

# Dealing with uncertainties in the design of bottom protection near quay walls

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During the design of bottom protection near a quay wall a civil engineer has to deal with several uncertainties. Therefore practical experience and insight in the consequences of the choice of the input variables in the present design formulas is a condition to guaranty an optimal design. To enlarge this insight in the present design formulas several bottom protections in the port of Rotterdam have been investigated. Because one of the bottom protections did not satisfy the demands of stability required to guarantee a stable bottom protection, this bottom protection is studied with soundings. Using these soundings the actual level of stability can be compared with the present design formulas. The loads on this bottom protection differ, because of diversity in shipping and tidal motion. Therefore a better comparison can be made by resembling the results of the soundings with a probabilistic approach. The probabilistic model is calibrated by the sounding results and by registrations of mooring and unmooring vessels. From these probabilistic approaches insight in the influence of each input variable can be derived. By using a combination of probabilistic results and a fault-tree the probability of a scour hole near a quay wall can be calculated. With these results it is still not possible to choose one strategy for designing bottom protections. The impact of a scour hole on the environment of a quay wall needs to be investigated. Therefore a study to the interaction between a scour hole and the quay wall is enclosed. With these results a risk based analysis is made to evaluate the different strategies and their consequences.

## INTRODUCTION

During the last 10 years there has been an increase of the loads on the harbour bottom. This increase is caused by the propeller loads of mooring and unmooring container vessels. At first, this increase is ascribed to the scaling-up of the vessels. This means more arrivals and departures of vessels with larger draft, larger thruster diameters and larger available thruster-power. Another important cause could be the increase in manoeuvrability of the container vessels, because they obtain bow-thrusters.

The increasing loads, this means the higher jet-flow above the bottom, can lead to undesirable scour holes.

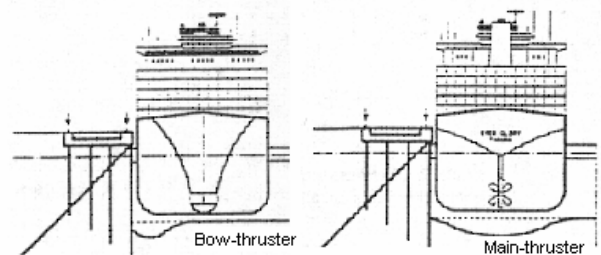


Figure 1: Bow- and main-thruster induced scour

Figure 1 presents possible loading conditions caused by container vessels which have sufficient available power to moor and unmoor near a quay wall by there own.

Currently much uncertainty exists in the reliability of the present design formulas that are required to design a stable bottom protection near a quay wall. In more detail the choices of the input-variables are not clearly defined. The consequences of this become visible during the maintenance-phase of the quay wall. To guarantee public safety during the lifetime of a quay wall and to make an optimal economical design it is necessary to design the bottom protection and a quay wall integrally.

## UNDESIRABLE EVENTS

When the current velocities above the bottom protection exceed a so-called critical value, the bottom protection material will locally be displaced by thruster induced jet-flows. This transport may eventually lead to scour holes. The depth of a scour hole increases with increasing current velocities. When the current velocities above the bottom protection near the quay wall will remain the same, the scour-depth will, in the time, search for equilibrium. This is because the bottom material has to be transported over the slope of the scour hole. Furthermore the current velocities at the bottom decrease as a consequence of the scour hole, depending on the scour size. Relatively large scour holes can lead to the next undesirable events:

- too large deformations of the quay wall;
- too large settlements of the area behind the quay wall.

On the one hand scour holes in the vicinity of the quay wall reduce the passive earth pressure in front of the quay wall, this results in a redistribution of the acting forces on the quay wall. This redistribution causes deformations of the quay wall, until a new equilibrium is reached. On the other hand however, piping can occur when the upward force performed by the groundwater flow on the bottom material locally is larger compared to the downward force caused by the underwater weight of the bottom material. A kind of pipe maybe generated in the sand layer. When this pipe reaches the underside of the sheet pile wall sand can flow out behind the quay wall.

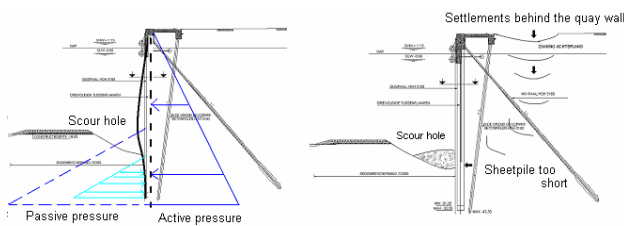


Figure 2: Deformations of and settlements behind the quay wall

### LOADS ON THE BOTTOM PROTECTION

On the location of maximum contraction of the thruster-jet, the initial velocity behind a thruster can be calculated with the following equation as mentioned in Blokland [2]:

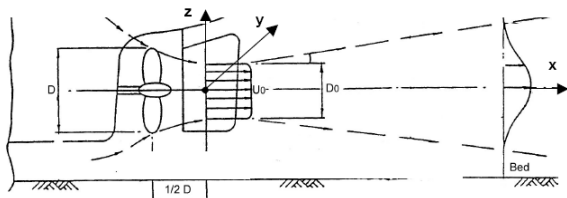


Figure 3: Velocity distribution behind a main-thruster

$$U_0 = C_1 \sqrt[3]{\frac{P}{\rho_w D_0^2}} \text{ with } D_0 = D_s / \sqrt{2} \text{ for main-thrusters}$$

$$D_0 = D_s \text{ for ducted bow-thrusters}$$

If the thrust and torque coefficients of a thruster are known  $C_1$  can be calculated with the following relation by Sorensen et al. [7]:

$$C_1 = \sqrt{\frac{4}{\pi} \frac{K_{T0}}{K_{Q0}^{2/3} (2\pi)^{2/3}}}$$

Often these coefficients are unknown, therefore the factor  $C_1$  is equated to the upper limit 1.17 in the probabilistic approach.

