Influence of longitudinal and transverse bulkheads on ship grounding resistance and damage size

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Abstract

This paper presents improvements to the simplified ship grounding resistance and damage opening model for double bottom tankers of Heinvee et al. (2013) by including the effect of longitudinal and transverse bulkheads. The study is based on numerical simulations of 90 grounding scenarios. The scenarios were constructed for three different size tankers, three rock sizes and five penetration depths. Influence of the longitudinal bulkhead on the grounding resistance is described via an additional term. The effect of the transverse bulkheads on the grounding resistance is less profound and thus, this influence is excluded from the simplified formulas. A new approach for the calculation of structural resistance coefficient, that allows scaling of the grounding resistance according to the ship size, is proposed based on the volume of deformed material. Moreover, it is shown that Minorsky’s formula (Minorsky, 1959) for ships collisions is also valid for ship grounding. Formulations for the prediction of the size of the damage opening were modified to include the effect of the bulkheads.

Keywords

Ship grounding; Simplified analytical method; Grounding damage assessment.

Introduction

The paper presents a simple formula for a rapid prediction of grounding damage of double hull tankers. These simplified formulation are aimed for risk analysis studies where there is only limited amount of information available regarding the ships. Several simplified models have been developed to describe a ship grounding accidents. The models either base on a simplified closed form expressions (Cerup-Simonsen et al. 2009), (Hong & Amdahl 2012) or on numerical simulations (Alsos & Amdahl 2007). Precise numerical simulations are too time consuming for risk analyses and require detailed input information. On the other hand, simplified models are often limited to a certain sea bottom topology or to ship’s structural configuration. Moreover, often the methods require that to some extent the damage mechanics are prescribed: for example, the description of contact energy is based on the fracture propagation in the bottom plating.

Simple formulation based on a small number of parameters that describe the grounding resistance of a tanker in a grounding accident was derived by Heinvee et al. (2013). The longitudinal and transverse bulkheads contribution was omitted. The aim of the current paper was to determine the effects of the longitudinal and transverse bulkheads to the average grounding resistance and to the damage size. Large number of grounding scenarios with three tankers including longitudinal and transverse bulkheads are simulated for three rock sizes at five penetration depths. Two transverse rock positions were selected for each grounding scenario, one being directly under the longitudinal bulkhead and other between the bulkhead and the side of the ship. With both rock positions, numerical grounding simulations were conducted in displacement controlled manner at constant grounding velocity. For each grounding simulation, average horizontal grounding force was calculated and the values corresponding to the both rock positions were compared.

The tankers used in the current paper are designed to meet higher strength requirements than tankers used in previous studies (Heinvee et al. 2013, Heinvee & Tabri 2015). Thus, the uniform pressure polynomial as the central element in the simplified approach and the function for the structural resistance coefficient \( c_r \), that scales the resistance according to the ship size, were updated using the same approach as in Heinvee et al. (2013). The structural resistance coefficient \( c_r \) is here evaluated based on the volume of the deformed material. Furthermore, it is shown that the simple formula between the dissipated energy and the volume of damaged material given by Minorsky (1959) is applicable also for ship groundings.

The effect of transverse and longitudinal bulkheads to the damage opening size is studied and equations for the outer and inner damage widths are updated compared to Heinvee & Tabri (2015).
Finite element simulations

This chapter presents an overview of numerical grounding simulations. The principles of numerical modeling and the post-processing of the analysis results are given.

FE models

Three double hull tankers with different dimensions are modeled. The cross-sections with the main structural dimensions are given in Fig. 1 and in Table 1. Hereinafter we use superscripts T150, T190 and T260 to denote the tankers. If the superscript is replaced by i, it means that the description is common to all three ships. Shipbuilding steel with yield stress of 285 [MPa] is used in the analysis. True stress-strain curve is presented in Fig. 3.

![Fig. 1: Tanker cross-sections (dimensions not in scale).](image)

Material failure was modeled with the fracture criterion developed by Kõrgesaar (2015). According to the criterion the fracture strain for shell element is calculated as a function of stress state and element size.

![Fig. 2: FE model of the tanker.](image)

Table 1: Main dimensions and parameters of the tankers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>T150</th>
<th>T190</th>
<th>T260</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [m]</td>
<td>150</td>
<td>190</td>
<td>260</td>
</tr>
<tr>
<td>Breadth [m]</td>
<td>20</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td>Draught [m]</td>
<td>8</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>Depth [m]</td>
<td>10</td>
<td>14</td>
<td>23</td>
</tr>
<tr>
<td>Design speed [kn]</td>
<td>15.4</td>
<td>15.4</td>
<td>15.4</td>
</tr>
<tr>
<td>Deadweight [tdw]</td>
<td>11499</td>
<td>28884</td>
<td>89971</td>
</tr>
<tr>
<td>Double bottom height [m]</td>
<td>1.4</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Outer plating thick. [mm]</td>
<td>14-15</td>
<td>15-18</td>
<td>17-21</td>
</tr>
<tr>
<td>Tank-top thick. [mm]</td>
<td>15</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>Girder spacing [m]</td>
<td>2.2</td>
<td>3.25</td>
<td>3.9</td>
</tr>
<tr>
<td>Floor spacing [m]</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Classification rules</td>
<td>HCSR-OT</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Grounding scenarios and rock locations

The grounding simulations were conducted for five different penetration depths $\delta$ (from 1.0 to 3.0 [m] with 0.5 [m] spacing) and for three rocks. All the rocks are axisymmetric with parabolic cross-sections given by $z=\gamma^2/a$, with $a$ being the parameter defining the rock size (Heinvee & Tabri 2015). Rocks ranged from sharp rocks denoted as rock A ($a=3$) and rock B ($a=6$) to blunt “shoal”-type rock C ($a=12$).

