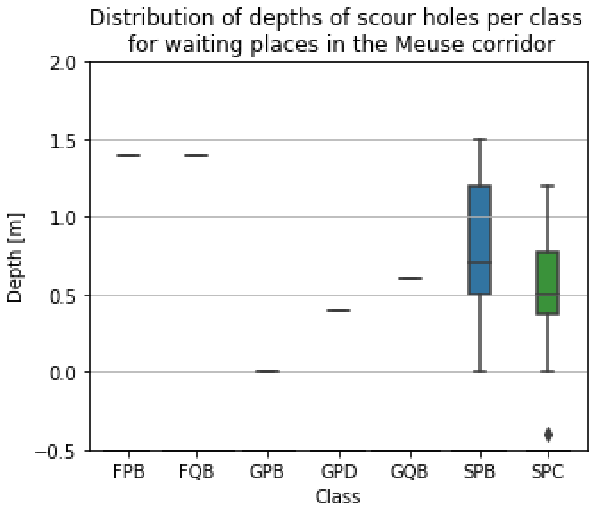


Figure 5.19: Distribution of depths of scour holes per class for waiting places in the Meuse corridor

Figure 5.20 shows the depth and location of the scour holes found at waiting places in the Meuse. The depth of the deepest scour hole is 1.5 m and is located at a waiting place with a finer bed. At the centre front of the waiting place, the scour holes are all measured at a very similar distance from the quay or piles. Where gravel is used as bed protection, the scour holes are smaller and further away from a bank or pile. If no gravel would have been placed here, the scour holes likely would have been closer to the quay and deeper. Standardisation might therefore not be beneficial in the Meuse. No scour hole of an unprotected bed is deeper than 1.8 m, so no further bed protections are required.

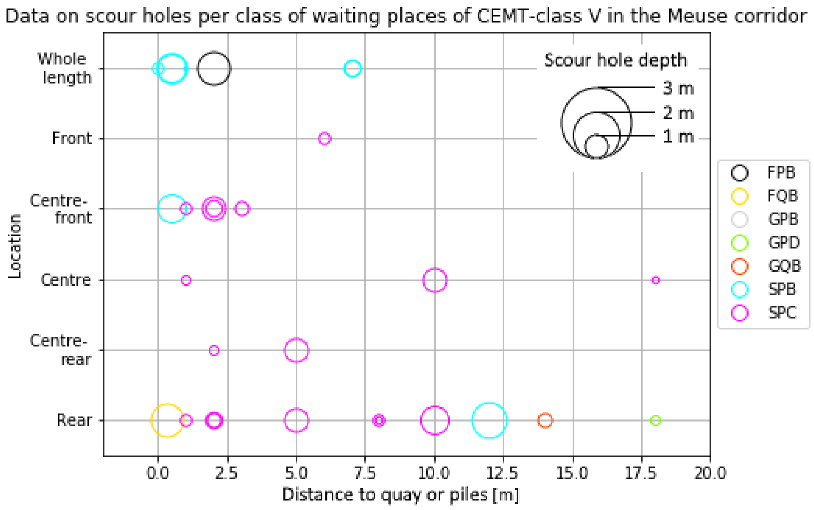


Figure 5.20: Location and depth of scour holes per class of waiting places in the Meuse

5.2.2. Nederijn-Lek

In the Nederijn-Lek, all waiting places have a sandy bed material, see Figure 5.21. Also at most waiting places, the maximum near-bed flow velocity is moderate. At one waiting place, the near-bed flow velocity is significantly higher, at the Noordersluis in Utrecht. This is because a smaller distance from the bow thrusters to the quay wall has been assumed, compared to other waiting places in the Nederijn-Lek. Also a smaller water depth was found here than at nearby locks, e.g. lock Hagestein or the princess Beatrix locks, see Figure 5.22. Furthermore, a higher near-bed flow velocity is expected at the Princess Beatrixlocks, resulting in class 'SPC'. This is caused by a smaller water depth than at other locks in the Nederijn-Lek.

The scour holes are only present at the level of the bow thrusters or main propellers, see Figure 5.23. Also the depths of the scour holes are of approximately the same magnitude, where none require a bed protection. At the rear of the waiting place, the distances to the bank or piles lie close together. The fact that the depths and locations of the scour holes are not large and similar, despite the different berth types and expected near-bed flow velocities, implies that there is potential for a more uniform approach. The solution is already standardised: at none of the waiting places, a protection is placed.

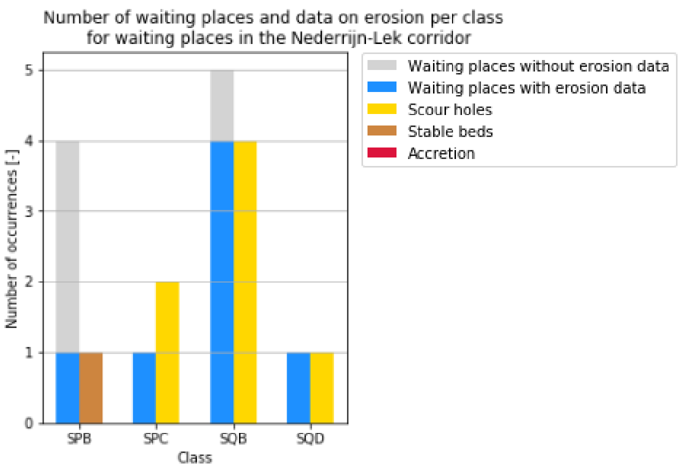


Figure 5.21: Number of waiting places, availability of erosion data, and state of bed for waiting places in the Nederijn-Lek

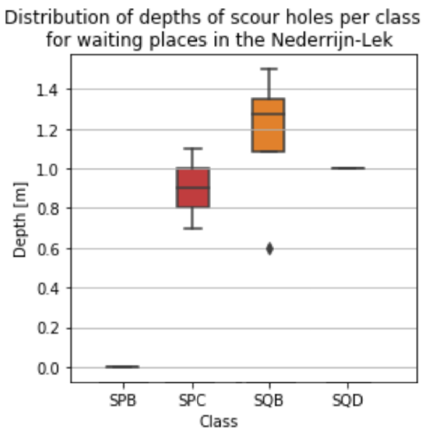


Figure 5.22: Distribution of depths of scour holes per class for waiting places in the Nederijn-Lek

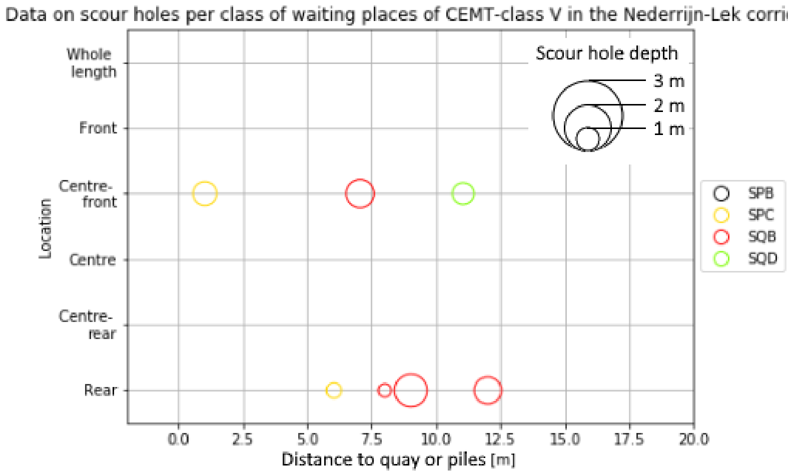


Figure 5.23: Location and depth of scour holes per class of waiting places in the Nederrijn-Lek

5.2.3. Twente channels

Figure 5.24 shows the classes of the waiting places in the Twente channels. At the Twente channels, both the bed material and the expected maximum near-bed flow velocities are similar, even though the berth type of the waiting places differ. Most scour holes are found more to the front of the waiting places. Two large scour holes are present in the Twente channels near a quay wall. On average, the holes in front of a quay wall are bigger than the holes near piles. This contradicts the expectation that the scour depth is larger around piles. It should be noted here that the Twente channels are being deepened and lower near-bed flow velocities are expected in the future, together with smaller scour holes. Because of the variation in scour hole depth and unexpectedly large scour depths shown in Figures 5.25 and 5.26, there are not many benefits for standardisation.

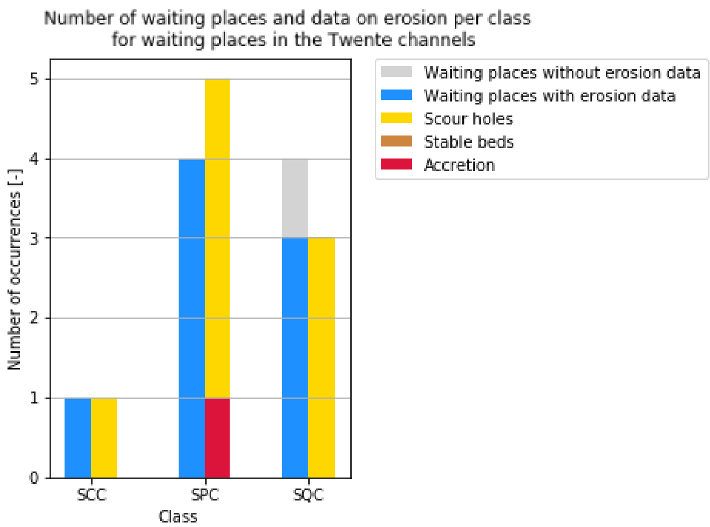


Figure 5.24: Number of waiting places, availability of erosion data, and state of bed for waiting places in the Twente channels

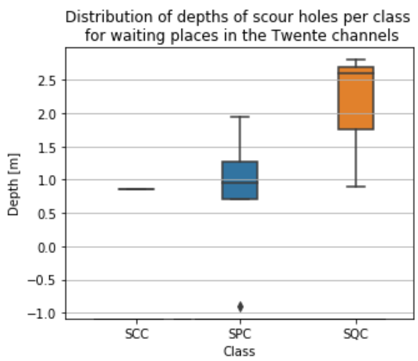


Figure 5.25: Distribution of depths of scour holes per class for waiting places in the Twente channels

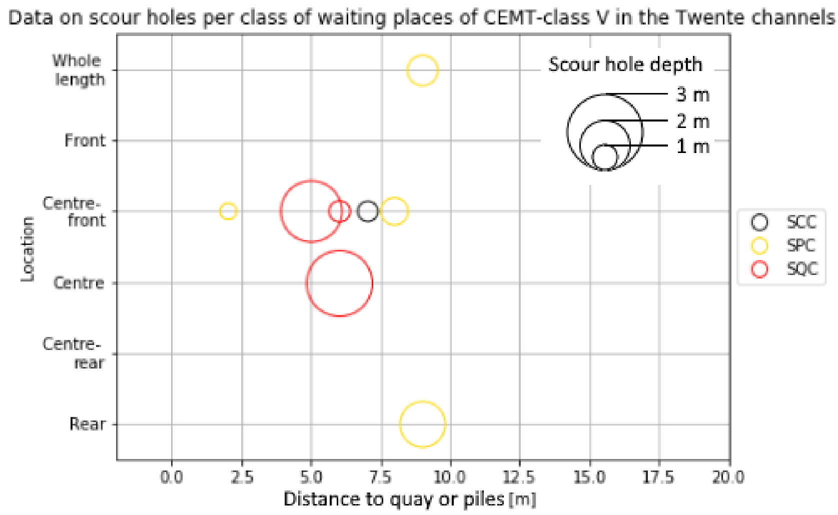


Figure 5.26: Location and depth of scour holes per class of waiting places in the Twente channels

6

Discussion

This Chapter will provide a discussion on the limitations of the research, its relation to other research, and the potential for standardisation.

6.1. Limitations

Critical points in this thesis are the quality and availability of the collected data. Also, information is lost during the classification analysis. This Section discusses the limitations of this research.

6.1.1. Quality of data

Uncertainty of data of actual bed protections

To find the most common type of bed protection that is used in approach harbours, research by De Kat (2021) was used. At 69% of all 236 (= 168) waiting places, a riprap bed protection was expected in the approach harbour and thus at the waiting places. However, upon further investigation of those waiting places, at only very few waiting places an actual bed protection was found. For approximately 60% of these waiting places (= 99), information was acquired regarding the design of a possible bed protection. In the RINK reports, the state of the bed is discussed and shown in multibeam drawings. For 68 waiting places, multibeam drawings were acquired. For 33 of those 68 waiting places, it was explicitly stated whether a bed protection is present at the location of the waiting place or not. For the remaining waiting places, a discussion on the bed protections within the scope of the multibeam is included. For none of those waiting places, a bed protection is mentioned. Therefore the assumption was made that no bed protection is present at those waiting places. However, it cannot be said that this assumption is true because it is based only on the fact that possible bed protections were not mentioned.

Data from RINK reports

The design parameters that were collected in Section 3.4 have been collected mostly from RINK reports. In the RINK reports, locks are reviewed. Regarding bed protections, new strength calculations were completed to see whether they still fulfilled the requirements of current guidelines and the state of the bed is discussed. For most waiting places, the RINK reports discuss only the bed protections directly next to the lock, whilst most waiting places are located further away. For this thesis, it was assumed that the same ships use the waiting places with the same power etc. as they would near and in the lock chamber. For several locks, the water depth differs between the lock and the waiting place, as shown in Figure 3.2. Here, the near-flow bed velocity has been recomputed to fit the correct water depth. For most locks, it is assumed that 100% of the power of the bow thrusters is used to manoeuvre in and out of the lock chamber, which is similar to manoeuvring at a waiting place (PIANC, 2015). For the main propeller, it was found that 70-100% of installed power was used for entering and leaving the lock. According to PIANC (2015), the same percentages can be assumed to be used during deberthing manoeuvres. PIANC (2015) recommends assuming 100% of installed power for the main propulsion system for smaller ships, decreasing to 50% for larger ships. However, as shown in Figure 3.6, not at all waiting places a bow thruster has been assumed. At several locks, it is stated that bow thrusters do not pose a risk at all for the bed protection in and near the lock. Just in front and behind the lock, the bow thruster is usually not near a quay wall that could direct the flow to the bed. The bow thruster is less strong and located higher on the ship and will be dispersed further when it reaches the bed than if it would be placed directly next to a quay wall. Inside the lock, the return flow usually causes the biggest near-bed flow velocity under the ship because of the sudden decrease of the wet area when the ship enters the lock. Upon leaving the lock, the main propellers cause the largest force because they are used at 100% and the initial jet is directed towards the bed by the closed lock doors directly behind the ship. The fact that the bow thrusters are not the governing load inside and near the lock, might be a reason why this load isn't always taken into consideration for the assessment of the bed protections. No pattern or reason has been found as to why for some locks the load by the bow thrusters are calculated and for others not.

Uncertainty in erosion data

For 68 waiting places, data on the state of the bed was acquired and collected. Next to the depth of scour holes or height of accumulated sand, also the lengthwise location in the waiting place and distance to either the quay or piles were measured. All erosion data have been gathered from multibeam drawings attached to RINK reports. All collected data on the bed profile contains uncertainty. First of all, the multibeam drawings only show the bed profile at one moment in time. It is possible that the scour hole present on the multibeam drawing is moved or filled up by another ship sometime after the bed was measured. It is possible that if the inspection was carried out at a different moment, the bed profile would have been different. This is more likely for smaller scour holes than for larger ones, because a large scour hole is developed over a longer time period. As shown in Figure 3.23, most scour holes are smaller than 1.5 meters and could thus have been moved or be of different depth if the bed was measured at another moment in time. The conclusions drawn from these data will therefore contain uncertainty.