To make a calculation of the velocity field behind a main-thruster the relation for unlimited jet-flow is assumed. Because of this assumption an underestimation of the real main-thruster induced velocity above the bottom will be obtained. Namely the presence of the harbour bottom acts as a boundary to the radial dispersion of the jet-flow. Therefore the velocity above the bottom is larger than according to the assumed unlimited jet-flow theory in which the jet is not limited at all.

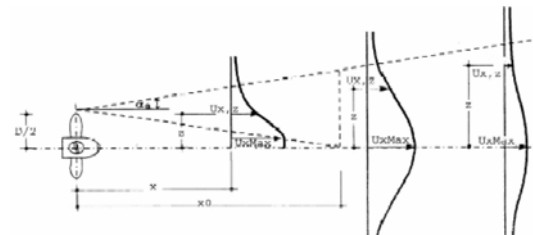


Figure 4: Velocity field at a certain distance behind a main-thruster

The maximum velocity above the bottom by one single main-thruster is calculated with the following relation as described by Blokland [2]:

$$U_{b,max} = f_{int} C_2 \frac{U_0 D_0}{h_{pb}}$$

The factor  $C_2$  is checked by comparing the in situ tests of Blokland [1] and the research of "Delft Hydraulics" [3] with the present design formulas. Both found an underestimation of about 30% between the theoretic formulas and practical applications. The factor  $C_2$  is set at 0,4 instead of the previous 0,306. The load  $S$  on the bottom protection by the main-thruster can be calculated with the following formula:

$$S_{main-thruster} = U_{b,max} = \frac{C_1 C_2}{h_w - h_b - d + k} \sqrt[3]{\frac{f P D_0}{\rho_w}}$$

When the velocity immediately behind the ducted bow-thruster is calculated, the maximum velocity of the jet-flow near the foot of the quay wall can be calculated with the following relation as mentioned in Blokland [2]:

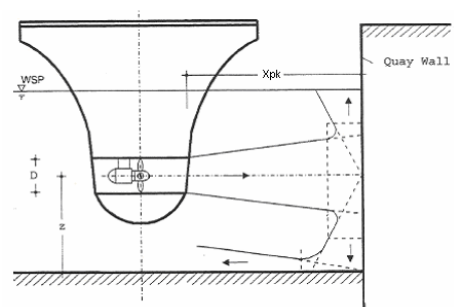


Figure 5: Bow thruster induced jet-flow 2-D

$$U_{b,\max} = C_3 \frac{U_0 D_0}{x_{pk} + h_{pb}} \text{ if } \frac{x_{pk}}{h_{pb}} \geq 1.8$$

According to the in situ test of Blokland [1] the factor  $C_3=2,8$  appeared to be a good approximation of the real acting maximum velocity above the bottom. The load  $S$  on the bottom protection induced by the bow-thruster can be calculated with the following equation:

$$S_{\text{bow-thruster}} = U_{b,\max} = \frac{C_1 C_3}{x_{pk} + h_w - h_b - d + k} \sqrt[3]{\frac{P D_0}{\rho_w}}$$

## STRENGTH OF THE BOTTOM PROTECTION

The previous equations of the "loads" calculated the average maximum velocity above the bottom. For dimensioning bottom protection the maximum velocity above the bottom has to be taken into account. This means, the influence of turbulence induced fluctuations must be added. The required median diameter of the bottom protection can be calculated with the following relation:

$$D_{50} = \beta_{\text{isb;crit}} \frac{U_{b,\max}^2}{2g\Delta}$$

The available literature, described in Roubos [6], shows different values for the critical stability coefficient:  $1,35 < \beta_{\text{isb;crit}} < 4,33$ . As mentioned above the relative turbulence intensity is added in this coefficient. This coefficient can also be seen as a mobility parameter. So if the bottom protection is subjected to different loading situations, different levels of stability can be distinguished.

The following relation is derived based on the Isbash equation valid for uniform flow conditions. The influence of the relative turbulence intensity  $r_u$  is added together with a factor  $p$ . This factor represents a probability of exceedance according to a normal distribution function. For the critical mobility parameter the value of  $p$  is supposed to equal 6.

$$\beta_{\text{isb;mob}} = 0,345(1 + p\sqrt{0,5r_u})^2$$

In the above, it is already mentioned that a particular critical velocity can be related to a level of stability. Actually **one** critical velocity doesn't exist, in fact this velocity differs at each location on a bottom protection due to diversity in positioning, protrusion and different loading situations. For large stone diameters the table 1 is valid for uniform flow conditions.

The presented mobility parameter is the Shields parameter  $\psi$  as described by Schiereck [8]. For a detailed description of the 7 phases Breusers [5] can be consulted.

Condition of the bottom protection		$\psi$
Threshold of motion	1) Completely stable	0.030
Occasionally movement some locations	2) Grains go for a roll; in places	0.035
Frequent movement at several locations	3) Grains go for a roll; at several places	0.040
Frequent movement at many locations	4) Grains go for a roll; at almost all places	0.045
Frequent movement at all locations	5) Grains go for a roll; all places not permanent	0.050
Continuous movement at all locations	6) Grains go for a roll; all places and permanent	0.055
General transport of the grains	7) Begin of the march of grains	0.060

Table 1: Conditions of a bottom protection

The strength  $R$  or the resistance against erosion can be expressed by the critical velocity. When this critical velocity is exceeded the bottom protection will fail to one of the above conditions. The next formula determines the strength  $R$ :

$$R = U_{b,\max;crit} = \sqrt{\frac{2g(\rho_s - \rho_w)D_{50}}{\rho_w \beta_{\text{isb;crit}}}}$$

## SOUNDINGS OF REFERENCE PROTECTION

Several bottom protections near quay walls have been investigated with the deterministic design formulas presented above. According to the present design formulas, one bottom protection didn't satisfy the demands of stability required to guarantee a stable bottom protection. This bottom protection is studied with soundings. The results of the study of soundings of the bottom level will form the basis for calibrating the design formulas. The following two changes of the bottom level are distinguished:

- *local change* ( $0.2m < \text{scour hole} < 0.3m$ );
- *maintenance necessarily* ( $\text{scour hole} > 0.6m$ ).

