Uncertainties in the design of bed protections near quay walls

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Abstract
Design formulas for bed protections in the port of Rotterdam were investigated. Using depthsoundings, the actual level of stability of a quay wall can be compared with the design formulas. The loads on a 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 model is calibrated by the sounding results and by registrations of mooring and unmooring vessels. From these 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. Also the impact of a scour hole on the environment of a quay wall was investigated. 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 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.

**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 [1997]:

\[
U_0 = C_1 \frac{P}{\rho_0 D_0^2}
\]

with \( D_0 = D_s / \sqrt{2} \) for main-thrusters

\( D_s = D_s \) 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 Smogeli et al. [2005]:

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

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 then according to the assumed unlimited jet-flow theory in which the jet is not limited at all.
The maximum velocity above the bottom by one single main-thruster is calculated with the following relation as described by Blokland [2]:

\[
U_{b,\text{max}} = f_{in} C_2 U_a D_0 h_{pb}^{1/2}
\]

The factor \(C_2\) is checked by comparing the in situ tests of Blokland [1996] and the research of “Delft Hydraulics” [1985] 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:

\[
S_{\text{main-thruster}} = U_{b,\text{max}} = \frac{C_1 C_2}{h_w - h_b - d + k} \sqrt{\frac{fPD_0}{\rho_w}}
\]

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 [1997]:

\[
U_{b,\text{max}} = C_3 \frac{U_a D_0}{x_{pk} + h_{pb}} \quad \text{if} \quad \frac{x_{pk}}{h_{pb}} \geq 1.8
\]

According to the in situ test of Blokland [1996] 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:

\[
S_{\text{bow-thruster}} = U_{b,\text{max}} = \frac{C_1 C_3}{x_{pk} + h_w - h_b - d + k} \sqrt{\frac{PD_0}{\rho_w}}
\]

**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:

\[
D_{50} = \beta_{ab,\text{crit}} \frac{U_{b,\text{max}}^2}{2g\Delta}
\]

The available literature, described in Roubos [2006], shows different values for the critical stability coefficient: 1.35 < \(\beta_{ab,\text{crit}}\) < 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.

\[
\beta_{mob} = 0.345(1 + p\sqrt{0.5r_u})^2
\]

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 exists, 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 [2004]. For a detailed description of the 7 phases Breusers [1976] can be consulted.

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 \( R \):

\[
R = U_{b: max,crit} = \sqrt{\frac{2g(\rho_s - \rho_w)D_{50}}{\rho_w \beta_{mob,crit}}}
\]

### Sounding 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 to 3m. The probability of changes of the bottom level can be calculated by the following equation:

\[ P_{\text{condition}} = \frac{n_{\text{changes/8 year}}}{n_{\text{manoeuvres/8 years}}} \]

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

<table>
<thead>
<tr>
<th>Condition Bow-thruster</th>
<th>( \psi )</th>
<th>( P(f) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local changes</td>
<td>0.055</td>
<td>5.13E-3</td>
</tr>
<tr>
<td>Maintenance necessarily</td>
<td>0.006</td>
<td>4.68E-4</td>
</tr>
</tbody>
</table>

*Table 2: Results soundings due to a bow-thruster*

<table>
<thead>
<tr>
<th>Condition Main-thruster</th>
<th>( \psi )</th>
<th>( P(f) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local changes</td>
<td>0.055</td>
<td>2.34E-3</td>
</tr>
<tr>
<td>Maintenance necessarily</td>
<td>0.006</td>
<td>4.68E-4</td>
</tr>
</tbody>
</table>

*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:

\[
Z_{\text{bow-thruster}} = \sqrt{\frac{2g(\rho_{\text{w}} - \rho_{\text{s}})D_{\text{w}}}{\rho_{\text{w}}B_{\text{w}}}} \left( \frac{C_{\text{C}}C_{\text{i}}}{s_{\text{act}} + h_{\text{w}} - h_{\text{s}} - d_{\text{act}} + k} \sqrt{\frac{PD_{\text{w}}}{\rho_{\text{w}}}} \right)
\]

\[
Z_{\text{main-thruster}} = \sqrt{\frac{2g(\rho_{\text{w}} - \rho_{\text{s}})D_{\text{m}}}{\rho_{\text{w}}B_{\text{m}}}} \left( \frac{C_{\text{C}}C_{\text{i}}}{h_{\text{w}} - h_{\text{s}} - d_{\text{act}} + k} \sqrt{\frac{IPD_{\text{m}}}{\rho_{\text{w}}}} \right)
\]

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.