Secondly, only the multibeam drawings were available; the documents containing xyz-coordinates of the bed were not. Therefore, the exact depth and location of each point of the bed were not known. The quality of the drawings can differ significantly per drawing: for some waiting places, the depth at the contour line was legible, for others, the depth had to be estimated using colours and a colour scale. There were also drawings without contour lines or colour scale which made finding the scour holes complicated. Also the exact distance from the deepest point to the closest quay or pile is not known. To estimate this distance, the multibeam drawing and top view of the lock and waiting place from Vaarweginformatie.nl were placed on top of each other, see Figure 6.1. Using the scale, a rough estimation of the distance could be made. For this waiting place, the recorded distance is twelve meters.

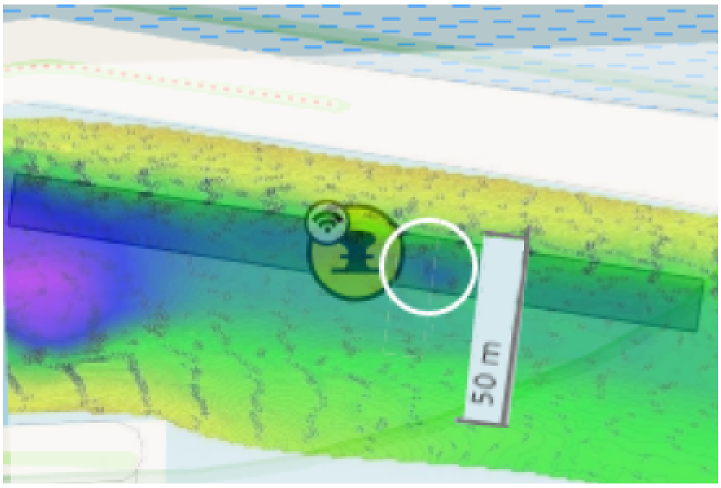


Figure 6.1: Snapshot from Vaarweginformatie.nl of outer waiting place the Zandkreek lock with the multibeam drawing placed on top of it. The white circle shows the location of the scour hole. Adapted from RWS Dienst VenW (2022) and RWS Dienst Infrastructuur (2013)

6.1.2. Availability of data

Most time of this research has been dedicated to acquiring data concerning design parameters and the state of the bed. Nevertheless, the required data have been found for all waiting places. First, the most common type of bed protection was searched for using data from De Kat (2021). For 19% of all waiting places (=46) this is unknown, seeTable 3.1. Then, many sources have been used to try to find the design parameters of the 168 waiting places where riprap was expected. For 60% of the 168 (=99) waiting places, these data were acquired. Figures 3.1 and 3.2 show at which waiting places these data were found. Less data was found on the state of the bed because some waiting places fell outside the scope of the multibeam drawings and some RINK reports did not include multibeam drawings. Most waiting places are located in a CEMT-class V waterway, so for this CEMT-class there are more data points. Compared to other CEMT-classes, the variety in design parameters, expected maximum near-bed flow velocity, and scour hole depths is the largest. If more data were known about the waiting places in waterways of other CEMT-classes, there is a chance that more extremes would also be observed there. For example for the 13 waiting places of CEMT-class VI, the maximum and minimum scour hole depths are respectively 1.5 m and 0.1 m. However, for 4 waiting places, no data is available on the state of the bed and there is a chance that the scour holes at those waiting places are much deeper or shallower. For waiting places in CEMT-class V, this chance is lower because more data is already available. The limited amount of erosion data that has been acquired of the waiting places introduces uncertainty in the conclusion of this thesis.

Although not all desired data has been acquired, there is a possibility that the data does exist and is stored by someone that was not approached during this thesis. This is however unlikely because a large number of employees and departments of Rijkswaterstaat have been approached. Information and lock managers of several regions have all been approached separately, but none could say where more data could be stored or point to someone that knew. The sources that have been consulted in this thesis are discussed in Section 3.2. Also nationwide and regional requests for documents from the physical archive led to little new data that wasn't obtained yet through the RINK reports.

6.1.3. Other types of bed protections

This research has limited itself to researching only the waiting places where the most common bed protection, riprap, was expected. Waiting places with bed protections of other types, such as concrete and set stone, were not analysed. The berth properties and maximum near-bed flow velocities can be grouped together with a classification analysis. The scour holes however develop very differently. For example, interlocking stones offer more resistance against uplift at first, but once one stone has cut loose, more stones will rapidly follow. For concrete slabs as well, the uplifting force is more important because the slabs are impermeable. If a part of the concrete slab were to break and drift off, immediately a large area of the bed would be exposed to the near-bed flow velocities, and large holes can form quickly.

6.1.4. Loss of information by classification analysis

In Chapter 2, the parameters required for the design of a bed protection at a waiting place were explained. However, if the classification analysis from Chapter 4 would have included all parameters, the analysis would have resulted in too many classes. Almost identical waiting places would have fallen into different classes, which defeats the purpose of the classification analysis. Therefore, the number of parameters used in the classification analysis was condensed using the literature discussed in Chapter 2. Finally, only the bed material, berth type, and maximum near-bed flow velocity were included. The maximum near-bed flow velocity is calculated using the power of the design ship, the draught, the water depth and many more parameters which are not represented directly. When looking at the results of the classification analysis in Chapter 5, information on these parameters cannot be obtained directly. However, Chapter 5 does discuss possible causes for deviating near-bed flow velocities, where these parameters are addressed. For example, the near-bed flow velocity in the Princess Beatrixlocks of class 'SPC', see Figure 5.21, is higher than at other waiting places in the Nederrijn-Lek. Here, the difference is caused by a smaller water depth.

Regarding the decision of the range boundaries for the classification, there are natural breaks in the dataset of expected maximum near-bed flow velocities at 1 and 4 m/s, see Figure 4.2. No natural break is however present at the range boundary of 2.5 m/s. As a result, two waiting places with the same berth properties and slightly different near-bed flow velocities can fall into different classes and can thus appear more different than they are. This is the case for the waiting places in CEMT-class VI: one waiting place has a slightly smaller water depth, which resulted in a slightly higher expected near-bed flow velocity. This made that one waiting place fall into a different class. This could however not have been prevented. If no range boundary would have been placed there, there would have been no differentiation between waiting places with an expected velocity of 1 and 4 m/s. Placing the boundary at 2.5 m/s is then the most logical location. At higher near-bed flow velocities, usually a bed protection should be placed.

6.2. Impact of other research on bow thrusters

This Section will relate the results of this thesis with other research. Currently, Deltares is doing research on the decay of the flow velocity of bow thrusters, which might influence the results of this thesis. It appears to be decreasing faster than described in current guidelines. If the guidelines are indeed too conservative, the expected near-bed flow velocities caused by bow thrusters calculated in RINK should be lower as well. As shown in Figures 3.18 and 4.2, the extreme near-bed flow velocities are mostly caused by bow thrusters. The results of the research of Deltares are not yet published so it is not yet known to what extent current guidelines underestimate the decay in flow velocity of bow thrusters. As a result, it is also not yet known how much the near-bed flow velocities in Figure 4.2 will decrease. It is however likely that more waiting places will fall into range 'B' (moderate velocity) instead of range 'C' (higher velocity). At other range boundaries, there is a prominent natural break in the data so there, it is less likely for waiting places to fall into a different range if the near-bed flow velocity would be lower.

6.3. Potential for standardisation

When the degree of variation between the design parameters assumed in the RINK assessment and between the state of the beds is low and the beds are behaving in accordance with literature, there is potential for standardisation. If the design parameters and state of each bed vary much between the waiting places, it is better to optimise the bed protection per waiting place. If, for example, the design of bed protections with different loads would be standardised, some bed protections will be over-dimensioned. The strongest load has to be assumed for all waiting places, or else some beds will fail. Over-dimensioning should be avoided because it requires more materials which might not be necessary. The smaller the degree of variation of hydrodynamic loads between the waiting places, the more benefits standardisation has. Next to the degree of variation, it should be considered whether the actual state of the bed is in accordance with literature, e.g. for finer beds, deeper scour holes are expected. When the actual scour holes are not in accordance with literature, it could indicate that the bed-load estimation or the scour depth measurement was incorrect. It is not likely that either the berth type or bed material is estimated wrong. A wrong bed-load estimation could be due to incorrect guidelines or incorrect design assumptions. For example, in reality, different ships could have used the waiting berth than expected. As discussed in Section 6.1.1, the erosion measurements were not exact and taken at only one moment in time and thus contain uncertainty. If the erosion and behaviour of the bed are unpredictable, these uncertainties should be factored in during the design. This can result in over-dimensioned and conservative bed protections. This Section will discuss the degree of variation of the waiting places, whether the measured erosion matches the expected erosion and the possible benefits of standardisation.

6.3.1. Degree of variation

The degree of variation is measured using the distribution of the waiting places in classes and the variation in erosion. Fewer classes indicate less variation in expected bed loads and scour holes which shows potential for standardisation. Furthermore, the variation of erosion within one class should be inspected. If little variation is found, the potential benefits of standardisation are higher. 19 different classes have been found for the waiting places where a riprap bed protection was expected and where data on erosion and expected near-bed flow velocity was found. Because of this high number of classes, the potential for standardisation is also investigated per CEMT-class.

Variation per CEMT-class

As shown in Section 5.1.1, there is little variation in berth properties, bed-load, and erosion for all waiting places in CEMT-class II. There are two classes, which only vary in expected near-bed flow velocity. Furthermore, the scour holes are small and similar in size. For CEMT-class V, there are 16 classes, and also many waiting places. Most waiting places fall into a class with a sandy upper layer and piles as berth type. However, due to the sheer amount of classes and the large variation in erosion, standardisation of all waiting places in class V will not be beneficial. More likenesses are expected per corridor, so the waiting places of CEMT-class V were further analysed per corridor. For CEMT-class VI, four waiting places were found, where most waiting places lie in one class, containing sand, piles, and a moderate bed load. The waiting places where erosion data is available show only small scour holes where no bed protection is required. For the classes where a bed protection is placed, no erosion data was available.

In Section 5.1, the causes for different classes were discussed for each CEMT-class. The differences are mostly caused by three parameters: whether a bow thruster was assumed in the design, water depths, and the assumed power of the thrusters. However, the resulting erosion depths per CEMT-class are very similar. Only for CEMT-class V, large holes were found. Based on the little variation in classes and erosion within CEMT-classes II and VI, it can be concluded that the design assumptions, e.g. assumed power of thrusters, in CEMT-class II and VI can be standardised. The water depths however are fixed and cannot be changed or standardised.

Variation per corridor of CEMT-class V

More similarity is expected for waiting places in one corridor. The corridors with the most waiting places were analysed further: the Meuse, Nederrijn-Lek, and Twente channels. There are also some distinct differences between the corridors. In the Twente channels, the near-bed flow velocity is on average significantly higher than in the Nederrijn-Lek due to a difference in water depth.

Most waiting places are located in the Meuse, where many differences were found in berth properties and estimated bed load. The difference in bed load is mainly due to different assumptions for power. It is possible that different assumptions for power are made because of differences in berth layouts, i.e. a waiting place with piles could be directly in front of a lock for which case bow thrusters are not required. However, due to similar layouts of berths over the Meuse, it is expected that the use of thrusters for berthing manoeuvres is also similar. The maximum erosion depth varies between -0.4 and +1.5 m, so at none of these waiting places more bed protection is required and there is a potential for standardisation. Research should be done into what the expected used power is per thruster over the whole Meuse to find the best-fitting standard.

In the Nederrijn-Lek, all waiting places have a sandy bed. There are however differences in berth type and near-bed flow velocities. Differences in bed load are mostly due to different assumptions for the distance between the quay and bow thruster. When looking at the berth layout of waiting places in the Nederrijn-Lek, for waiting places with piles, the distance is indeed larger since the piles are not placed directly next to the quay wall. There are however only small differences in distance between piles to the quay wall. The observed scour holes are not very threatening. Because of the little variation in scour hole depths, there is a potential for standardisation of design assumptions.

In the Twente channels, three different classes have been found, for which the expected flow velocities are similar. The only difference originates from the berth type. Although the expected bed-loads are similar, varying sizes of scour holes have been found, of which some are alarmingly big. This discourages the effort for standardisation. At the moment, the waiting places with large scour holes are being deepened, so smaller holes are expected in the future.

After dividing the waiting places from CEMT-class V into corridors, much more similarities were found. In the Meuse and the Nederrijn-Lek, there is definitely potential for standardisation because of the little variation in scour hole depths. In the Twente channels, there is not as much potential for standardisation. By standardising design assumptions such as the power used during berthing, a better approximation of the maximum near-bed flow velocity can be made.

6.3.2. Measured erosion vs. expected erosion

The expected scour depends on the design parameters as concluded in Section 2.6. For the classification analysis, these were condensed into three parameters: bed material, berth type, and maximum near-bed flow velocity. Per parameter, the relation with scour depth is explained below. The actual scour depths, estimated with multibeam drawings, are compared to the relations to determine whether the actual scour holes are in accordance with literature.

Römisch (2006) developed empirical guidelines for the scour depth, see Equations 2.6 and 2.7. These equations are valid to calculate the scour depth in front of a quay wall for non-cohesive soils when transverse thrusters are used. The equations are visualised in Figure 6.2. At thirteen waiting places, the conditions are similar so that the scour holes can be compared to the guidelines. However, at eight of those waiting places, no data on the state of the bed was found. Finally, at two waiting places, no scour was found. The three scour holes that remain are shown in Figure 6.2. The actual scour hole depths should be compared to the red line, because a steady state situation is very rare for a waiting place (PIANC, 2015). The graph shows the relative scour depth. Römisch (2006) used D_{85} as diameter. However, this soil characteristic is not known for the measurements of this thesis. Instead, $D50$, which could be obtained from RINK reports, is used. For sand and gravel, D_{50} does not differ a lot from D_{85} because of its steep particle size distributions (Xing et al., 2014). For an estimation, it is therefore sufficient to use D_{50} to calculate the relative scour depth. The observed scour holes are in the same order as the formula of Römisch (2006). As discussed in Section 6.1.1, there is some inaccuracy in the measurements of the erosion depth, which should be kept in mind when discussing the state of the bed.