The local change is indicated as "continuous movement at all locations". This assumption is supposed to equal the mobility parameter according to Shields  $\psi = 0.055$ .

When maintenance due to scour holes is necessary, this is assumed to correspond to "general transport at all locations". The mobility parameter of Shields is then equal to  $\psi = 0.06$ . When the entire layer-thickness has been eroded, the sandy layers with a relative low mean grain diameter will erode much faster. The expected maximum scour-dept near the quay wall maximally will become 2 à 3m.

The probability of changes of the bottom level can be calculated by the following equation:

$$P_{(f)condition} = \frac{n_{changes/8year}}{n_{manoeuvres/8years}}$$

The results for respectively the bow- and main-thruster induced changes can be seen in the tables 2 and 3 below:

Condition Bow-thruster	$\psi$	$P(f)$
Local changes	0.055	5.15E-3
Maintenance necessarily	0.006	4.68E-4

Table 2: Results soundings due to a bow-thruster

Condition Main-thruster	$\psi$	$P(f)$
Local changes	0.055	2.34E-3
Maintenance necessarily	0.006	4.68E-4

Table 3: Results soundings due to a main-thruster

Due to the scaling-up in container shipping in general more activity occurred in the period 1998-2006. In proportion to the bow-thruster the influence of the main-thruster induced loads increases.

Local changes can be seen as an incidental load, because the size and depths of the scour holes did not increase in the time. The holes are regularly filled with sand and again partly washed out. Therefore the probability to find the scour hole decreased.

Scour holes less deep then 0.6m also can be seen as an incidental load. The entire layer-thickness is washed out. Each following jet-flow near this location will increase the scour hole. But a jet-flow relative further away will fill the scour hole again.

## PROBABILISTIC MODEL AND DATA ANALYSIS

The reliability of a bottom protection is the probability that the limit state will not be exceeded. The limit state is the state just before the bottom protection fails to a certain condition. On the basis of the limit state the next general form of the reliability function can be defined:

$$Z = R - S$$

Where  $R$  is the strength of the bottom protection or more general the resistance to failure and  $S$  is the load or the action which causes failure. The limit state is described by  $Z=0$  and failure is defined as  $Z<0$ . In the present design formulas the resistance is expressed in a critical velocity. The loads are the induced jet-flow velocities by the bow- and main-thruster, as already mentioned above.

The following reliability functions are defined for respectively the bow- and main-thruster:

$$Z_{bow-thruster} = \sqrt{\frac{2g(\rho_s - \rho_w)D_{50}}{\rho_w \beta_{isb}}} - \frac{C_1 C_3}{x_{pk} + h_w - h_b - d_{actual} + k} \sqrt[3]{\frac{PD_0}{\rho_w}}$$

$$Z_{main-thruster} = \sqrt{\frac{2g(\rho_s - \rho_w)D_{50}}{\rho_w \beta_{isb}}} - \frac{C_1 C_2}{h_w - h_b - d_{actual} + k} \sqrt[3]{\frac{fPD_0}{\rho_w}}$$

A first probabilistic approach showed no failure at all. This was ascribed to the dependency in the input-variables of the reliability function. A relative large vessel also has a relative large draft and relative large thrusters. Therefore the following equations presented in table 4 are obtained by the method of least squares. These equations are based upon 45 relatively large container vessels.

Dependency Bow-thruster	Dependency Main-thruster
$P_{max} = 261.9B_s - 1392.1$ [kW]	$P_{max} = 2111B_s - 37334$ [kW]
$D_s = 0.05 B_s + 0.464$ [m]	$D_s = 0.153 B_s + 1.1679$ [m]
$k = 1.5 D_s$ [m]	$k = 0.5 D_s$ [m]
$x_{pk} = 0.5B_s$ [m]	

Table 4: Dependency between input-variables of the Z-function

Figure 6 shows the diversity in sizes of the container vessels which have called the port authorities in Rotterdam. The length over all (LOA), the width and the actual draft before mooring and unmooring of all vessels are registered by the port authorities. Figure 6 also shows that mainly a few vessels can be distinguished. Therefore the actual vessels sizes  $B_s$  and  $d_{actual}$  will be chosen randomly out of a database into the probabilistic model. The database contains 3206 arrivals and departures of container vessels which have used the chosen quay wall. This is necessary because otherwise the model will be subjected to relative large standard deviations.

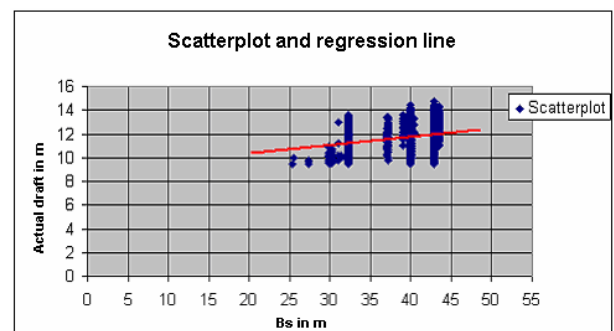


Figure 6: Scatterplot of the diversity in arrivals of the terminal

Besides the dependency of some input-variables the reliability functions also have a number of independent input-variables. These independent input-variables are assumed to be normally distributed. From the figure 7 it appears that this is not valid for the water level in the harbour.