<table>
<thead>
<tr>
<th>Dependency Bow-thruster</th>
<th>Dependency Main-thruster</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{act}} = 261.9B_{\text{w}} \cdot 1392.1 \text{ [kW]} )</td>
<td>( P_{\text{act}} = 2111B_{\text{w}} \cdot 37334 \text{ [kW]} )</td>
</tr>
<tr>
<td>( D_{\text{w}} = 0.05 \text{ B}_{\text{w}} + 0.464 \text{ [m]} )</td>
<td>( D_{\text{m}} = 0.153 \text{ B}_{\text{m}} + 1.1679 \text{ [m]} )</td>
</tr>
<tr>
<td>( k = 1.5 D_{\text{w}} \text{ [m]} )</td>
<td>( k = 0.5 D_{\text{m}} \text{ [m]} )</td>
</tr>
<tr>
<td>( s_{\text{act}} = 0.5B_{\text{w}} \text{ [m]} )</td>
<td></td>
</tr>
</tbody>
</table>

*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.

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.

**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 $\beta_{ub,mob} = 1.65$ appeared to be the best approximation. This parameter forms the basis for the remaining probabilistic calculations.

The mobility parameter $\beta_{ub,mob} = 1.65$ 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 $\psi_e$ during jet-flow is proportional to the reciprocal of $\beta_{ub,cri}$. See the equation above.
This proportionality results in the adjacent table. For the critical mobility parameter for the condition “threshold of motion” the value $\beta_{isp, mob} \approx 3$ is found. Remarkably $\beta_{isp, mob} = 3$ 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 $\beta_{isp, mob} = 1.65$. With a “mean value approach” the influence of each input-variable on the standard deviation of the reliability function can be calculated.

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 $D_{50}$.

From figure 9 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 then 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. 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.

The 10-60kg and the 40-200kg bottom protection will not be in a stable condition during respectively 19% and the 2% of the periodic 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 induced currents dominates the normative loading situations. Figure 10 presents the influence of the grain size $D_{50}$. 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 model, 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.

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

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

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 binominal distribution. Therefore the number of vessels which uses the quay wall in a period of 50 year 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.

<table>
<thead>
<tr>
<th>$\alpha^2$</th>
<th>$C_2$</th>
<th>$D_{real}$</th>
<th>$h_b$</th>
<th>$D_h$</th>
<th>$\beta_{ib}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.34</td>
<td>0.22</td>
<td>0.19</td>
<td>0.09</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>$h_b$</td>
<td>$D_h$</td>
<td>$\rho_{ib}$</td>
<td>$\rho$</td>
<td>$C_1$</td>
<td></td>
</tr>
<tr>
<td>0.007</td>
<td>0.004</td>
<td>0.003</td>
<td>0.003</td>
<td>0.002</td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Influence of each input-variable

![Figure 10: Effects of a chosen $D_{50}$ on stability and transport](image1)

![Figure 11: Fault-tree scour hole in a bottom protection](image2)
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.

**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 for designers**

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 lever during one year;
- upper limit for $C_1=1.17$;
- upper limit for $C_2=0.4$;
- $C_3=2.8$;

<table>
<thead>
<tr>
<th>Bottom protection</th>
<th>10-60kg</th>
<th>40-200kg</th>
<th>60-300kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of manoeuvres in 50 years</td>
<td>14000</td>
<td>14000</td>
<td>14000</td>
</tr>
<tr>
<td>Bow-thruster induced number of scour holes</td>
<td>24.076</td>
<td>0.043</td>
<td>0.002</td>
</tr>
<tr>
<td>Main-thruster induced number of scour holes</td>
<td>3.184</td>
<td>0.085</td>
<td>0.003</td>
</tr>
<tr>
<td>Number of manoeuvres in 50 years</td>
<td>14000</td>
<td>14000</td>
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</table>

*Table 10: Bow- and main-thruster induce scour holes*
• \( f=10\% \) 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 specifications.

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.

**Recommendations for 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.

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