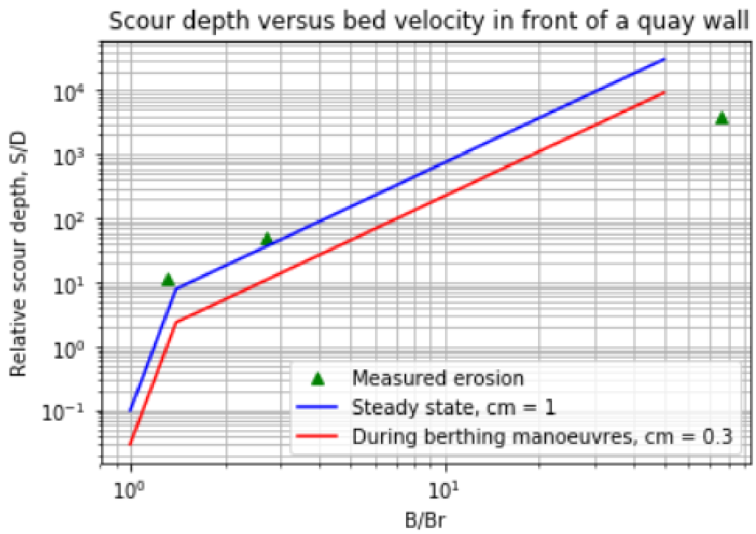


Figure 6.2: Measured erosion of this thesis compared to empirical formulas based on measurements of Römisch (2006)

Bed material

The finer the bed, the larger the expected scour depths. Particles of less weight are picked up more easily by the flow. The waiting places of CEMT-class II and VI can't confirm nor deny this because all waiting places with data on erosion have the same bed material. In CEMT-class V however, several different bed types exist. It is surprising that at protected beds, see Figure 5.10c, there are scour holes of 1 and 1.5 meters, without the expectation of extreme flow velocities. The average scour depth of holes in finer beds is higher than for rougher or protected beds, see Figure 5.10d. Most holes in sandy beds are less deep than in finer beds and on average slightly deeper than in protected beds. This is in accordance with expectations based on literature.

Berth type

As explained in Section 2.2.2, the expected depth of a scour hole around a pile is larger than in front of a quay, due to the contraction of flow lines around a pile. This causes a higher near-bed flow velocity which results in larger scour holes. Figure 5.10b shows the scour depths of six waiting places. Scour depths of classes 'GQB', 'SQB', and 'SQC' were compared to their respective counterparts 'GPB', 'SPB', and 'SPB' to research the influence of piles. For none of these pairs, the scour hole depth is deeper for the class with piles. This contradicts the guidelines which may complicate standardisation.

Maximum near-bed flow velocity

For higher near-bed flow velocities, deeper scour holes are expected. In CEMT-class II, the average scour hole depth is indeed larger for higher flow velocities, see Figure 5.5. In CEMT-class V however, the scour depth does not change for increasing bed loads, even for beds with the same material, see Figure 5.10a. For CEMT-class VI, the scour depth is smaller for a higher expected near-bed flow velocity. However, only one data point with a higher flow velocity is available.

Conclusion

In conclusion, the actual scour is not always in accordance with expectations based on literature. Especially the relations between scour depth and both piles and near-bed flow velocity are not represented in the data. There can be multiple causes for these anomalies, e.g. inaccurate erosion measurements, incorrect design assumptions, etc., as discussed at the beginning of Section 6.3.

6.3.3. Benefits of standardisation

There are guidelines for the formulas and design assumptions that engineers need to use in the design of a bed protection at a waiting place. Within a CEMT-class or corridor, it was expected that the design assumptions would not differ much from each other. However, the assumptions, such as used power, have been observed to differ even within corridors. Due to the large number of assumptions that need to be taken, it is difficult to test which assumptions are correct, because there are not many other waiting places where the exact same assumptions have been done. By standardising the design assumptions, it would become clearer what conditions a protection should meet. This simplifies monitoring of the design as well. Furthermore, if more waiting places are designed with the exact same method, the estimations of building duration and cost, lifespan, and required maintenance will contain more certainty because there are more reference projects to compare the new waiting places to. Finally, the duration and complexity of the design phase will be smaller which saves money. However, sufficient research should be done to find the appropriate standard per CEMT-class and corridor.

On the other hand, standardisation has some disadvantages. If the degree of variation is large, standardisation will lead to an overly conservative design for some waiting places, as explained in Section 6.3. From a sustainability perspective, optimisation per waiting place is usually preferred. Also development of new creative solutions for bed protections is not encouraged by standardisation. However, specialisation and research are needed for developing the correct standard.

A risk for the benefits of standardisation is that in the future, new developments may occur with regard to requirements, conditions, or guidelines. For example, the vessels using the waterways can become either larger or smaller, or new propulsion systems can be developed that exert a large force on the bed. Due to climate change, the water depths will be subjected to more extremes. However, the current guidelines describe which water depths should be used. The bed protections are not designed for incidentally low or high water depths. During occasional droughts, temporary draught or power restrictions may be imposed on certain waterways to prevent damage to the bed.

7 Conclusion and recommendations

This Chapter will answer the question: ”what are the potential benefits of standardisation of the design of bed protections at waiting places of ship locks in the Netherlands?”. Also, recommendations that follow from this research will be discussed.

7.1. Conclusion

Standardisation is beneficial when the variation in the state of the bed and design parameters between waiting places is low. If, for example, there is significant variation in the loads on the bed, standardisation will lead to some over-dimensioned bed protections, which should be avoided. To determine the potential benefits of standardisation, the waiting places were compared based on design parameters assumed in RINK assessments. Three sub-questions were answered to arrive at an answer to the main question.

To answer the first question, a literature review was conducted to find which parameters are required to calculate the dimensions of a bed protection at a waiting place of an inland ship lock in the Netherlands. By researching Dutch guidelines, four categories of design parameters were identified:

- Ship dimensions: beam, and design draught
- Propeller characteristics for main and bow propeller: type, number of thrusters, used power, diameter, distance from propeller axis to the bed, and distance from propeller axis to the quay
- Hydraulic boundary conditions: design water depth
- Berth properties: berth type, slope angle, and bed material

Next, data on these design parameters were collected for all waiting places where the most common bed protection type was expected. Choosing only the most common bed protection type simplified the analysis on erosion. In total, there are 236 waiting places for inland ship locks. Based on data from De Kat (2021), at a significant portion of the waiting places, 168 out of 236, riprap was expected. For 59% of the waiting places where riprap is expected as bed protections, the design parameters listed above were acquired. For 60.9% of the waiting places where riprap is expected, the expected maximum near-bed flow velocities were acquired. Using multibeam drawings, data on the state of the bed was acquired for 68 waiting places. Almost all data was obtained via RINK reports, which were made in 2010 and include an assessment of current beds and expected loads. From the multibeam drawings, it can be concluded that most scour holes are not very deep, i.e. less than 1.8 m deep. Only four holes are deeper than 1.8 m, which is the limit, under which it is economically unattractive to place a bed protection, as defined by Blokland et al. (2018). At 15 waiting places, a riprap or gravel protection was found; at 18 waiting places, it was certain no bed protection is present. At the remaining waiting places, it cannot be said with full certainty whether there is a bed protection or not. However for the waiting places where the bed was discussed in RINK reports, the assumption was made that there are no protections, else they should have been mentioned there. For 81 out of the 99 waiting places where a riprap bed protection was expected, this expectation was inaccurate. Figure 7.1 shows an overview of which data was available and the occurrence of bed protection types. Overall, it can be concluded that for many waiting places, no data was available.

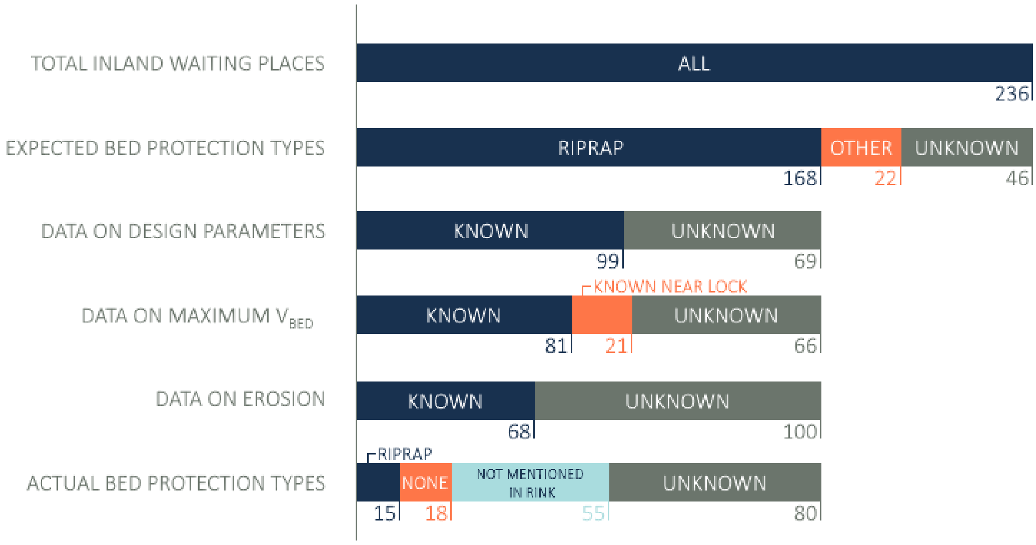


Figure 7.1: Overview of occurrence of bed protection types and availability of data for the most commonly expected bed protection type

Then, similarities between the bed protections regarding the design of bed protections at waiting places were found in order to examine whether there is potential for standardisation. The design parameters were condensed and compared on three parameters: bed material, berth type, and maximum expected near-bed flow velocity. In addition, the state of the bed was used in the comparison between waiting places. Using a classification analysis, similar waiting places were grouped together in a class. Classification of the whole dataset resulted in 19 different classes. There is too much variation in erosion and design vessels between all waiting places to find one standard solution for all of them. More similarities were found for waiting places in the same CEMT-class or corridor: in CEMT-class II and VI, similarities were found that show potential for standardisation of the design per CEMT-class. Waiting places in CEMT-class IV already have similar solutions for bed protections and might therefore be standardised. For waiting places of CEMT-class V, too much variation was found. Therefore, the waiting places of CEMT-class V were analysed per corridor. In these corridors, only waiting places in the Nederrijn-Lek corridor show enough similarities for standardisation to be beneficial. In the Meuse and Twente channels, the observed scour hole depths differ too much; so where bed protections are required, they should be optimised per waiting place. Other corridors contain so few waiting places that the effort for standardisation does not outweigh the potential benefits. The actual scour holes were not all in accordance with the expectation. Especially where larger velocities were expected, no larger scour holes were found. A reason for these anomalies could be that actual use deviates from the assumed use in the design, e.g. used power of thrusters. Actual loads on the beds could thus be similar.

For the groups with a low degree of variation - CEMT-class II, VI, and the Nederrijn-Lek corridor - no scour holes were observed that require protection. Even when taking into consideration that the erosion data were not exact and taken at only one moment in time, the observed scour holes did not pose a significant risk to the quay walls and piles. One standardised solution could be to allow these holes and not protect the bed. However, due to the number of uncertainties, as explained in Chapter 6, there is a not insignificant chance that in waiting places where no data was acquired, larger scour holes have developed. Also in the Meuse, no large scour holes were found. However, the holes were found in protected beds, making it likely that at these waiting places higher bed-loads occur. Because the scour and assumed maximum near-bed flow velocities vary a lot between waiting places, the potential for standardisation in the Meuse is low. In the Twente channels, there is also too much variation in scour holes for standardisation to be beneficial.

For corridors and CEMT-classes with a good potential for standardisation, standardising the design assumptions concerning ship dimensions and propeller characteristics might be beneficial. A potential standard design vessel per corridor or CEMT-class can lead to a more reliable estimation of the expected scour at the waiting places. Furthermore, estimations for new bed protections at waiting places on lifetime, building duration and cost, and required maintenance will be more substantial because there are more reference projects to compare the new waiting places to.

7.2. Recommendations

First of all, it is recommended that a clear overview is available of which data is available and where the data can be found. The largest portion of this thesis was dedicated to finding data. As shown in Section 3.2, many databases have been searched. However, only the RINK database contained the required data for multiple waiting places. Many information- and lock managers have been approached during this thesis, but none had a clear overview containing all data sources. The fact that information is stored differently in each region, complicates network- or nationwide research.

Secondly, from a researcher's perspective, it is recommended to collect more data on erosion, design parameters, and the expected near-bed flow velocity. By doing a second multibeam measurement, the uncertainty in the erosion data will be decreased, because the erosion is then measured at two moments in time instead of one. This can give a better idea of the change in scour depth as a function of time. If data on erosion etc. is known for more waiting places, then the conclusion of whether standardisation is beneficial can be drawn with more certainty. Contrarily, it can be refuted from a more practical point of view that additional data are necessary. At only very few waiting places, large scour holes have been found. Therefore, a trade-off has to be made between the extra effort and the potential gain of collecting more data. A middle ground could be to measure the bed when a lock is inspected for other reasons. The results of these measurements should then be kept in a logical and easily locatable place.

Thirdly, it is recommended to standardise ship dimensions and propeller characteristics per CEMT-class and corridor. At the moment, the minimum ship dimensions for a ship to use the waiting place are fixed in the CEMT-class. However, for example in the Brabant channels, larger beams than the minimum should be assumed because wider ships use the locks. Also properties such as the assumed used power per thruster, distance from bow thruster to quay etc. vary within one corridor or CEMT-class. By standardising the ship dimensions and propeller characteristics per CEMT-class and corridor, better estimates of building cost, lifetime, etc. can be obtained. Further research should be done to find those standard vessels per corridor and CEMT-class. If this standard were to be developed, it is interesting to review whether the observed scour holes are more in accordance with the new-found expected near-bed flow velocities than with the current expected near-bed flow velocities.

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A

Type of protection per lock

Table A.1: Type of protection in approach harbour per lock (De Kat, 2021)

Object code	Object name	Type
06H-350-02	Gaarkeuken	Riprap
07C-003-01	Dorkwerdersluis	-
07D-002-04	Oostersluis	-
07D-135-01	Slochtersluis	Riprap
07D-136-01	Driewegsluis	-
07F-002-01	Zeesluizen Farmsum klein	-
07F-002-02	Zeesluizen Farmsum kamer 2	-
07F-124-01	Groevesluis-Zuid	Riprap
07F-125-01	Groevesluis-Noord	Riprap
10B-001-05	Lorentzsluizen kamer 1	-
10B-001-06	Lorentzsluizen kamer 2	-
11C-350-01	Terhornesluis	Riprap
14E-001-01	Stevinsluizen	-
15F-001-01	Prinses Margrietsluis	-
20A-001-01	Krabbersgatsluis	Concrete
20A-100-01	Naviduct Krabbersgat	-
20A-100-02	Naviduct Krabbersgat	-
20D-001-01	Houtribsluizen	Concrete
20D-001-02	Houtribsluizen	Concrete
21C-001-01	Roggebotsluis	-
21E-001-01	Grote Kolksluis	-
21E-002-03	Meppelerdiepsluis	-
21G-350-01	Spooldersluis	Riprap
25A-001-01	Noordersluis	Riprap
25A-001-02	Middensluis	Riprap
25A-001-03	Zuidersluis	Riprap
25A-001-04	Kleine Sluis zuidersluis	Riprap
25E-001-01	Noordersluis (Oranjesluizen)	-

Table A.1: Type of protection in approach harbour per lock (De Kat, 2021)