The water levels near the chosen quay wall are measured every 10 minutes. The berthing time near the quay wall is also about 10 minutes. Because the water levels not correspond to a normal distribution, the water level will also be randomly chosen out of a database. This database contains 50,000 water levels measured in 2005 near the chosen quay wall.

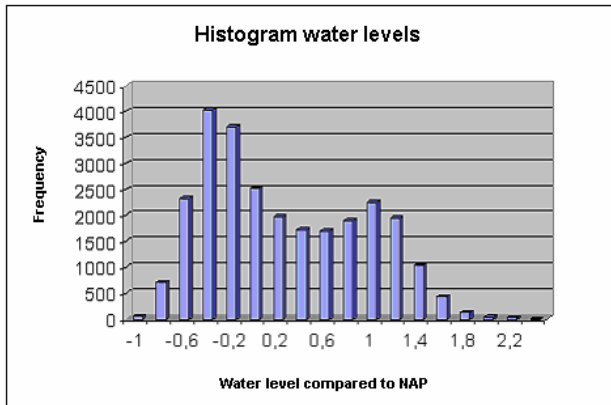


Figure 7: Histogram water levels in front of the quay wall

### CALIBRATING THE PROBABILISTIC MODEL

The results of the study with the soundings have been coupled to a mobility parameter as mentioned above. Then it becomes possible to make an estimation of the mobility parameter during a jet-flow by using the probabilistic model. A probabilistic method is very suitable for modelling diversity in loading combinations on a bottom protection. This means diversity by difference in strength of the protection, tidal differences in water levels and diversity in container vessels using the quay wall. The probabilistic model of the bow-thruster is calibrated to condition 6 "continuous movement at all locations". The mobility parameter  $\beta_{isb;mob} = 1,65$  appeared to be the best approximation. This parameter forms the basis for the remaining probabilistic calculations.

$$U_{b,max} = \sqrt{\frac{2g\Delta D_{50}}{\beta_{isb;crit}}} = C_{chezy} \sqrt{\Delta d_{n50} \psi_c} \Rightarrow \psi_c \sim \frac{1}{\beta_{isb;crit}}$$

The mobility parameter  $\beta_{isb;mob} = 1,65$  of "continuous movement at all locations" can be converted to condition 1 "threshold of motion". For this conversion the relation of Shields is compared with the Isbash relation during jet-flow conditions. The Shields parameter  $\psi_c$  during jet-flow is proportional to the reciprocal of  $\beta_{isb;crit}$ . See the equation above.

This proportionality results in the following table:

Condition of the bottom protection	$\psi$	$\beta_{isb;mob}$
1) Threshold of motion	0.030	3.03
2) Occasionally movement some locations	0.035	2.59
3) Frequent movement at several locations	0.040	2.27
4) Frequent movement at many locations	0.045	2.02
5) Frequent movement at all locations	0.050	1.82
6) Continuous movement at all locations	0.055	1.65
7) General transport of the grains	0.060	1.51

Table 5: Mobility parameter of Isbash for the 7 conditions

For the critical mobility parameter for the condition "threshold of motion" the value  $\beta_{isb;mob} \approx 3$  is found.

Remarkably  $\beta_{isb;mob} = 3$  is also determined according to the current design formulas for condition 1 "threshold of motion".

### RESULTS BOW-THRUSTER MODEL

With a Monte Carlo simulation the probability of occurrence of each condition can be calculated. This is done by using the reliability function  $Z$  for the bow-thruster. Figure 8 is the result of the condition "continuous movement at all locations" where  $\beta_{isb;mob} = 1.65$ .

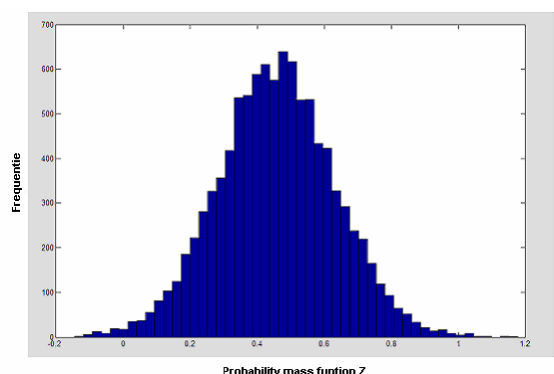


Figure 8: Probability-mass diagram of the bow-thruster

With a "mean value approach" the influence of each input-variable on the standard deviation of the reliability function can be calculated.

	$P_{max}$	$X_{pb}$	$D_{50}$	$\beta_{isb}$	$d_{werkelijk}$	$h_w$
$\alpha^2$	0.370	0.310	0.089	0.081	0.069	0.026
	$D_s$	$C_3$	$C_1$	$\rho_s$	$h_b$	$\rho_w$
$\alpha^2$	0.042	0.014	0.003	0.003	0.003	0.002

Table 6: Influence of each input-variable

From this level II analysis can be seen that the diversity in vessels, which call the port, is an important design criterion. But more remarkable is the influence of the median grain size on the bottom protection.

The 10-60kg and the 40-200kg bottom protection will not be in a stable condition during respectively 83% and the 13% of the periodical bow-thruster jet-flow. When a 40-200kg bottom protection had been chosen the ratio of "general transport at all locations" decreases a factor 580. Figure 9 presents the influence of the gain size  $D_{50}$ .

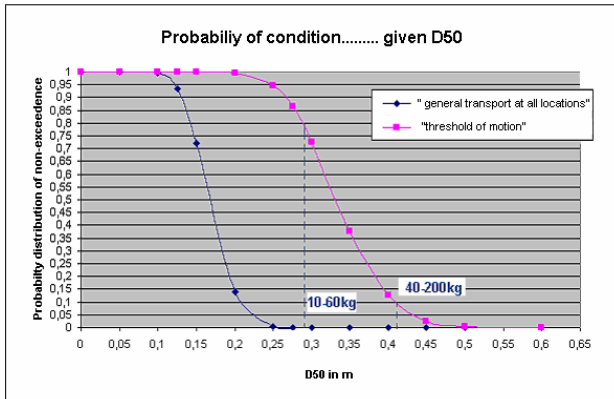


Figure 9: Effects of a chosen  $D_{50}$  on stability and transport

From the figure above it can be seen that there is a large difference between the "threshold of motion" and truly "general transport at all locations". Therefore it is yet not possible to conclude the 10-60kg bottom protection is undesirable.