Object code	Object name	Type
25E-001-02	Middensluis	-
25E-001-03	Zuidersluis	-
25E-001-07	Prins Willem Alexandersluis	Riprap
31H-006-01	Zuidersluis	Concrete
31H-007-01	Noordersluis Kleine westelijke sluis	Riprap
31H-007-02	Noordersluis Grote oostelijke sluis	Riprap
31H-008-02	2e Sluis Bewesten Utrecht (Muntsluis)	Riprap
32E-001-01	Nijkerkersluis	-
33F-001-01	Sluis Eefde	Riprap
34E-001-01	Sluis Delden	-
34F-001-01	Sluis Hengelo	Riprap
37C-001-01	Goereese sluis	Riprap
37H-001-02	Algerasluis	Riprap
38F-001-02	Sluis Hagestein	Riprap
38F-006-01	Koninginnensluis	Set stone
38F-352-01	Prinses Beatrixsluis oostelijke sluis (sluis 1)	Riprap
38F-352-02	Prinses Beatrixsluis westelijke sluis (sluis 2)	Concrete
38F-352-05	Prinses Beatrixsluis nieuwe sluis (sluis 3)	Riprap
39B-001-01	Prinses Marijkesluis westelijke sluis	Concrete
39B-001-02	Prinses Marijkesluis oostelijke sluis	Concrete
39B-002-01	Prinses Irenesluis Duwvaartsluis (sluis 2)	-
39B-002-02	Prinses Irenesluis Oude sluis (sluis 1)	Concrete
39B-003-01	Sluis Amerongen	Riprap
39D-001-01	Prins Bernhardsluis Oude sluis (westelijke sluis - sluis 1)	Riprap
39D-001-02	Prins Bernhardsluis Duwvaartsluis (oostelijke sluis - sluis 2)	Riprap
40A-004-01	Sluis Driel	Concrete
40C-004-01	Sluis Weurt west	Riprap
40C-004-02	Sluis Weurt oost	Concrete
42D-001-05	Roompotsluis	Riprap
43C-001-01	Grevelingensluis	Riprap
43C-002-01	Krammersluizencomplex 2e Jachtensluis (noord)	-
43C-002-02	Krammersluizencomplex 2e Duwvaartsluis (noord)	-
43C-002-03	Krammersluizencomplex 1e Duwvaartsluis (zuid)	-
43C-002-04	Krammersluizencomplex 1e Jachtensluis (zuid)	-
43G-001-01	Sluis 1 (Volkerak)	-

Table A.1: Type of protection in approach harbour per lock (De Kat, 2021)

Object code	Object name	Type
43G-001-02	Sluis 2 (Volkerak)	-
43G-001-03	Sluis 3 (Volkerak)	-
43G-001-05	Jachtensluis sluizencomplex Volkerak	-
44B-001-01	Biesboschsluis	Riprap
44B-002-01	Spieringsluis	Riprap
44B-003-01	Ottersluis	-
44B-353-01	Helsluis	-
44D-001-01	Marksluis	-
44D-002-01	Sluis I	-
44F-002-01	Wilhelminasluis Andel	Riprap
44G-350-01	Sluis II	Riprap
45B-001-01	Sluis St. Andries	Riprap
45B-351-01	Prinses Maximasluis zuid (oud)	Riprap
45B-351-03	Prinses Maximasluis noord (nieuw)	Riprap
45B-352-01	Sluis Empel	Riprap and concrete
45D-358-01	Sluis Hintham	Riprap
45F-001-01	Sluis Grave noord (nieuw)	Riprap
45G-350-03	Sluis 4	Riprap
45G-352-01	Sluis Schijndel	Riprap
46A-001-01	Sluis Heumen	Riprap
46D-350-01	Schutsluis Sambeek oost	Riprap
46D-350-02	Schutsluis Sambeek west	Riprap
46D-350-03	Schutsluis Sambeek midden	Riprap
48E-001-01	Zandkreeksluis	Riprap
48H-353-01	Hansweert Oostelijke sluis	-
48H-353-02	Hansweert Westelijke sluis	-
49B-001-01	Bergsediepsluis	
49D-350-01	Kreekraksluizen (oostsluis)	Riprap
49D-350-02	Kreekraksluizen (westsluis)	Riprap
50F-350-02	Sluis III (nieuw)	-
51A-002-01	Sluis IV	Riprap
51E-001-04	Sluis 5	Riprap
51E-002-02	Sluis V	Riprap
51F-001-04	Sluis 6	Riprap
51H-003-01	Sluis 11	-
51H-004-03	Sluis 10	-
51H-357-01	Sluis Helmond	-
54E-001-01	Oostsluis, Terneuzen	Set stone
54E-001-04	Middensluis, Terneuzen	Concrete and riprap
54E-001-07	Westsluis, Terneuzen	Set stone and riprap

Table A.1: Type of protection in approach harbour per lock (De Kat, 2021)

Object code	Object name	Type
57F-001-01	Sluis 12	Riprap
57H-001-01	Sluis 16	Riprap
58A-001-01	Sluis 13	Riprap
58A-002-01	Sluis 15	Riprap
58A-351-01	Sluis Hulsen	Riprap
58C-001-01	Sluis Panheel (oude kolk, noord)	Riprap
58C-001-04	Sluis Panheel (nieuwe kolk)	-
58C-002-01	Sluis Maasbracht oost	Riprap
58C-002-02	Sluis Maasbracht midden	Riprap
58C-002-03	Sluis Maasbracht west	Riprap
58D-001-01	Sluis Heel west	Riprap
58D-001-02	Sluis Heel oost	Riprap
58D-002-01	Sluis Linne	Riprap
58D-350-01	Sluis Roermond	Riprap
58E-350-01	Schutsluis Belfeld oost (oude sluis)	Riprap
58E-350-02	Schutsluis Belfeld west	Riprap
58E-350-03	Schutsluis Belfeld midden	Riprap
60A-001-01	Sluis Born midden	Riprap
60A-001-02	Sluis Born oost	Riprap
60A-001-06	Sluis Born west	Riprap
61F-002-01	Sluis Bosscherveld	Riprap

B

Used databases

This Appendix discusses the consulted databases in more detail. Per region, there is a difference in which databases are used and how the information is stored. For an overview of the regions, see Figure B.1.

DISK

DISK stands for 'Data Informatie Systeem voor Kunstwerken', which translates to 'Data Information System for Structures'. It can be accessed by Rijkswaterstaat employees through this webpage from within the RWS network (Rijkswaterstaat, 2022b). DISK is the management and information system of Rijkswaterstaat for the data on structures that are managed by Rijkswaterstaat. DISK provides an overview of complexes of structures which consist of multiple objects with each their own components. Each complex and object has its own DISK-code. DISK object codes are used in other databases as well. For example, the DISK-code of the Prinses Beatrix lock complex is 38F-352. The Central Prinses Beatrix lock is one of its objects and has the object code 38F-352-01. Using the object code, one can find the passport of an object, which contains all components and basic information such as built year, location, etc. Furthermore, inspection reports can be found in DISK. These reports contain information on the condition of all underlying components which were defined in the passport. Also a short risk assessment is provided.

RINK-database

RINK is an acronym for 'Risico Inventarisatie Natte Kunstwerken', which translates to 'Risk Inventory Hydraulic Structures'. The RINK project was initiated around 2010 because Rijkswaterstaat did not have a complete quantitative overview of the risks of hydraulic structures. In RINK reports, different components of a lock are analysed and assessed. Control calculations were explained regarding the strength of the structures and inspection results were attached. Based on the analyses, measures to improve performance are recommended for each object (Movares & Gerdessen, 2013). The client, Rijkswaterstaat, prescribed which components were to be reviewed by a subcontractor. The reports are divided into various categories, such as 'Analysis steel components' and 'Analysis hydraulic components'. To obtain the required data from Table 2.1, the analysis of hydraulic components, which include bed protections, and inspection report were studied for each lock.

The RINK reports can be found on a drive within a protected Rijkswaterstaat environment. Many RINK reports have been made, but they do not cover all the locks studied in this thesis. However, the reports that were available, have been used extensively during the collection of the required data.

Meridian UIM

Meridian UIM is a Technical Document Management System where all technical documentation of the areal are managed. This includes various types of as-built and detailed drawings and documents such as manuals and certificates. There is a separate Meridian environment for each region. It can be accessed through this link (Rijkswaterstaat, 2022a).

Figure B.1: Map of regions in the Netherlands (Dooren & Rijkswaterstaat, 2022)

There is also an application containing more documents: BC-Meridian Poweruser. This application can be downloaded only after access has been requested and approved. Inside the app, several vaults can be found, each containing data of a different region or department. For this thesis, entrance to the vaults of regions Sea and Delta and Southern Netherlands was allowed.

Geoweb

GeoWeb is a webviewer which makes it easy to offer large amounts of geographical data within an organisation. The catalogue of GeoWeb maps which contain data of Rijkswaterstaat can be found with this link (Rijkswaterstaat & Sweco Nederland B.V., 2022). Some maps are password protected and some are open to the public. The profile tool of the Southern Netherlands region is also linked to GeoWeb. For this thesis, it is used to find the slope of the bank and bed level at waiting places of locks. Also Meridian UIM can be accessed through the GeoWeb viewer. The documents are linked to their location on the map. By clicking on a structure, e.g. a lock, the attached documents from Meridian can be viewed and download. No further documents were however found using Meridian through GeoWeb.

Ultimo RWS

Ultimo is an Infra AssetmanagementSystem (AMS) where all dynamic area data are registered and stored. It can be accessed using this link (Rijkswaterstaat, 2022f). In Ultimo, mostly qualitative information such as general information and the configuration manager can be found. Lots of documents are stored, for example manuals for the use of a bridge, or product information and warranties for components. Through Areal information - Complexes, a large list of complexes can be found. By searching with a specific DISK code, it is possible to find all documents attached to a (lock) complex.

Ultimo RWS is partly coupled to Meridian. Figure B.2 shows per region which documents from Meridian are coupled to Ultimo. Regions Northern Netherlands and Central Netherlands use Ultimo the most, which is reflected in the figure.

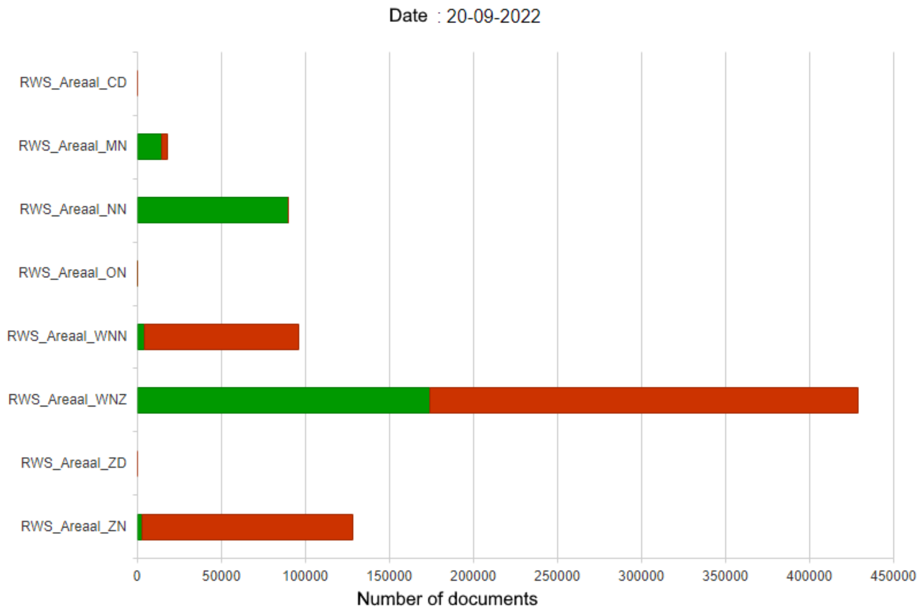

Figure B.2: Overview of number of Meridian documents coupled to Ultimo per region (green) and total number of Meridian documents (green + red) (Rijkswaterstaat, 2022d)

Vaarweginformatie.nl

On the website Vaarweginformatie.nl, up-to-date information can be found on the availability of a waterway, next to real-time information on a multitude of waterways, waiting places, and locks (RWS Dienst VenW, 2022). This data originates from several organisations, e.g. provinces or water boards are authorities on 'their' waterways and deliver data. This data is then verified by the Waterkamer of Rijkswaterstaat. From Vaarweginformatie.nl, information was retrieved on the location of all locks and waiting places. Also the size of the waterways were identified here.

C

CEMT-classification

Table C.1: CEMT-classification for waterways west of the Elbe (CEMT, 1992)

Type de voies navigables Type of Inland waterways	Classe de voies navigables Classes of navigables waterways	Automoteurs et chalands Motor vessels and barges					Convois poussés Pushed convoys					Hauteur minimale sous les ponts Minimum height under bridges
		Type de bateaux: caractéristiques générales Type of vessel: générales characteristics					Type de convoi- Caractéristiques générales Type of convoy- Générales characteristics					
		Dénomination Designation	Longueur Length	Largeur Beam	Tirant déau Draught	Tonnage Tonnage		Longueur Length	Largeur Beam	Tirant déau Draught	Tonnage Tonnage	
			m	m	m	t		m	m	m	t	m
D'INTERET REGIONAL OF REGIONAL IMPORTANCE	I	Péniche Barge	38.50	5.05	1.80-2.20	250-400						4.00
	II	Kast-Caminois Campine-Barge	50-55	6.60	2.50	4.00-650						4.00-5.00
	III	Gustav Koenings	67-80	8.20	2.50	650-1000						4.00-5.00
D'INTERET INTERNATIONAL OF INTERNATIONAL IMPORTANCE	IV	Johan Welker	80-85	9.50	2.50	1000-1500		85	9.50	2.50-2.80	1250-1450	5.25/or 7.00
	Va	Grand bateaux Rhenands/Large Rhine Vessels	95-110	11.40	2.50-2.80	1500-3000		95-110	11.40	2.50-4.50	1600-3000	5.25/or 7.00/or 9.10
	Vb							172-185	11.40	2.50-4.50	3200-6000	
	VIa							95-110	22.80	2.50-4.50	3200-6000	7.10/or 9.10
	VIb		140	15.00	3.90			185-195	22.80	2.50-4.50	6400-12000	7.10/or 9.10
	VIc							270-280 193-200	22.80 33.00-34.20	2.50-4.50 2.50-4.50	9600-18000	9.10
	VII							285 195	33.00 34.20	2.50-4.50	14500-27000	9.10

D

Collected data

This appendix contains all the data that was collected for this thesis. Only data have been researched for waiting places where the most common type bed protection, riprap, was found in the approach harbour. Not for all waiting places data have been found.

Table D.1: Waiting places for which no relevant data have been found

Complex	**Name waiting place**	**Complex**	**Name waiting place**
Gaarkeuken	Oost	Sluis IV	Boven linkeroever
	West		Boven rechteroever
Groevesluis-Zuid	Wachtplaats Zuid		Beneden linkeroever
Groevesluis-Noord	Wachtplaats Noord		Beneden rechteroever
Algerasluis	Boven	Sluis 5	Boven sluis - Rechteroever
	Beneden		Beneden sluis - Linkeroever
Bernhardsluizen	Noord 1	Sluis V	Boven sluis - Rechteroever 1
	Noord 2		Boven sluis - Rechteroever 2
	Noord 3		Beneden sluis - Linkeroever
	Noord 4	Sluis 6	Boven sluis - Rechteroever
	Noord 5	Sluis 12	Boven sluis - Rechteroever
	Zuid 1		Beneden sluis - Linkeroever
	Zuid 2	Sluis 13	Boven sluis - Linkeroever 1
	Zuid 3		Beneden sluis - Linkeroever
	Zuid 4		Beneden sluis - Rechteroever
	Zuid 5	Sluis Hulsen	Beneden
Grevelingen	Oost	Maasbracht	Boven 1
	West		Boven 2
Sluis II	Boven rechts		Boven 3
	Boven links		Boven 4
	Beneden rechts		Beneden 1
	Beneden links		Beneden 2
Prinses Maximasluizen	Boven 1		Beneden 3
	Boven 2	Heel	Boven 1
	Boven 3		Boven 2
	Boven 4		Boven 3

Table D.1: Waiting places for which no relevant data have been found

Complex	Name waiting place	Complex	Name waiting place
	Beneden 1		Beneden 1
	Beneden 2		Beneden 2
	Beneden 3		Beneden 3
	Boven 2	Born	Boven 1
	Beneden 1		Boven 2
	Beneden 2		Boven 3
Sluis 4	Boven sluis - Rechteroever		Boven 4
	Beneden sluis - Link-eroever		Beneden 1
			Beneden 2
			Beneden 3
			Beneden 4

D.1. Ship dimensions and hydraulic boundary conditions

Table D.2: Dimensions design vessel and water depth per waiting place

Complex	Name waiting place	Beam [m]	Draught [m]	Water depth [m]
Spooldersluis	Binnenkant 1	11.45	3.76	4.35
	Buitenkant 1	11.45	3.76	4.35
Ijmuiden zuider-sluizen (kleine sluis + zuidersluis)	Wachtpalen sluis west	17	5.8	8.15
	Wachtplaats zuidersluis binnen	17	5.8	8.15
	Wachtplaats zuidersluis buiten	17	5.8	6
Prins Willem Alexandersluis	Remmingwerk Buiten IJ	22.8	3.5	4.25
	Binnen IJ	22.8	3.5	4.25
	Binnen IJ Noord	22.8	3.5	4.25
Noordersluis (utrecht)	Zuid	11.5	2.8	3.25
Sluis Eefde	Boven Midden	11.5	2.8	3.6
	Boven 1	11.5	2.8	3.6
	Boven 2	11.5	2.8	3.6
	Boven 3	11.5	2.8	3.6
	Beneden 1	11.5	2.8	3.6
	Beneden 2	11.5	2.8	3.6
	Beneden 3	11.5	2.8	3.6
Sluis Hengelo	Boven 1	11.45	3.35	4.25
	Beneden 1	11.45	3.35	4.25
Sluis Hagestein	Beneden 1	11.4	1.85	4.25
	Boven 2	11.4	1.85	6.75

Table D.2: Dimensions design vessel and water depth per waiting place

Complex	Name waiting place	Beam [m]	Draught [m]	Water depth [m]
	Boven 1	11.4	1.85	6.75
Prinses Beatrixs-luizen	Westzijde Zuid 1	17	3.5	5.3
	Westzijde Zuid 2	17	3.5	5.3
	Oostzijde Zuid	17	3.5	5.3
	Oostzijde Noord	17	3.5	4.7
Sluis Amerongen	Beneden 1	11.4	1.85	4.1
	Boven 2	11.4	1.85	4.1
	Boven 1	11.3	1.85	4.1
Wilhelminasluis Andel	Boven 2	11.4	1.9	2.69
	Beneden 1	11.4	1.9	2.55
	Beneden 2	11.4	1.9	2.55
Sluis St. Andries	Boven	11.4	3.5	4
	Beneden 1	11.4	3.5	4
	Beneden 2	11.4	3.5	4
Sluis Empel	Boven	9.5	3	4.27
	Beneden 1	9.5	3	4.4
	Beneden 2	9.5	3	4.4
Sluis Hintham	Boven 1	9.5	3	4.27
	Boven 2	9.5	3	4.4
	Beneden	9.5	3	4.4
Sluis Grave noord	Boven 1	11.4	3.4	4.9
	Boven 2	11.4	3.4	4.9
	Beneden 1	11.4	3.4	4.75
	Beneden 2	11.4	3.4	4.75
Sluis Schijndel	Boven 1	9.5	3	3.9
	Boven 2	9.5	3	3.9
	Beneden 1	9.5	3	3.9
	Beneden 2	9.5	3	3.9
Sluis Heumen	Boven rechteroever	11.4	3.2	4.98
	Beneden linkeroever	11.4	3.2	4.98
Sambeek	Boven 1	11.4	3	3.9
	Boven 2	11.4	3	3.9
	Boven 3	11.4	3	3.9
	Boven 4	11.4	3	3.9
	Beneden 1	11.4	3	3.9
	Beneden 2	11.4	3	3.9
	Beneden 3	11.4	3	3.9
	Beneden 4	11.4	3	3.9
Zandkreeksluis	Binnen	11.5	4.25	5.55
	Buiten	11.5	4.25	6.45
Kreekraksluizen	Noordzijde 1	22.8	4.3	6.7

Table D.2: Dimensions design vessel and water depth per waiting place

Complex	Name waiting place	Beam [m]	Draught [m]	Water depth [m]
	Noordzijde 2	22.8	4.3	6.7
	Zuidzijde 1	22.8	4.3	4.6
	Zuidzijde 2	22.8	4.3	4.6
	Zuidzijde 3	22.8	4.3	4.6
	Zuidzijde 4	22.8	4.3	4.6
Terneuzen	Oost binnen west	23	4	6.88
	Oost binnen oost	23	4	6.88
	Oost buiten west	23	4	6.38
	Oost buiten oost	23	4	6.38
Sluis 16	Boven 1	7.5	2.72	3.22
	Boven 2	7.5	2.72	3.22
	Beneden 1	7.5	2.72	3.22
	Beneden 2	7.5	2.72	3.22
Sluis 15	Boven 1	6.64	2.72	3.22
	Boven 2	6.64	2.72	3.22
	Beneden 1	6.64	2.72	3.22
	Beneden 2	6.64	2.72	3.22
Sluis Panheel	Boven 1	9.5	2.1	2.8
	Boven 2	9.5	2.1	2.8
	Beneden 1	9.5	2.1	3.08
	Beneden 2	9.5	2.1	3.08
Sluis Linne	Boven1	9.5	3	4.5
	Beneden 1	9.5	3	3.5
Sluis Roermond	Boven	11.4	3.5	4
	Beneden 1	11.4	3.5	4
	Beneden 2	11.4	3.5	4
Belfeld	Boven 1	11.4	3.5	4
	Boven 2	11.4	3.5	4
	Boven 3	11.4	3.5	4
	Beneden 1	11.4	3.5	4
	Beneden 2	11.4	3.5	4
	Beneden 3	11.4	3.5	4
	Beneden 4	11.4	3.5	4
	Beneden 5	11.4	3.5	4
Bosscherveld	Boven 1	8.3	2.5	3.9
	Boven 2	8.3	2.5	3.9
	Beneden 1	8.3	2.5	3.9
	Beneden 2	8.3	2.5	3.9

D.2. Characteristics of main propulsion system

Table D.3: Characteristics of the main propulsion system per waiting place

Complex	Name waiting place	Diameter [m]	Used power per propeller [kW]	Number of thrusters [-]	Factor nozzle type [-]	Vertical distance thruster - bed [m]
Spooldersluis	Binnenkant 1	1.8	1103	2	0.85	1.65
	Buitenkant 1	1.8	1103	2	0.85	1.65
Ijmuiden zuidersluizen (kleine sluis + zuidersluis)	Wachtpalen sluis west	3.4	3730	2	0.71	4.55
	Wachtplaats zuidersluis binnen	3.4	3730	2	0.71	4.55
	Wachtplaats zuidersluis buiten	3.4	3730	2	0.71	3.2
Prins Willem Alexandersluis	Remmingwerk Buiten IJ	1.8	927.5	2	0.85	1.65
	Binnen IJ	1.8	927.5	2	0.85	1.65
	Binnen IJ Noord	1.8	927.5	2	0.85	1.65
Noordersluis (utrecht)	Zuid	1.8	687.5	2	0.85	1.35
Sluis Eefde	Boven Midden	2	1257.8	2	1	1.25
	Boven 1	2	1257.8	2	1	1.25
	Boven 2	2	1257.8	2	1	1.25
	Boven 3	2	1257.8	2	1	1.25
	Beneden 1	2	1257.8	2	1	1.8
	Beneden 2	2	1257.8	2	1	1.8
	Beneden 3	2	1257.8	2	1	1.8
Sluis Hengelo	Boven 1	1.8	883	2	1	1.4
	Beneden 1	1.8	883	2	1	1.4
Sluis Hagestein	Beneden 1	1.943	920	2	1	2.4
	Boven 2	1.943	920	2	1	4.9

Table D.3: Characteristics of the main propulsion system per waiting place

Complex	Name waiting place	Diameter [m]	Used power per propeller [kW]	Number of thrusters [-]	Factor nozzle type [-]	Vertical distance thruster - bed [m]
	Boven 1	1.943	920	2	1	4.9
Prinses Beatrixsluizen	Westzijde Zuid 1	1.8	930	2	1	2.7
	Westzijde Zuid 2	1.8	930	2	1	2.7
	Oostzijde Zuid	1.8	930	2	1	2.7
	Oostzijde Noord	1.8	930	2	1	2.1
Sluis Amerongen	Beneden 1	1.943	920	2	1	2.25
	Boven 2	1.943	920	2	1	2.25
	Boven 1	1.943	920	2	1	2.25
Wilhelminasluis Andel	Boven 2	2	1324	2	1	1.79
	Beneden 1	2	1324	2	1	1.65
	Beneden 2	2	1324	2	1	1.65
Sluis St. Andries	Boven	1.8	490	2	0.85	2.62
	Beneden 1	1.8	490	2	0.85	2.62
	Beneden 2	1.8	490	2	0.85	2.62
Sluis Empel	Boven	1.76	1074	1	1	2.2
	Beneden 1	1.76	1074	1	1	2.33
	Beneden 2	1.76	1074	1	1	2.33
Sluis Hintham	Boven 1	1.76	1074	1	1	2.2
	Boven 2	1.76	1074	1	1	2.33
	Beneden	1.76	1074	1	1	2.33
Sluis Grave noord	Boven 1	1.8	500	2	0.85	2.35
	Boven 2	1.8	500	2	0.85	2.35
	Beneden 1	1.8	500	2	0.85	2.2
	Beneden 2	1.8	500	2	0.85	2.2
Sluis Schijndel	Boven 1	2.11	1070	1	0.71	2.46
	Boven 2	2.11	1070	1	0.71	2.46

Table D.3: Characteristics of the main propulsion system per waiting place

Complex	Name waiting place	Diameter [m]	Used power per propeller [kW]	Number of thrusters [-]	Factor nozzle type [-]	Vertical distance thruster - bed [m]
	Beneden 1	2.11	1070	1	0.71	2.46
	Beneden 2	2.11	1070	1	0.71	2.46
Sluis Heumen	Boven rechteroever	1.6	578	3	1	2.58
	Beneden linkeroever	1.6	578	3	1	2.58
Sambeek	Boven 1	1.8	500	2	0.85	1.13
	Boven 2	1.8	500	2	0.85	1.13
	Boven 3	1.8	500	2	0.85	1.13
	Boven 4	1.8	500	2	0.85	1.13
	Beneden 1	1.8	500	2	0.85	1.13
	Beneden 2	1.8	500	2	0.85	1.13
	Beneden 3	1.8	500	2	0.85	1.13
	Beneden 4	1.8	500	2	0.85	1.13
Zandkreeksluis	Binnen	2	1324	2	1	2.3
	Buiten	2	1324	2	1	3.2
Kreekraksluizen	Noordzijde 1	2	1545	3	1	3.4
	Noordzijde 2	2	1545	3	1	3.4
	Zuidzijde 1	2	1545	3	1	2.7
	Zuidzijde 2	2	1545	3	1	2.7
	Zuidzijde 3	2	1545	3	1	2.7
	Zuidzijde 4	2	1545	3	1	2.7
Terneuzen	Oost binnen west	1.8	928	2	1	2.88
	Oost binnen oost	1.8	928	2	1	2.88
	Oost buiten west	1.8	928	2	1	2.38
	Oost buiten oost	1.8	928	2	1	2.38
Sluis 16	Boven 1	1.5	590	1	0.85	1.25
	Boven 2	1.5	590	1	0.85	1.25

Table D.3: Characteristics of the main propulsion system per waiting place

Complex	Name waiting place	Diameter [m]	Used power per propeller [kW]	Number of thrusters [-]	Factor nozzle type [-]	Vertical distance thruster - bed [m]
	Beneden 1	1.5	590	1	0.85	1.25
	Beneden 2	1.5	590	1	0.85	1.25
Sluis 15	Boven 1	1.5	590	1	0.85	1.25
	Boven 2	1.5	590	1	0.85	1.25
	Beneden 1	1.5	590	1	0.85	1.25
	Beneden 2	1.5	590	1	0.85	1.25
Sluis Panheel	Boven 1	1.33	300	1	0.71	1.21
	Boven 2	1.33	300	1	0.71	1.21
	Beneden 1	1.33	300	1	0.71	1.49
	Beneden 2	1.33	300	1	0.71	1.49
Sluis Linne	Boven1	1.8	350	2	0.85	2.3
	Beneden 1	1.8	350	2	0.85	1.3
Sluis Roermond	Boven	1.8	350	2	0.85	2.03
	Beneden 1	1.8	350	2	0.85	2.03
	Beneden 2	1.8	350	2	0.85	2.03
Belfeld	Boven 1	1.8	490	2	0.85	1.4
	Boven 2	1.8	490	2	0.85	1.4
	Boven 3	1.8	490	2	0.85	1.4
	Beneden 1	1.8	490	2	0.85	1.4
	Beneden 2	1.8	490	2	0.85	1.4
	Beneden 3	1.8	490	2	0.85	1.4
	Beneden 4	1.8	490	2	0.85	1.4
	Beneden 5	1.8	490	2	0.85	1.4
Bosscherveld	Boven 1	1.6	420	2	0.96	1.3
	Boven 2	1.6	420	2	0.96	1.3
	Beneden 1	1.6	420	2	0.96	1.3

Table D.3: Characteristics of the main propulsion system per waiting place

Complex	Name waiting place	Diameter [m]	Used power per propeller [kW]	Number of thrusters [-]	Factor nozzle type [-]	Vertical distance thruster - bed [m]
	Beneden 2	1.6	420	2	0.96	1.3

D.3. Characteristics of bow thrusters

Table D.4: Characteristics of the bow thrusters per waiting place

Complex	Name waiting place	Diameter [m]	Used power per propeller [kW]	Number of thrusters [-]	Factor nozzle type [-]	Vert. distance thruster - bed [m]	Hor. distance thruster - bank [m]
Spooldersluis	Binnenkant 1	1	840	1	1	1.65	5.95
	Buitenkant 1	1	840	1	1	1.65	5.95
Ijmuiden zuidersluizen (kleine sluis + zuidersluis)	Wachtpalen sluis west	1.14	300	1	1	3.12	7
	Wachtplaats zuidersluis binnen	1.14	300	1	1	3.12	7
	Wachtplaats zuidersluis buiten	1.14	300	1	1	1.77	7
Prins Willem Alexander-sluis	Remmingwerk Buiten IJ	1	750	1	1	1.65	16.3
	Binnen IJ	1	750	1	1	1.65	16.3
	Binnen IJ Noord	1	750	1	1	1.65	16.3
Noordersluis (utrecht)	Zuid	1	217.5	1	1	0.6	2
Sluis Eefde	Boven Midden	-	-	-	-	-	-
	Boven 1	-	-	-	-	-	-
	Boven 2	-	-	-	-	-	-
	Boven 3	-	-	-	-	-	-
	Beneden 1	-	-	-	-	-	-
	Beneden 2	-	-	-	-	-	-
	Beneden 3	-	-	-	-	-	-
Sluis Hengelo	Boven 1	-	-	-	-	-	-
	Beneden 1	-	-	-	-	-	-
Sluis Hagestein	Beneden 1	-	-	-	-	-	-
	Boven 2	-	-	-	-	-	-