## RESULTS MAIN-THRUSTER MODEL

With a Monte Carlo simulation the probability of occurrence of each condition can again be calculated. This is done by filling the reliability function  $Z$  for the main-thruster. Unlike the bow-thruster, the main-thruster uses less than the maximum available thruster-power. Therefore the model is calibrated again. Now the mobility parameter is assumed to be equal to the mobility parameter of the bow-thruster. With the help of 16 records of manoeuvring vessels using their main-thrusters near several quay walls the used percentage is determined at 10% of the maximum available thruster-power.

With a "mean value approach" the influence of each input-variable on the standard deviation of the reliability function is calculated again.

	$P_{max}$	$C_2$	$d_{werkelijk}$	$h_w$	$D_{50}$	$\beta_{isb}$
$\alpha^2$	0.34	0.22	0.19	0.09	0.07	0.06
	$h_b$	$D_s$	$\rho_w$	$\rho_s$	$C_1$	
$\alpha^2$	0.007	0.004	0.003	0.003	0.002	

Table 8: Influence of each input-variable

From table 8 it can be seen that not only a relative large vessel is a requirement for failure, but also the water level and grain size are important input-variables. It has to be noticed that the uncertainty in the factor  $C_2$  dominates this relation. Therefore more investigation is necessary to make a better approach.

Condition	$\beta_{isb}$	$P(f)$ 10-60kg	$P(f)$ 40-200kg	Ratio
1) Threshold	3.03	1.87E-01	2.19E-02	9
2) Occasionally	2.59	8.70E-02	5.21E-03	17
3) Frequently	2.27	3.82E-02	1.17E-03	33
4) Frequently	2.02	1.74E-02	2.97E-04	58
5) Frequently	1.82	5.74E-03	7.04E-05	81
6) Continuously	1.65	2.20E-03	1.99E-05	110
7) Transport	1.51	7.49E-04	5.23E-06	143

Table 9: Probability of exceedance by 10-60kg and 40-200kg

The 10-60kg and the 40-200kg bottom protection will not be in a stable condition during respectively 19% and the 2% of the periodical main-thruster jet-flow. When a 40-200kg bottom protection had been chosen the ratio of "general transport at all locations" decreases a factor 140. Comparing the ratio between the bow-thruster and the main-thruster model, the bow-thruster induced currents dominates the normative loading situations. Figure 10 presents the influence of the grain size  $D_{50}$ .

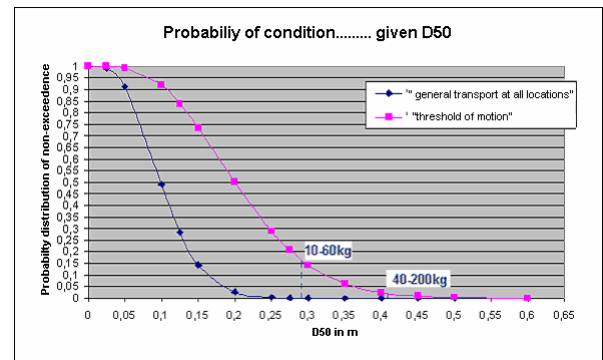


Figure 10: Effects of a chosen  $D_{50}$  on stability and transport

The steepness of the curves in figure 10 is relative flat in comparison with the bow-thruster influence in figure 9. When the used percentage of the maximum available thruster-power remains the same, future scaling-up can enlarge influence of the main-thruster induced jet-flow. Therefore more investigation to the minimum necessity of main-thruster power is desired.

## PROBABILITY OF SCOUR

To calculate the probability of a scour hole in the bottom protection near a quay wall a fault-tree has been constructed.

The fault-tree directly is divided by scour due to the bow-thruster and scour due to the main-thruster. Both these elements distinguish scour due to:

- too large jet-flow  $\beta_{isb,crit} = 1,51$ ;
- jet-flow and design faults  $\beta_{isb,crit} = 1,65$ ;
- jet-flow and construction faults  $\beta_{isb,crit} = 1,65$ .

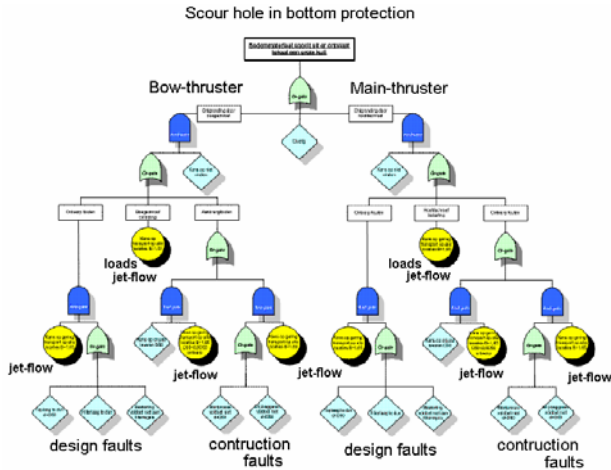


Figure 11: Fault-tree scour hole in a bottom protection

The probability of a scour hole in a 10-60kg, a 40-200kg and a 60-300kg bottom protection have been calculated by using the probabilistic models and the fault-tree in the figure above. The number of scour holes corresponds to a binomial distribution. Therefore the number of vessels which uses the quay wall in a period of 50 years has been estimated at 14,000. Now the expectation of the number scour holes for each protection can be made. The results are presented in table 10.

Bottom protection	10-60kg	40-200kg	60-300kg
Number of manoeuvres in 50 years	14000	14000	14000
Bow-thruster induced number of scour holes	24.076	0.043	0.002
Main-thruster induced number of scour holes	3.184	0.085	0.003

Table 10: Bow- and main-thruster induce scour holes

The bow-thruster induced jet-flow will cause relative more scour holes if the loads remain unchanged. This means scaling-up in shipping is not taken into consideration. It can be seen that a 10-60kg bottom protection results in about 24 bow-thruster induced scour holes. When instead of a 10-60kg a 40-200kg bottom protection had been chosen no scour holes were to be expected.

#### QUAY WALL TEMPORARY UNAVAILABLE

The effects of a scour hole next to a quay wall are investigated. Only scour holes caused by bow-thrusters are taken into account, because these scour holes dominate the consequences:

- collapse of the quay wall due to too large deformations;
- settlements of the area behind the quay wall.

The economic damage to the terminal due to bow- and main-thruster induced scour holes is not taken into consideration in this investigation. However it is advised to investigate this damage in relation to the developed model as this damage may be considered.

#### DEFORMATIONS DUE TO SCOUR

The interpretations of the deformations differ for each quay wall. Therefore a distinction is made between anchored and unanchored quay walls. The chosen bottom protection is situated in front of an anchored quay wall. This anchor has a large impact on the deformations that become visible on top of the quay wall during its lifetime. Possible causes of deformations are:

- loads on the top of the quay wall;
- scour of the harbour bottom immediately in front of the sheet pile wall;
- accelerated consolidation of soft soils;
- too much tension in relative deep soils, causes sliding.

Only the loads on top and a scour hole in front of the quay have been worked out further. This is done by working out a model in PLAXIS 2-D. Figure 12 shows a deformed combi-wall due to a combination of a scour hole besides and a load on top of the quay wall. It has to be noticed that these deformations are strongly enlarged presented.

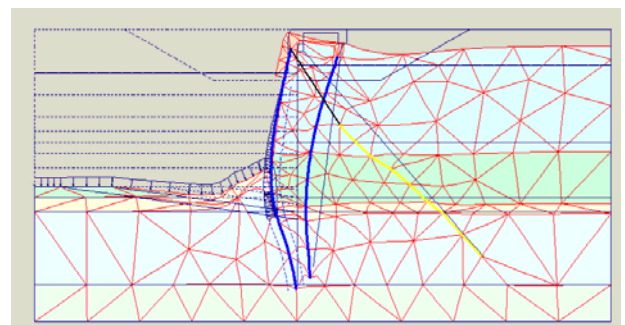


Figure 12: Deformed quay wall due to scour and loads on top

The figure above is derived just before the quay wall collapses. This means the decrease of the passive pressure-zone became too high. Obviously the deformations at the top of the quay wall are relative small compared to the deformations of the combi-wall. During the life time of a quay wall the settlements on top of the quay wall have to be minimized.

During the design of an anchored quay wall larger partial safety factors are applied for the anchor design. Therefore the deformations in the combi-wall will not be visible on the top of the quay wall, so the construction doesn't give a sign of warning before collapsing due to a scour hole.

The results of varying scour-depths and loads are mentioned in table 10. This table shows that loads on top of the quay wall have a different impact on the deformations of the quay wall compared to a scour hole.

Scour depth [m]	Max moment combi wall [kNm]	Max tension force in MV-pile [kN]	Deformations at the top [mm]	Deformations at the top [mm]	Max deformations in the combi wall [mm]	Max deformations in the combi wall [mm]
			+ ← ⇒ -	↓ - + ↑	+ ← ⇒ -	↓ - + ↑
<b>Without variable loads</b>						
0.5	1420	646	0.119	0.009	0.007	0.037
1.5	1500	675	1.530	0.083	10.00	0.625
2.5	1610	724	4.000	0.493	25.92	1.802
3.5	1750	766	7.970	1.482	47.67	3.835
>3.50	Failure due to passive earth pressure					
<b>With variable loads</b>						
0.5	1640	639	3.860	8.363	3.861	5.862
1.5	1680	668	5.667	9.054	6.667	6.153
2.5	1810	729	9.899	10.876	9.998	6.985
3.5	1970	812	15.667	13.274	15.667	8.223
>3.50	Failure due to passive earth pressure					

Table 10: Results PLAXIS calculations

A scour hole particularly has a large impact on maximum moment in the combi-wall and has relatively little influence on the increasing deformations on top of the quay wall. The loads on top of the wall dominate the anchor force and the deformations on top of the quay deck.

## SETTLEMENTS DUE TO SCOUR

A boundary condition for settlements behind the quay wall is the presence of a water head between both sides of the quay wall. Due to a reduction of the seepage length piping can occur. In case of a vertical quay wall a check for heave also has to be carried out. Figure 13 below shows the beginning of piping.

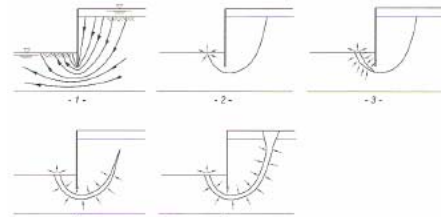


Figure 13: Initiation of piping

A permeable soil-layer must be in contact with a water bearing stratum upstream and have an outflow point downstream. From this outflow the permeable soil-layer in upstream direction has to be bounded by a relative impermeable and coherent soil-layer. This can for instance be the cohesive clay-layer as presented in the figure 14 below.