Table D.4: Characteristics of the bow thrusters per waiting place

Complex	Name waiting place	Diameter [m]	Used power per propeller [kW]	Number of thrusters [-]	Factor nozzle type [-]	Vert. distance thruster - bed [m]	Hor. distance thruster - bank [m]
	Boven 1	-	-	-	-	-	-
Prinses Beatrixsluizen	Westzijde Zuid 1	1	750	2	1	2.9	10
	Westzijde Zuid 2	1	750	2	1	2.9	10
	Oostzijde Zuid	1	750	2	1	2.9	10
	Oostzijde Noord	1	750	2	1	2.3	10
Sluis Amerongen	Beneden 1	-	-	-	-	-	-
	Boven 2	-	-	-	-	-	-
	Boven 1	-	-	-	-	-	-
Wilhelminasluis Andel	Boven 2	1	380.8	1	1	1.49	1.59
	Beneden 1	1	380.8	1	1	1.35	1.59
	Beneden 2	1	380.8	1	1	1.35	1.59
Sluis St. Andries	Boven	1	480	1	1	1.3	-
	Beneden 1	1	480	1	1	1.3	-
	Beneden 2	1	480	1	1	1.3	-
Sluis Empel	Boven	1.05	320	1	1	1.97	0
	Beneden 1	1.05	320	1	1	2.1	0
	Beneden 2	1.05	320	1	1	2.1	0
Sluis Hintham	Boven 1	1.05	320	1	1	1.97	0
	Boven 2	1.05	320	1	1	2.1	0
	Beneden	1.05	320	1	1	2.1	0
Sluis Grave noord	Boven 1	-	-	-	-	-	-
	Boven 2	-	-	-	-	-	-
	Beneden 1	-	-	-	-	-	-
	Beneden 2	-	-	-	-	-	-
Sluis Schijndel	Boven 1	1.24	250	1	1	2.76	1.55

Table D.4: Characteristics of the bow thrusters per waiting place

Complex	Name waiting place	Diameter [m]	Used power per propeller [kW]	Number of thrusters [-]	Factor nozzle type [-]	Vert. distance thruster - bed [m]	Hor. distance thruster - bank [m]
	Boven 2	1.24	250	1	1	2.76	1.55
	Beneden 1	1.24	250	1	1	2.76	1.55
	Beneden 2	1.24	250	1	1	2.76	1.55
Sluis Heumen	Boven rechteroever	1	500	1	1	1.65	2.3
	Beneden linkeroever	1	500	1	1	1.65	2.3
Sambeek	Boven 1	1	420	1	1	3.63	1
	Boven 2	1	420	1	1	3.63	1
	Boven 3	1	420	1	1	3.63	1
	Boven 4	1	420	1	1	3.63	1
	Beneden 1	1	420	1	1	3.63	1
	Beneden 2	1	420	1	1	3.63	1
	Beneden 3	1	420	1	1	3.63	1
	Beneden 4	1	420	1	1	3.63	1
Zandkreeksluis	Binnen	0.7	975	1	1	1.65	-
	Buiten	0.7	975	1	1	2.55	-
Kreekraksluizen	Noordzijde 1	0.7	417	2	1	2.75	-
	Noordzijde 2	0.7	417	2	1	2.75	-
	Zuidzijde 1	0.7	417	2	1	2.05	-
	Zuidzijde 2	0.7	417	2	1	2.05	-
	Zuidzijde 3	0.7	417	2	1	2.05	-
	Zuidzijde 4	0.7	417	2	1	2.05	-
Terneuzen	Oost binnen west	1	750	1	1	3.28	10.58
	Oost binnen oost	1	750	1	1	3.28	10.58
	Oost buiten west	1	750	1	1	2.78	10.58
	Oost buiten oost	1	750	1	1	2.78	10.58

Table D.4: Characteristics of the bow thrusters per waiting place

Complex	**Name waiting place**	**Diameter [m]**	**Used power per propeller [kW]**	**Number of thrusters [-]**	**Factor nozzle type [-]**	**Vert. distance thruster - bed [m]**	**Hor. distance thruster - bank [m]**
Sluis 16	Boven 1	-	-	-	-	-	-
	Boven 2	-	-	-	-	-	-
	Beneden 1	-	-	-	-	-	-
	Beneden 2	-	-	-	-	-	-
Sluis 15	Boven 1	-	-	-	-	-	-
	Boven 2	-	-	-	-	-	-
	Beneden 1	-	-	-	-	-	-
	Beneden 2	-	-	-	-	-	-
Sluis Panheel	Boven 1	0.98	91	1	1	2.17	6.35
	Boven 2	0.98	91	1	1	2.17	6.35
	Beneden 1	0.98	91	1	1	2.45	6.35
	Beneden 2	0.98	91	1	1	2.45	6.35
Sluis Linne	Boven1	1	300	1	1	2	2
	Beneden 1	1	300	1	1	2	2
Sluis Roermond	Boven	2	420	1	1	2	2
	Beneden 1	2	420	1	1	3.63	1
	Beneden 2	2	420	1	1	3.63	1
Belfeld	Boven 1	1	420	1	1	3.63	7.5
	Boven 2	1	420	1	1	3.63	7.5
	Boven 3	1	420	1	1	3.63	7.5
	Beneden 1	1	420	1	1	3.63	7.5
	Beneden 2	1	420	1	1	3.63	7.5
	Beneden 3	1	420	1	1	3.63	7.5
	Beneden 4	1	420	1	1	3.63	7.5
	Beneden 5	1	420	1	1	3.63	7.5

Table D.4: Characteristics of the bow thrusters per waiting place

Complex	**Name waiting place**	**Diameter [m]**	**Used power per propeller [kW]**	**Number of thrusters [-]**	**Factor nozzle type [-]**	**Vert. distance thruster - bed [m]**	**Hor. distance thruster - bank [m]**
Bosscherveld	Boven 1	1	360	1	1	3.8	-
	Boven 2	1	360	1	1	3.8	1
	Beneden 1	1	360	1	1	4.21	1
	Beneden 2	1	360	1	1	4.21	1

D.4. Berth properties

Table D.5: Berth properties per waiting place

Complex	Name waiting place	Berth type	Angle slope [°]	Material top layer
Spooldersluis	Binnenkant 1	Piles	18.43	Fine grained sand
	Buitenkant 1	Piles	18.43	Fine grained sand
Ijmuiden zuidersluizen (kleine sluis + zuidersluis)	Wachtpalen sluis west	Piles	-	10-60 kg rocks
	Wachtplaats zuidersluis binnen	Piles	-	10-60 kg rocks
	Wachtplaats zuidersluis buiten	Piles	-	10-60 kg rocks
Prins Willem Alexandersluis	Remmingwerk Buiten IJ	Piles	0	Middle coarse grained sand
	Binnen IJ	Piles	0	Middle coarse grained sand
	Binnen IJ Noord	Piles	0	Middle coarse grained sand
Noordersluis (utrecht)	Zuid	Quay wall	90	Middle coarse grained sand
Sluis Eefde	Boven Midden	Piles	-	Fine grained sand
	Boven 1	Quay wall	90	Fine grained sand
	Boven 2	Quay wall	90	Fine grained sand
	Boven 3	Quay wall	90	Fine grained sand
	Beneden 1	Piles	-	Fine grained sand
	Beneden 2	Piles	-	Fine grained sand
	Beneden 3	Quay wall	90	Fine grained sand
Sluis Hengelo	Boven 1	Quay wall and piles	90	Fine grained sand
	Beneden 1	Piles	-	Fine grained sand
Sluis Hagestein	Beneden 1	Quay wall	90	Fine grained sand
	Boven 2	Quay wall	90	Fine grained sand
	Boven 1	Quay wall	90	Fine grained sand
Prinses Beatrixsluizen	Westzijde Zuid 1	Piles	-	Middle coarse grained sand
	Westzijde Zuid 2	Piles	-	Middle coarse grained sand
	Oostzijde Zuid	Piles	-	Middle coarse grained sand

Table D.5: Berth properties per waiting place

Complex	Name waiting place	Berth type	Angle slope [°]	Material top layer
	Oostzijde Noord	Piles	-	Middle coarse grained sand
Sluis Amerongen	Beneden 1	Quay wall	90	Fine grained sand
	Boven 2	Piles	-	Fine grained sand
	Boven 1	Quay wall	90	Fine grained sand
Wilhelminasluis Andel	Boven 2	Piles	45	Fine grained sand
	Beneden 1	Piles	45	Fine grained sand
	Beneden 2	Piles	45	Fine grained sand
Sluis St. Andries	Boven	Piles	-	Coarse grained sand
	Beneden 1	Piles	-	Coarse grained sand
	Beneden 2	Piles	-	Coarse grained sand
Sluis Empel	Boven	Piles	-	10-60 kg rocks
	Beneden 1	Piles	-	10-60 kg rocks
	Beneden 2	Piles	-	10-60 kg rocks
Sluis Hintham	Boven 1	Piles	-	10-60 kg rocks
	Boven 2	Piles	-	10-60 kg rocks
	Beneden	Quay wall	90	10-60 kg rocks
Sluis Grave noord	Boven 1	Piles	88	Middle coarse gravel
	Boven 2	Piles	88	Middle coarse gravel
	Beneden 1	Piles	88	Middle coarse gravel
	Beneden 2	Piles	88	Middle coarse gravel
Sluis Schijndel	Boven 1	Quay wall	90	Cobbles
	Boven 2	Quay wall	90	Silty sand
	Beneden 1	Quay wall	90	Cobbles
	Beneden 2	Quay wall	90	Coarse silt
Sluis Heumen	Boven rechteroever	Piles	78.94	Middle coarse gravel
	Beneden linkeroever	Piles	78.94	Middle coarse gravel
Sambeek	Boven 1	Piles	90	Fine grained sand

Table D.5: Berth properties per waiting place

Complex	Name waiting place	Berth type	Angle slope [°]	Material top layer
	Boven 2	Piles	88	Fine grained sand
	Boven 3	Piles	90	Fine grained sand
	Boven 4	Piles	90	Fine grained sand
	Beneden 1	Piles	89	Fine grained sand
	Beneden 2	Piles	89	Fine grained sand
	Beneden 3	Piles	90	Fine grained sand
	Beneden 4	Piles	90	Fine grained sand
sandkreeksluis	Binnen	Piles	-	Coarse silt
	Buiten	Piles	-	Coarse silt
Kreekraksluizen	Noordzijde 1	Piles	-	Middle coarse grained sand
	Noordzijde 2	Piles	-	Middle coarse grained sand
	Zuidzijde 1	Piles	-	Middle coarse grained sand
	Zuidzijde 2	Piles	-	Middle coarse grained sand
	Zuidzijde 3	Piles	-	Middle coarse grained sand
	Zuidzijde 4	Piles	-	Middle coarse grained sand
Terneuzen	Oost binnen west	Quay wall	90	Gravel
	Oost binnen oost	Quay wall	90	Gravel
	Oost buiten west	Piles	-	Gravel
	Oost buiten oost	Piles	-	Gravel
Sluis 16	Boven 1	Quay wall	90	Fine grained sand
	Boven 2	Quay wall	90	Fine grained sand
	Beneden 1	Quay wall	90	Fine grained sand
	Beneden 2	Quay wall	90	Fine grained sand
Sluis 15	Boven 1	Quay wall	90	Fine grained sand
	Boven 2	Quay wall	90	Fine grained sand
	Beneden 1	Quay wall	90	Fine grained sand
	Beneden 2	Quay wall	90	Fine grained sand

Table D.5: Berth properties per waiting place

Complex	Name waiting place	Berth type	Angle slope [°]	Material top layer
Sluis Panheel	Boven 1	Quay wall	90	Middle coarse grained sand
	Boven 2	Quay wall	90	Middle coarse grained sand
	Beneden 1	Quay wall	90	Middle coarse grained sand
	Beneden 2	Quay wall	90	Middle coarse grained sand
Sluis Linne	Boven1	Piles	73.26	Coarse grained sand
	Beneden 1	Piles	53.37	Coarse grained sand
Sluis Roermond	Boven	Piles	85.62	Middle coarse grained sand
	Beneden 1	Piles	18.5	Middle coarse grained sand
	Beneden 2	Piles	18.5	Middle coarse grained sand
Belfeld	Boven 1	Piles	89.61	Middle coarse grained sand
	Boven 2	Piles	89.61	Middle coarse grained sand
	Boven 3	Piles	89.61	Middle coarse grained sand
	Beneden 1	Piles	89.61	Middle coarse grained sand
	Beneden 2	Piles	89.61	Middle coarse grained sand
	Beneden 3	Piles	89.61	Middle coarse grained sand
	Beneden 4	Piles	89.61	Middle coarse grained sand
	Beneden 5	Piles	89.61	Middle coarse grained sand
Bosscherveld	Boven 1	Piles	73	Coarse silt
	Boven 2	Quay wall	90	Coarse silt
	Beneden 1	Piles	89	Middle coarse gravel
	Beneden 2	Quay wall	90	Middle coarse gravel

D.5. Flow velocities

Table D.6: Overview of near-bed flow velocities per waiting place

Complex name	Name waiting place	Vbed main [m/s]	Vbed bow [m/s]
Spooldersluis	Binnenkant 1	5.28	7.60
	Buitenkant 1	5.28	7.60
Ijmuiden zuidersluizen (kleine sluis + zuidersluis)	WachtPiles sluis west	2.23	2.55
	Wachtplaats zuidersluis binnen	2.23	2.55
	Wachtplaats zuidersluis buiten	1.57	2.21
Prins Willem Alexandersluis	Remmingwerk Buiten IJ	2.81	1.79
	Binnen IJ	2.23	0.61
	Binnen IJ Noord	2.23	0.61
Noordersluis (utrecht)	Zuid	3.67	5.73
Sluis Eefde	Boven Midden	3.4	-
	Boven 1	3.4	-
	Boven 2	3.4	-
	Boven 3	3.4	-
	Beneden 1	2.7	-
	Beneden 2	2.7	-
	Beneden 3	2.7	-
Sluis Hengelo	Boven 1	3.85	-
	Beneden 1	3.85	-
Sluis Hagestein	Beneden 1	1.55	-
	Boven 2	1.24	-
	Boven 1	1.24	-
Prinses Beatrixsluizen	Westzijde Zuid 1	2.15	1.05
	Westzijde Zuid 2	2.15	1.05
	Oostzijde Zuid	2.15	1.05
	Oostzijde Noord	2.76	2.12
Sluis Amerongen	Beneden 1	2.13	-
	Boven 2	1.99	-
	Boven 1	1.99	-
Wilhelminasluis Andel	Boven 2	0.68	8.34
	Beneden 1	0.94	8.34
	Beneden 2	0.94	8.34
Sluis St. Andries	Boven	1.7	1.7
	Beneden 1	1.7	1.7
	Beneden 2	1.7	1.7
Sluis Empel	Boven	1.99	3.77
	Beneden 1	1.89	3.53
	Beneden 2	1.89	3.53
Sluis Hintham	Boven 1	1.985	3.77

Table D.6: Overview of near-bed flow velocities per waiting place

Complex name	Name waiting place	Vbed main [m/s]	Vbed bow [m/s]
	Boven 2	1.985	3.77
	Beneden	1.89	3.53
Sluis Grave noord	Boven 1	1.54	-
	Boven 2	1.54	-
	Beneden 1	1.59	-
	Beneden 2	1.59	-
Sluis Schijndel	Boven 1	1.65	2.82
	Boven 2	1.65	2.82
	Beneden 1	1.65	2.82
	Beneden 2	1.65	2.82
Sluis Heumen	Boven rechteroever	3.55	5.46
	Beneden linkeroever	3.55	5.46
Sambeek	Boven 1	2.2	2.2
	Boven 2	2.2	2.2
	Boven 3	2.2	2.2
	Boven 4	2.2	2.2
	Beneden 1	2.2	2.2
	Beneden 2	2.2	2.2
	Beneden 3	2.2	2.2
	Beneden 4	2.2	2.2
Zandkreeksluis	Binnen	2.1	-
	Buiten	1.5	-
Kreekraksluizen	Noordzijde 1	1.5	-
	Noordzijde 2	1.5	-
	Zuidzijde 1	1.7	-
	Zuidzijde 2	1.7	-
	Zuidzijde 3	1.7	-
	Zuidzijde 4	1.7	-
Terneuzen	Oost binnen west	1.53	2.77
	Oost binnen oost	1.53	2.77
	Oost buiten west	1.43	2.77
	Oost buiten oost	1.43	2.77
Sluis 16	Boven 1	2.5	-
	Boven 2	2.5	-
	Beneden 1	2.5	-
	Beneden 2	2.5	-
Sluis 15	Boven 1	2.51	-
	Boven 2	2.51	-
	Beneden 1	2.5	-
	Beneden 2	2.5	-
Sluis Panheel	Boven 1	3.26	3.26
	Boven 2	3.26	3.26
	Beneden 1	2.97	2.97

Table D.6: Overview of near-bed flow velocities per waiting place

Complex name	Name waiting place	Vbed main [m/s]	Vbed bow [m/s]
	Beneden 2	2.97	2.97
Sluis Linne	Boven1	1.66	3.57
	Beneden 1	2.93	3.57
Sluis Roermond	Boven	1.39	3.57
	Beneden 1	3.17	3.57
	Beneden 2	3.17	3.57
Belfeld	Boven 1	2.2	3.26
	Boven 2	2.2	3.26
	Boven 3	2.2	3.26
	Beneden 1	2.2	3.26
	Beneden 2	2.2	3.26
	Beneden 3	2.2	3.26
	Beneden 4	2.2	3.26
	Beneden 5	2.2	3.26
Bosscherveld	Boven 1	2	2
	Boven 2	2	2
	Beneden 1	1.8	1.8
	Beneden 2	1.8	1.8

D.6. Erosion

Table D.7 displays the found data on the depth and location of the scour holes per waiting place. Some waiting place have two scour holes that are worth mentioning.

Table D.7: Overview of data on erosion per waiting place

Complex name	Name waiting place	Min. distance to quay/piles [m]	Depth [m]	Location	Depth [m]	Location	Min. distance to quay/piles [m]
Spooldersluis	Binnenkant 1	1	Centre-front	6	0.85	Centre-rear	6
	Buitenkant 1	1.31	Centre	0	1.15	Rear	1
Ijmuiden zuidersluis	WachtPiles sluis west	No information					
	Wachtplaats zuidersluis binnen	0	Whole length	0			
	Wachtplaats zuidersluis buiten	1	Centre-front	9			
Prins Willem Alexandersluis	Remmingwerk Buiten IJ	0.5	Rear	6			
	Binnen IJ	0.1	Rear	12			
	Binnen IJ Noord	0.1	Front	10			
Noordersluis (utrecht)	Zuid	1	Centre-front	11			
Sluis Eefde	Boven Centre	0.7	Centre-front	2			
	Boven 1	2.8	Centre	6			
	Boven 2	No information					
	Boven 3	0.9	Centre-front	6			
	Beneden 1	-0.9	Centre-front	0			
	Beneden 2	1.3	Whole length	9			
	Beneden 3	2.6	Centre-front	5			
Sluis Hengelo	Boven 1	0.86	Centre-front	7			
	Beneden 1	1.16	Centre-front	8	1.94	Rear	9

Table D.7: Overview of data on erosion per waiting place

Complex name	Name waiting place	Depth [m]	Location	Min. distance to quay/piles [m]	Depth [m]	Location	Min. distance to quay/piles [m]
Sluis Hagestein	Beneden 1	1.5	Rear	9	0.75	Centre-front	10
	Boven 2	1.25	Rear	12			
	Boven 1	No information					
Prinses Beatrixsluizen	Westzijde Zuid 1	0	Whole length	0			
	Westzijde Zuid 2	No information					
	Oostzijde Zuid	No information					
	Oostzijde Noord	1.1	Centre-front	1	0.7	Rear	6
Sluis Amerongen	Beneden 1	1.3	Centre-front	7			
	Boven 2	No information					
	Boven 1	0.6	Rear	8			
Wilhelminasluis Andel	Boven 2	0.7	Centre-front	4	0.5	Rear	8
	Beneden 1	1.1	Centre-front	5			
	Beneden 2	1.1	Whole length	5			
Sluis St. Andries	Boven	1.5	Rear	12			
	Beneden 1	0.5	Whole length	0			
	Beneden 2	0.2	Whole length	1			
Sluis Empel	Boven	No information					
	Beneden 1	No information					
	Beneden 2	No information					
Sluis Hintham	Boven 1	No information					
	Boven 2	No information					
	Beneden	No information					

Table D.7: Overview of data on erosion per waiting place

Complex name	Name waiting place	Depth [m]	Location	Min. distance to quay/piles [m]	Depth [m]	Location	Min. distance to quay/piles [m]
Sluis Grave noord	Boven 1	No information					
	Boven 2	No information					
	Beneden 1	No information					
	Beneden 2	No information					
Schijndel	Boven 1	No information					
	Boven 2	No information					
	Beneden 1	1.5	Centre-front	4			
	Beneden 2	No information					
Heumen	Boven rechteroever	No information					
	Beneden linkeroever	0.4	Rear	18			
Sambeek	Boven 1	0	Whole length	0			
	Boven 2	1.2	Whole length	0.5			
	Boven 3	1.2	Centre-front	0.5			
	Boven 4	1.3	Whole length	0.5			
	Beneden 1	0.7	Whole length	7			
	Beneden 2	No information					
	Beneden 3	0.7	Whole length	7			
	Beneden 4	No information					
Zandkreeksluis	Binnen	3.4	Whole length	0			
	Buiten	0.3	Centre	12			

Table D.7: Overview of data on erosion per waiting place

Complex name	Name waiting place	Depth [m]	Location	Min. distance to quay/piles [m]	Depth [m]	Location	Min. distance to quay/piles [m]
Kreekraksluizen	Noordzijde 1	1.5	Whole length	4			
	Noordzijde 2	1.5	Centre	4			
	Zuidzijde 1	1	Whole length	10.5			
	Zuidzijde 2	1.5	Whole length	0			
	Zuidzijde 3	1	Rear	10			
	Zuidzijde 4	1.5	Rear	5			
Terneuzen	Oost binnen west	No information					
	Oost binnen oost	No information					
	Oost buiten west	No information					
	Oost buiten oost	No information					
Sluis 16	Boven 1	-1.5	Rear	0.5			
	Boven 2	-1.5	Whole length	0.5			
	Beneden 1	0.2	Centre	18			
	Beneden 2	0	Whole length	0			
Sluis 15	Boven 1	No information					
	Boven 2	1	Centre-front	7	1.5	Rear	0.3
	Beneden 1	1.5	Centre-rear	0.2			
	Beneden 2	0.25	Centre-front	4			
Panheel	Boven 1	No information					
	Boven 2	No information					

Table D.7: Overview of data on erosion per waiting place

Complex name	Name waiting place	Depth [m]	Location	Min. distance to quay/piles [m]	Depth [m]	Location	Min. distance to quay/piles [m]
	Beneden 1	0	Whole length	0			
	Beneden 2	0	Whole length	0			
Sluis Linne	Boven1	0	Whole length	0			
	Beneden 1	No information					
Sluis Roermond	Boven	-0.7	Centre-front	0	-0.4	Centre	0
	Beneden 1	0.7	Centre-front	2	1	Rear	10
	Beneden 2	1	Centre-front	5	1	Centre-rear	5
Belfeld	Boven 1	1.2	Centre-front	10	0.7	Rear	2
	Boven 2	1	Centre-front	2	0.6	Rear	2
	Boven 3	0.6	Centre-front	3	0.3	Rear	8
	Beneden 1	0.4	Centre	1	0.5	Rear	1
	Beneden 2	0.5	Rear	8			
	Beneden 3	0.5	Front	6	0.3	Rear	18
	Beneden 4	0.5	Centre-front	1	0.4	Rear	2
	Beneden 5	No information					
Bosscherveld	Boven 1	1.4	Whole length	2			
	Boven 2	1.4	Rear	0.3			
	Beneden 1	0	Whole length	0			
	Beneden 2	0.6	Rear	14			

D.7. References

Table D.8: Overview of references used per lock complex

Complex name	References
Spooldersluis	RWS Dienst Infrastructuur, Arcadis. (2012). Integrale Rapportage Spooldersluis Bijlage 6: Analyse Waterbouwkundige Onderdelen-Rink 2011-Cluster 2. *C02021.000165.0100*. RWS Dienst Infrastructuur, Arcadis. (2011). Integrale Rapportage Spooldersluis Bijlage 13A: Inspectierapportage sluis Rink 2011 - Cluster 2. *C02021.000165.0100*, (Revisie B).
Ijmuiden zuidersluizen (kleine sluis + zuidersluis)	RWS Dienst Noord-Holland, DHV B.V., Iv-Infra B.V. (2012). R-350 Analyse Waterbouw - Zuidersluis (25A-001-03). *Proj. Nr. BA 3334 (DHV)*. (Revisie 1.0). RWS Dienst Noord-Holland, DHV B.V., Iv-Infra B.V. (2012). Bijlage 5: Inspectierapport Project Zeetoegang IJmond - T0. *Document Nr. R-360*, (Revisie 1.0D).
Prins Willem Alexandersluis	RWS Dienst Infrastructuur, Iv-Infra B.V. (2011). Rink 2011-Analyserapport Waterbouw - Prins Willem Alexandersluis(25E-001-07). *proj. Nr. INPA100687-R-850*, (Revisie 2D). RWS Dienst Infrastructuur, Iv-infra B.V. (2011). Bijlage 5: Inspectierapport Risico Inventarisatie Natte Kunstwerken Complexcode: 25E-001. *Document Nr. INPA100687-R-860*, (Revisie 2D).
Noordersluis (utrecht)	Movares. (2013). Noordersluis Kleine Sluis/Grote sluis 31H-007-01 en 31H-007-02 - Integrale RAMS analyse-Rink 2012. (Versie 2.1). Movares. (2013). Noordersluis Kleine sluis/Grote sluis 31H-007-01 en 31H-007-02 Integrale RAMS analyse.
Sluis Eefde	RWS Dienst Infrastructuur, Arcadis. (2014). Rink 2012/2013 Cluster 2, sluiscomplex Eefde Bijlage 6: analyse waterbouwkundige onderdelen. *c02021.000227.0100*. RWS Dienst Infrastructuur. (2014). Inspectierapport programmeringsinspectie (RINK 2012/2013) Beheerobjectcode: 33F-001-01. (Revisie C).
Sluis Hengelo	RWS Dienst Infrastructuur. (2012). Rink 2011-Integrale rapportage Hengelo, Bijlage 6: analyse waterbouwkundige onderdelen. *C02021.000165.0100*, (Revisie C). RWS Dienst Infrastructuur. (2012). Integrale rapportage Hengelo Bijlage 13: Inspectierapportage Rink 2011 - Cluster 2. *C02021.000165.0100*, (Revisie C).
Sluis Hagestein	RWS Dienst Infrastructuur, Arcadis. (2010). RINK SSC-Risico Inventarisatie Natte Kunstwerken-Analyse Waterbouw Stuw-en Sluiscomplex Hagestein. *C02021.000130*. RWS Dienst Infrastructuur, Arcadis. (2010). Inspectierapport programmeringsinspectie Beheerobjectcode: 38B-001-02.

Table D.8: Overview of references used per lock complex

Complex name	**References**
Prinses Beatrixsluizen	RWS Dienst Infrastructuur, Iv-Infra B.V. (2011). Rink 2011-Analyserapport Waterbouw - Beatrixsluis (38F-352-01). *proj. Nr. INPA100687-R-550*, (Revisie 2D). RWS Dienst Infrastructuur, Iv-Infra B.V. (2011). Bijlage 5: Inspectierapport Risico Inventarisatie Natte Kunstwerken Complexcode: 38F-352. *Document Nr. INPA100687-R-560*, (Revisie 2D).
Sluis Amerongen	RWS Dienst Infrastructuur, Arcadis. (2010). RINK SSC-Risico Inventarisatie Natte Kunstwerken-Analyse Waterbouw Stuw- en Sluiscomplex Amerongen. *C02021.000130*. RWS Dienst Infrastructuur (2010). Inspectierapport programmeringsinspectie beheerobjectcode: 39B-003-01. (Revisie 1).
Wilhelminasluis Andel	RWS Dienst Infrastructuur. (2013) Rink 2012/2013 Cluster 2, Wilhelminasluis Bijlage 6, analyse waterbouwkundige onderdelen. *c02021.000277.0100* RWS Dienst Infrastructuur. (2013). Inspectierapport programmeringsinspectie (RINK 2012/2013) Beheerobjectcode: 44F-002-01. (Revisie C).
Sluis St. Andries	RWS Dienst Infrastructuur, Iv-Infra B.V. (2011). Rink 2010 - Risico Inventarisatie Natte Kunstwerken Sluis St. Andries (45B-001-01) - Analyse Waterbouw. *Proj. Nr. INPA090575-R-124)*, (Revisie 3D). RWS Dienst Infrastructuur, Iv-Infra B.V., Witteveen+Bos. (2010). Bijlage 6: Inspectierapport, bijlage 1A - Multibeam - Complexcode: 45B-001. *Proj. Nr. INPA090575-R-122*. (Revisie 2D).
Sluis Empel	RWS Dienst Infrastructuur, WillemsUnie. (2012). Ontwerp oever- en bodembescherming, omlegging Zuid-WIllemsvaart. *Proj. Nr. C3774, Document Nr. WU-RAP-0308*, (Revisie 4.0).
Sluis Hintham	RWS Dienst Infrastructuur, WillemsUnie. (2012). Ontwerp oever- en bodembescherming, omlegging Zuid-WIllemsvaart. *Proj. Nr. C3774, Document Nr. WU-RAP-0308*, (Revisie 4.0).
Sluis Grave noord	RWS Dienst Infrastructuur, Iv-Infra B.V. (2010). Rink 2010 - Risico Inventarisatie Natte Kunstwerken Stuw Grave (45F-001-02) - Analyse Waterbouw. *Proj. Nr. INPA090575-R-104*, (Revisie 2D). RWS Dienst Infrastructuur, Iv-Infra B.V. (2010). Bijlage 6: Inspectierapport Risico Inventarisatie natte Kunstwerken Complexcode: 45F-001. *Document Nr. INPA090575-R-102*, (Revisie 2D).
Sluis Schijndel	Rijkswaterstaat Bouwdienst. (1992). Zuid-Willemsvaart Geedeelte Veghel - Den Bosch Sluis Schijndel. *NBWZ-1994-05632*. Movares. (2013). Sluis Schijndel Schutkolk 45G-352-01 Analyserapport Civiele bouw en Waterbouw. *D90-WPE-KA-1200384*, (Versie 2.1). Movares. (2013) Sluis Schijndel Schutkolk 45G-352-01 Inspectierapport. *D90-MGE-KA-12000845*, (Versie 2.1).