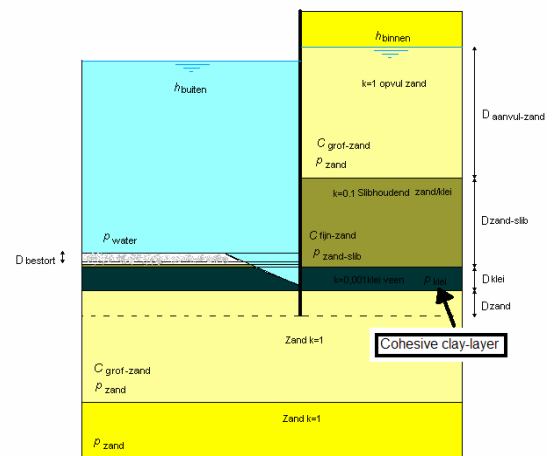


Figure 14: Soil-layers near the quay wall

On the one hand the clay-layer downstream must be cracked. This can be caused by a scour hole or a relative large head difference. On the other hand the upstream side of the clay-layer must be locally disturbed by for example probing. To reduce the water head differences a drainage system is added to a quay wall. Therefore the probability of piping will be reduced.



With the probabilistic upper limit approaches, the probability of settlements due to piping and heave are calculated. An overview can be seen in table 13.

Probability of...	P(f) Too large deformations	Settlements behind the quay wall	
		P(f) Piping	P(f) Heave
	1.0E-01	3.83E-03	8.70E-04

Table 13: probability of deformations and settlements

The consequences of settlements are assumed to be twice as small compared to the consequences of the too large deformations. The reparation costs in table 4 are equalized to twice the construction costs of one pipe pile and two sheet piles.

Costs deformations by a scour hole	Costs settlements by a scour hole
€ 280,000	€ 140,000

Table 14: Costs of deformations and settlements

After determining the consequences and the accompanying probabilities, the risk can be determined and an evaluation can take place. Generally a risk will be checked by, on beforehand known, standards. As mentioned above the chosen 10-60kg bottom protection still satisfies the safety demands of the quay wall. Therefore the 10-60kg, the 40-200kg and the 60-300kg bottom protections are resembled. The results can be seen in the table 15 below.

$$C_{event} = P_{(f)event} C_{one,event}$$

$$C_{total} = n_{bow} (C_{bow} + C_{settlements} + C_{deformations}) + n_{main} C_{main} + C_{construction}$$

Bottom protection	10-60kg	40-200kg	60-300kg
Number of manoeuvres	14000	14000	14000
Bow-thruster induced scour holes	24,076	0,043	0,002
Main-thruster induced scour holes	3,184	0,085	0,003
Reparation costs bow-thruster holes	€ 75.875	€ 148	€ 7
Reparation costs main-thruster holes	€ 20.066	€ 592	€ 6
Construction costs	€ 943.128	€ 1.396.282	€ 1.765.655
Costs settlements	€ 14.157	€ 25	€ 1
Costs deformations	€ 674.122	€ 1.198	€ 61
Total costs	€ 1.727.348	€ 1.398.247	€ 1.765.732

Table 15: Results of risk based analysis

Due to the consequence "temporarily unavailability of the quay wall" the 40-200kg bottom protection is recommended. The "coarse" assumptions in the above risk based assessment can be seen as a support for making a decision.

Although satisfying the safety requirements, the application of a 10-60kg bottom protection results in a relative large number of scour holes. The number of scour holes due to a 10-60kg protection results in a too large risk. In the former analysis future scaling-up in shipping and economic damage for the terminal are not taken into consideration. It is expected that when these unwanted consequences also are to be analyzed, the 10-60kg bottom protection becomes more unfavourable in comparison within the former mentioned risk analysis.

## CONCLUSIONS

During designing bottom protections near quay walls a civil engineer has to make a distinction between bow- and main-thruster induced jet-flow.

Although the theoretical backgrounds of the present bow-thruster design formulas still can be criticized, these formulas satisfy the safety demands of the quay wall and appeared to be the best solution according to the risk based analysis. Special attention must be paid to the design vessel and the median grain diameter. The probabilistic results of the bow-thruster induced scour can be related to other bottom protections near quay walls used by relative large container vessels. The distinguished 7 conditions can be taken into consideration during the design of a bottom protection. For example the design vessel may cause some movement of stones but no general transport.

The main-thruster design formula still contains input-variables which have been estimated in this investigation. The probabilistic model suggested that the design ship, the water level and the median grain size dominate the main-thruster equation. The value and uncertainty in the factor  $C_2$  still have a large impact on the main-thruster formula. Furthermore, the applied percentage of maximum available main-thruster power for this situation is approximated by 10%, because the manoeuvrability area of the chosen harbour is limited. Because the performance of a main-thruster is optimized for conditions outside the harbour, it is expected that the mobility parameter of the main-thruster is not equal to the bow-thruster mobility parameter. Because of all these assumptions the results of the main-thruster model can be seen as a first practical test case. It will be hard or even not possible comparing the results with other bottom protections with relative more manoeuvrability space.

## RECOMMENDATIONS

Recommendations will be done for several stake holders respectively researchers, civil engineers, supervisors and port managers.

### Researchers

The following is recommended:

- model tests are often not reliable due to scaling. But with these models insight can be obtained in the difference between the relative turbulence induced fluctuations by respectively the bow- and main-thruster induced jet-flow;
- in situ tests are desired. It could be possible to measure the induced jet-flow velocities in front of a quay wall by applying measure equipment;
- obtaining insight in the percentage of the maximum power used by main-thrusters and related this power to the vessel sizes;
- more research to the development of scour holes due to periodically thruster induced jet-flows;
- modelling a scour hole in PLAXIS 3-D;
- studying the effects of a scour hole by applying one in front of a used quay wall.