Table D.8: Overview of references used per lock complex

Complex name	References
Sluis Heumen	RWS Dienst Infrastructuur, Witteveen+Bos, Iv-Infra B.V. (2010). Rink 2010-Risico Inventarisatie Natte Kunstwerken, Sluis Heumen (46A-001-01)-Analyse Waterbouw. *proj. Nr. INPA090575*, (Revisie 2D). RWS Dienst Infrastructuur, Witteveen+Bos, Iv-Infra B.V. (2011). Bijlage 6: Inspectierapport Risico Inventarisatie Natte Kunstwerken. *Document Nr. INPA090575-R-022*, (Revisie 3D).
Sambeek	RWS Dienst Infrastructuur, Iv-Infra B.V. (2010). Rink 2010 - Risico Inventarisatie Natte Kunstwerken Sluis Sambeek (46D-350-03) - Analyse Waterbouw. *Proj. Nr. INPA090575* RWS Dienst Infrastructuur, Witteveen+Bos, Iv-Infra B.V. (2010). Bijlage 6: Inspectierapport Risico Inventarisatie natte Kunstwerken Complexcode:46D-350-03. *Document Nr. INPA090575-R-072*, (Revisie 2D).
Zandkreeksluis	RWS Dienst Infrastructuur, Arcadis. (2013). Rink 2012/2013 Cluster 2: Complex Zandkreeksluis bijlage 6, analyse waterbouwkundige onderdelen. *C02021.000227.0100*. RWS Dienst Infrastructuur. (2013). Inspectierapport programmeringsinspectie (RINK 2012) Beheerobjectcode: 48E-001-01. (Revisie C).
Kreekraksluizen	RWS Dienst Infrastructuur, Arcadis. (2012). Rink 2012/2013 Cluster 2, sluizencomplex kreekrak bijlage 6, analyse waterbouwkundige onderdelen. *C02021.000227.0100* RWS Dienst Infrastructuur. (2012). Inspectierapport programmeringsinspectie (RINK 2012) Beheerobjectcode: 49D-350-01. (Revisie A). RWS Dienst Infrastructuur. (2012). Inspectierapport programmeringspectie (RINK 2012) Beheerobjectcode: 49D-350-02). (Revisie B).
Terneuzen	RWS Dienst Infrastructuur, Iv-Infra B.V. (2011). Analyserapport Waterbouw-Oostsluis Terneuzen (54E-001-01). *Proj. Nr. INPA100687-R-350)*, (Revisie 2D). RWS Dienst Infrastructuur, Iv-Infra B.V. (2011). Bijlage 5: Inspectierapport Risico Inventarisatie Natte Kunstwerken Complexcode: 54E-001. *Document Nr. INPA100687-R-360*, (Revisie 2D).
Sluis 16	RWS Dienst Infrastructuur. (2012a). Integrale Rapportage Sluis 16 Bijlage 6: Analyse Waterbouwkundige Onderdelen RINK 2011 -Cluster 2. *C02021.000165.0100*. RWS Dienst Infrastructuur, Arcadis. (2012). Integrale Rapportage sluis 15 bijlage 13: inspectierapportage Rink 2011- cluster 2. *C02021.000165.0100*. (Revisie 2.0).
Sluis 15	RWS Dienst Infrastructuur. (2012a). Integrale Rapportage Sluis 15 Bijlage 6: Analyse Waterbouwkundige Onderdelen RINK 2011 -Cluster 2. *C02021.000165.0100*.

Table D.8: Overview of references used per lock complex

Complex name	**References**
	RWS Dienst Infrastructuur, Arcadis. (2012). Integrale Rapportage sluis 15 bijlage 13: inspectierapportage Rink 2011- cluster 2. *C02021.000165.0100*. (Revisie 2.0).
Sluis Panheel	Movares. (2013). Sluiscomplex Panheel Sluiskolk noord 58C-001-01 Analyserapport Civiele bouw en Waterbouw. *D90-WPE-KA-1200333*, (Versie 4.0). Movares. (2013). Sluiscomplex Panheel Sluiskolk noord 58C-001-01 Inspectierapport.
Sluis Linne	RWS Dienst Infrastructuur, Iv-Infra B.V. (2010). Rink 2010 - Risico Inventarisatie natte Kunstwerken Sluis Linne (58D-002-01) - Analyse Waterbouw. *Proj. Nr. INPA090575*, (Versie 2D). RWS Dienst Infrastructuur, Iv-Infra B.V. (2010). Bijlage 6: Inspectierapport Risico Inventarisatie Natte Kunstwerken Complexcode: 58D-002. *Document Nr. INPA090575-R-132-2D*, (Revisie 2D).
Sluis Roermond	RWS Dienst Infrastructuur, Witteveen+Bos, Iv-Infra B.V. (2010). Rink 2010 - RIsico Inventarisatie Natte Kunstwerken Waterbouw - Sluis Roermond (58D-350-01) - Bijlage 2. *Proj. Nr. INPA090575-R-002*, (Revisie 2D). RWS Dienst Infrastructuur, Iv-Infra B.V. (2010). Bijlage 6: InspectieRapport Risico Inventarisatie Natte Kunstwerken Complexcode: 58D-350. *Document Nr. INPA090575-R-182-2D*, (Revisie 2D).
Belfeld	RWS Dienst Infrastructuur, Iv-Infra B.V. Royal Haskoning. (2010). Rink 2010 - Risico Inventarisatie Natte Kunstwerken Sluis Belfeld West (58E-350-02) - Analyse Waterbouw. *Proj. Nr. INPA090575-R-054*, (Revisie 2D). RWS Dienst Infrastructuur, Iv-Infra B.V. (2010). Bijlage 6: Inspectierapport Risico Inventarisatie Natte Kunstwerken Complexcode: 58E-350. *Document Nr. INPA090575-R-052-2D*, (Revisie 2D).
Bosscheveld	RWS Dienst Infrastructuur, Iv-Infra B.V., Witteveen + Bos. (2010). Rink 2010 - Risico Inventarisatie Natte Kunstwerken SLuis Bosscheveld (61F-002-01) - Analyse Waterbouw. *Proj. Nr. INPA090575-R-114*, (Revisie 2D). RWS Dienst Infrastructuur, Witteveen + Bos, Iv-Infra B.V. (2010). Bijlage 6: Inspectierapport Risico Inventarisatie Natte Kunstwerken Complexcode 61F-002. *Document Nr. INPA090575-R-112*, (Revisie 2D).
Roompotsluis	Rijkswaterstaat Deltadienst. (1980). Kolkomzetting en stortebedkonstrukties van de roompotsluis. *Projectcode: K9006s00*

Next to the references shown per lock in the table above, the following source has been used to determine the water depth of several locks:

RWS Dienst Verkeerskunde (1990). *Wegwijzer Voor De Binnenscheepvaart*. ed. 6, SDU Uitgeverij, 's-Gravenhage

E

Results classification analysis

This Appendix shows the result of the classification analysis done in Chapter 4. For easy reference, Table E.1 shows the ranges per parameter.

Table E.1: Ranges per parameter

Bed material	
Fine	F
Sand	S
Gravel	G
Cobbles	C
10-60 kg rocks	R

Berth type	
Piles	P
Quay	Q
Combination	C

Max V_{bed} [m/s]	
0 - 1	A
1 - 2.5	B
2.5 - 4.5	C
> 4.5	D

Table E.2: Result of classification of waiting places

Complex	Name waiting place	CEMT-class	Bed material	Berth type	Max. V_{bed}	Total string
Spooldersluis	Binnenkant 1	V	S	P	D	SPD
	Buitenkant 1	V	S	P	D	SPD
Ijmuiden zuidersluizen (kleine sluis + zuidersluis)	Wachtpalen sluis west	V	R	P	C	RPC
	Wachtplaats zuidersluis binnen	V	R	P	C	RPC
	Wachtplaats zuidersluis buiten	V	R	P	B	RPB
Prins Willem Alexander-sluis	Remmingwerk Buiten IJ	VIa and VIb	S	P	C	SPC
	Binnen IJ	VIa and VIb	S	P	B	SPB
	Binnen IJ Noord	VIa and VIb	S	P	B	SPB
Noordersluis (utrecht)	Zuid	V	S	Q	D	SQD
Sluis Eefde	Boven Midden	V	S	P	C	SPC
	Boven 1	V	S	Q	C	SQC
	Boven 2	V	S	Q	C	SQC
	Boven 3	V	S	Q	C	SQC

Table E.2: Result of classification of waiting places

Complex	Name waiting place	CEMT-class	Bed material	Berth type	Max. V_{bed}	Total string
	Beneden 1	V	S	P	C	SPC
	Beneden 2	V	S	P	C	SPC
	Beneden 3	V	S	Q	C	SQC
Sluis Hengelo	Boven 1	V	S	C	C	SCC
	Beneden 1	V	S	P	C	SPC
Sluis Hagestein	Beneden 1	V	S	Q	B	SQB
	Boven 2	V	S	Q	B	SQB
	Boven 1	V	S	Q	B	SQB
Prinses Beatrixsluizen	Westzijde Zuid 1	V	S	P	B	SPB
	Westzijde Zuid 2	V	S	P	B	SPB
	Oostzijde Zuid	V	S	P	B	SPB
	Oostzijde Noord	V	S	P	C	SPC
Sluis Amerongen	Beneden 1	V	S	Q	B	SQB
	Boven 2	V	S	P	B	SPB
	Boven 1	V	S	Q	B	SQB
Wilhelminasluis Andel	Boven 2	V	S	P	D	SPD
	Beneden 1	V	S	P	D	SPD
	Beneden 2	V	S	P	D	SPD
Sluis St. Andries	Boven	V	S	P	B	SPB
	Beneden 1	V	S	P	B	SPB
	Beneden 2	V	S	P	B	SPB
Sluis Empel	Boven	IV	R	P	C	RPC
	Beneden 1	IV	R	P	C	RPC
	Beneden 2	IV	R	P	C	RPC
Sluis Hintham	Boven 1	IV	R	P	C	RPC
	Boven 2	IV	R	P	C	RPC
	Beneden	IV	R	Q	C	RQC
Sluis Grave noord	Boven 1	V	G	P	B	GPB
	Boven 2	V	G	P	B	GPB
	Beneden 1	V	G	P	B	GPB
	Beneden 2	V	G	P	B	GPB
Sluis Schijndel	Boven 1	V	C	Q	C	CQC
	Boven 2	V	F	Q	C	FQC
	Beneden 1	V	C	Q	C	CQC
	Beneden 2	V	F	Q	C	FQC
Sluis Heumen	Boven rechteroever	V	G	P	D	GPD
	Beneden linkeroever	V	G	P	D	GPD
Sambeek	Boven 1	V	S	P	B	SPB
	Boven 2	V	S	P	B	SPB
	Boven 3	V	S	P	B	SPB

Table E.2: Result of classification of waiting places

Complex	Name waiting place	CEMT-class	Bed material	Berth type	Max. V_{bed}	Total string
	Boven 4	V	S	P	B	SPB
	Beneden 1	V	S	P	B	SPB
	Beneden 2	V	S	P	B	SPB
	Beneden 3	V	S	P	B	SPB
	Beneden 4	V	S	P	B	SPB
Zandkreeksluis	Binnen	V	F	P	B	FPB
	Buiten	V	F	P	B	FPB
Kreekraksluizen	Noordzijde 1	VIa and VIb	S	P	B	SPB
	Noordzijde 2	VIa and VIb	S	P	B	SPB
	Zuidzijde 1	VIa and VIb	S	P	B	SPB
	Zuidzijde 2	VIa and VIb	S	P	B	SPB
	Zuidzijde 3	VIa and VIb	S	P	B	SPB
	Zuidzijde 4	VIa and VIb	S	P	B	SPB
Terneuzen	Oost binnen west	VIa and VIb	G	Q	C	GQC
	Oost binnen oost	VIa and VIb	G	Q	C	GQC
	Oost buiten west	VIa and VIb	G	P	C	GPC
	Oost buiten oost	VIa and VIb	G	P	C	GPC
Sluis 16	Boven 1	II	S	Q	B	SQB
	Boven 2	II	S	Q	B	SQB
	Beneden 1	II	S	Q	B	SQB
	Beneden 2	II	S	Q	B	SQB
Sluis 15	Boven 1	II	S	Q	C	SQC
	Boven 2	II	S	Q	C	SQC
	Beneden 1	II	S	Q	B	SQB
	Beneden 2	II	S	Q	B	SQB
Sluis Panheel	Boven 1	II	S	Q	C	SQC
	Boven 2	II	S	Q	C	SQC
	Beneden 1	II	S	Q	C	SQC
	Beneden 2	II	S	Q	C	SQC
Sluis Linne	Boven1	V	S	P	C	SPC
	Beneden 1	V	S	P	C	SPC
Sluis Roermond	Boven	V	S	P	C	SPC
	Beneden 1	V	S	P	C	SPC
	Beneden 2	V	S	P	C	SPC
Belfeld	Boven 1	V	S	P	C	SPC
	Boven 2	V	S	P	C	SPC
	Boven 3	V	S	P	C	SPC
	Beneden 1	V	S	P	C	SPC
	Beneden 2	V	S	P	C	SPC
	Beneden 3	V	S	P	C	SPC

Table E.2: Result of classification of waiting places

Complex	Name waiting place	CEMT-class	Bed material	Berth type	Max. V_{bed}	Total string
	Beneden 4	V	S	P	C	SPC
	Beneden 5	V	S	P	C	SPC
Bosscherveld	Boven 1	V	F	P	B	FPB
	Boven 2	V	F	Q	B	FQB
	Beneden 1	V	G	P	B	GPB
	Beneden 2	V	G	Q	B	GQB

F Corridors

Table F.1: Overview of lock complexes and in which corridor they are situated, retrieved from Rijkswaterstaat (2022c)

Complex	**Corridor**
Spooldersluis	Meppelerdiep
Ijmuiden zuidersluizen (kleine sluis + zuidersluis)	North sea channel
Prins Willem Alexandersluis	North sea channel
Noordersluis (utrecht)	Nederrijn-Lek
Sluis Eefde	Twente channels
Sluis Hengelo	Twente channels
Sluis Hagestein	Nederrijn-Lek
Prinses Beatrixsluizen	Nederrijn-Lek
Sluis Amerongen	Nederrijn-Lek
Wilhelminasluis Andel	Other
Sluis St. Andries	Meuse
Sluis Empel	Brabant channels
Sluis Hintham	Brabant channels
Sluis Grave noord	Meuse
Sluis Schijndel	Brabant channels
Sluis Heumen	Meuse
Sambeek	Meuse
Zandkreeksluis	Veersemeer
Kreekraksluizen	Volkerak zoommeer
Terneuzen	Gent-Terneuzen
Sluis 16	Brabant channels
Sluis 15	Brabant channels
Sluis Panheel	Brabant channels
Sluis Linne	Meuse
Sluis Roermond	Meuse
Belfeld	Meuse
Bosscherveld	Meuse