### Civil engineers

Depending on the frequency in arrivals of the design ship and future scaling-up in container shipping, the civil engineer can consider different design strategies. It is advised to optimize the design of the quay wall in an economical perspective. After this, the desired bottom protection has to be chosen. For achieving the desired bottom protection several options are possible. The following input-variables are recommended:

- normative design vessel;
- 10% probability of non-exceedance of the water level during one year;
- upper limit for  $C_1=1.17$ ;
- upper limit for  $C_2=0.4$ ;
- $C_3=2.8$ ;
- $f=10\%$  when relative large vessels needs tug assistance,;
- $f=10\%-20\%$  when relative large vessels can reach the quay wall by their own;
- choose the under limit of  $D_{50}$  in the cutlery.

Accept some movement when mooring and unmooring locations differs. The scour hole will not expand due to the periodically pulses of the jet-flow. The possibility exists for choosing a relative low median grain size in combination with a geotextile or a mattress. The probability of damage or losses to the quay wall will in this case not increase, because the mattress will prevent outflow of the bottom material.

### Supervisors

A supervisor will check if the contractor fulfils the demands in the cutlery.

- A check must be made for the median grain size before constructing the bottom protection.

### Port managers

A possibility to combine the application of the probabilistic model with a targeted implementation of bottom depth soundings can lead to solving the uncertainties in the design formulas and to an optimisation of the total number of soundings. On the one hand it is possible to reduce the costs by reducing the number of soundings. On the other hand it is possible to reduce undesirable impact of the scaling-up in shipping. In fact this means, shortening the time period between a sounding and the occurrence of a scour hole. So the safety demands for the quay wall remain guaranteed. During the first time of the required life time no soundings have to be done. In the second part of the life cycle relative more soundings are necessary due to scaling-up. A kind of "loop" would be derived:

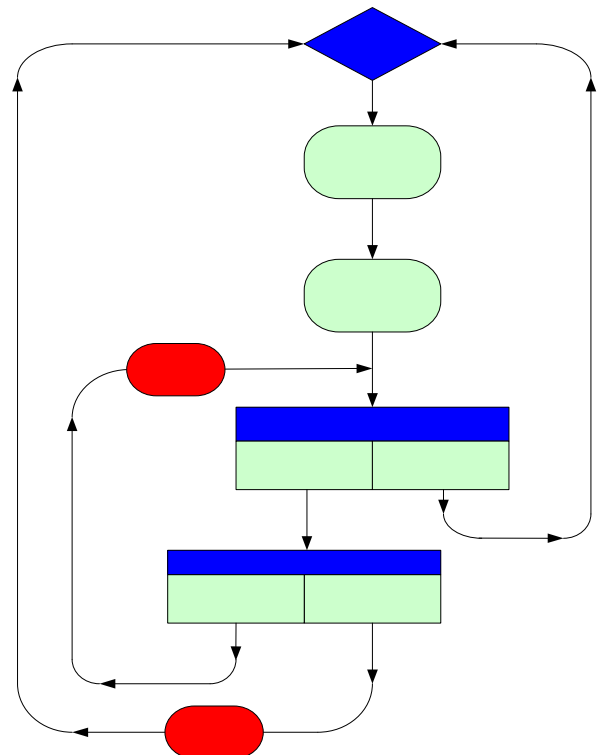


Figure 15: Optimisation plan

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## LIST OF SYMBOLS

$B_s$	width of a vessel [m]
$C$	costs [€]
$C_1$	factor for initial thruster jet-flow [-]
$C_2$	factor maximal main-thruster jet-flow[-]
$C_3$	factor maximal bow-thruster jet-flow[-]
$C_{creep}$	creep coefficient according to Bligh [-]
$d$	draft of a vessel [m]
$D$	layer thickness [m]
$D_0$	diameter of the jet at location of maximum contraction [m]
$D_{50}$	median grain diameter [m]
$d_{actual}$	actual draft of a vessel [-]
$D_s$	diameter of the thruster [m]
$f$	percentage of used thruster power[-]
$f_{int}$	correction factor for under estimation [-]
$g$	acceleration of gravity [m/s <sup>2</sup> ]
$h_b$	bottom level [m+NAP]
$h_{pb}$	distance between the propellor and the quay [m]
$h_w$	water level [m+NAP]
$i$	gradient [-]
$i_{crit}$	critical gradient [-]
$k$	distance of the bow-thruster above the keel [m]
$K_Q$	torque coefficient [-]
$K_T$	thrust coefficient [-]
$L$	seepage length [m]
$n_{bow}$	number of bow-thruster induce scour holes
$n_{changes}$	number of changes in bottom level [-]
$n_{main}$	number of main-thruster induce scour holes
$n_{manoeuvres}$	number of manoeuvres [-]
$\sigma^1$	ground pressure [kN/m <sup>2</sup> ]
$p$	factor of exceedance according to a normal distribution [-]
$P$	thruster power [W]
$P(f)$	probability of exceedance [-]
$R$	strength of reliability function
$r_u$	relative turbulence intensity [-]
$S$	load of reliability function
$\beta_{sb,mob}$	mobility parameter[-]
$\beta_{sb}$	mobility parameter [-]
$\beta_{sb,crit}$	critical mobility parameter [-]
$U_0$	time averaged maximum initial velocity behind a thruster [m]
$U_{b,max}$	average maximum velocity above the bottom [m/s]
$U_{b,max,crit}$	critical average maximum velocity above the bottom [m/s]
$x_{pk}$	distance of thruster to the quay [m].
$\gamma_s$	volumical weight water [kg/m <sup>3</sup> ]
$\gamma_w$	volumical weight material [kg/m <sup>3</sup> ]
$Z$	reliability function
$\rho_s$	density of the bottom material [kg/m <sup>3</sup> ]
$\rho_w$	density of the water [kg/m <sup>3</sup> ]
$\Psi$	mobility parameter of Shields [-]
$\Psi_{crit}$	critical mobility parameter of Shields [-]
$\Delta$	relative density bottom material[-]
$\Delta H$	water head [m]
$\Delta H_{crit}$	critical water head [m]
$\Delta\sigma_w$	water pressure [kN/m <sup>2</sup> ]

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