The grounding simulations are done for two transverse rock locations (see Fig. 4a):

i) location $B/4$: between the longitudinal bulkhead and the ship side i.e. at $B/4$;

ii) location $B/2$: directly under the central longitudinal bulkhead i.e. at $B/2$.

Horizontal rock travel starts two web frame distances before the transverse bulkhead and terminates at two web frame distances before the next bulkhead, see Fig. 4b. For each simulation, time histories for the horizontal grounding force (Fig. 4b), deformation energy and the volume of the deformed elements are obtained. From each force time histories two average force values are evaluated, Fig. 4b:

$$F_{B/2}^B$$ (or $F_{B/4}^B$) – average force over the whole horizontal travel distance including the effect of the transverse bulkhead, see red solid line in the figure;

$$F_{wf}^B$$ (or $F_{wf}^B$) – average force over the reduced horizontal travel distance excluding the effect of the transverse bulkhead, see red dashed line in the figure;

The effect of longitudinal bulkhead can be determined by comparing the average forces $F_{wf}^B$ and $F_{wf}^B$. Similarly, the effect of transverse bulkheads is determined by comparing the average forces $F_{B/4}^B$ and $F_{B/4}^B$.

Furthermore, to study the opening widths in outer and inner bottom, the corresponding values are measured from each FE simulation.

Effect of longitudinal bulkhead

The effect of longitudinal bulkhead to the grounding force is presented in Fig. 5 via comparison of average forces $F_{wf}^B$ (longitudinal bulkhead contributes to the grounding resistance) and $F_{wf}^B$ (no resistance contribution by longitudinal bulkhead). Fig. 5 presents the ratio $F_{wf}^B/F_{wf}^B$ as a function of penetration depth for different rocks and ships. Figure reveals that at low penetration depths the longitudinal bulkhead increases the resistance about 10% regardless of ship and rock size. The influence of the bulkhead increases at higher penetration depths. For $\delta=3$ [m] the maximum force ratios for ships T150, T190 and T260 are 1.3 (30%), 1.46 (46%) and 1.36 (36%) respectively.

It should be noted that at $\delta>1$ [m] the ratio continues to increase for rocks A and B, while for the rock C the ratio remains almost constant. As the rock C is relatively large compared to the ship cross-sections, the double side starts to contribute to the resistance at higher penetration depths. Thus, it can be concluded that with large shoal-type rocks ($a\geq12$) the influence of the longitudinal bulkhead is small as it is partly compensated by the contribution from the double side structure. Furthermore in Fig. 5a the ratio decreases for rock C at $\delta=1.5$ [m] due to the crushing of the ship side that gives significant additional resistance. As the purpose was to determine the effect of longitudinal bulkhead, these scenarios are omitted in subsequent development of the term describing the effect of longitudinal bulkhead (Eq. 1 and Fig. 6).

In Fig. 6 the regression curve is fitted through all the $F_{wf}^B/F_{wf}^B$ ratios, giving a term describing the effect of
the longitudinal bulkhead:

\[
\bar{F}_{wf}^{B/4} = 0.105\delta + 1.04. \tag{1}
\]

In order to employ the obtained relationship, we derive formula for the average force \( \bar{F}_{wf}^{B/4} \) by using the approach presented in Heinvee et al. (2013).

Thus, the rock directly under the longitudinal bulkhead, the average grounding force can be calculated as

\[
\bar{F}_{wf}^{B/2} = \bar{F}_{wf}^{B/4} \cdot (0.105\delta + 1.04), \tag{2}
\]

where \( \bar{F}_{wf}^{B/4} \) is average grounding force without the contribution from the longitudinal bulkhead.

**Fig. 5**: Increase of average grounding force due to the longitudinal bulkhead presented as a ratio \( \bar{F}_{wf}^{B/2}/\bar{F}_{wf}^{B/4} \). Dashed vertical line indicates the double bottom height.

**Fig. 6**: The effect of longitudinal bulkhead to the average grounding force: The ratio between average forces calculated at \( B/2 \) and \( B/4 \).

**Fig. 7**: The effect of transverse bulkhead to the grounding force presented as a ratio \( \bar{F}_{wf}^{B/4}/\bar{F}_{wf}^{B/4} \). Dashed vertical line indicates the double bottom height.
Effect of transverse bulkhead

To study the influence of transverse bulkheads we compare two average forces $F_{B/4}^2$ and $F_{w/4}^2$. The average forces ratios $F_{B/4}^2/F_{w/4}^2$ are presented in Fig. 7 for three ships and for three rock sizes.

In Fig. 7 the force ratios $F_{B/4}^2/F_{w/4}^2$ for both rock positions remain almost constant and are approximately equal to 1, which means that bulkhead has only small influence to the average grounding force. Similar behavior of the ratio was observed also for $F_{B/2}^2/F_{w/2}^2$. As the influence of the transverse bulkhead to the average grounding force is small, its contribution is not explicitly presented in the simplified equations.

Updated formulas for the grounding force

The simplified formula for the average horizontal grounding force $F_H$ was given by Heinvee et al. (2013) as

$$F_H = \bar{c}_T^i \cdot \bar{P} \cdot A,$$  \hspace{1cm} (3)

where $\bar{c}_T^i$ is a coefficient for ship $i$ and is characterizing ship’s structural resistance and defined via bilinear function of ship length $L$, $\bar{c}_T^i = f_{C_T}(L)$, $\bar{P}$ is the uniform pressure polynomial describing the contact pressure as a function of rock size $a$ and $A$ is the projected contact area between the rock and the ship double-bottom (Heinvee et al. 2013) given in Appendix A.

The current paper updates the function for the structural resistance coefficient $\bar{c}_T^i$ and the uniform pressure polynomial $\bar{P}$ using the same procedure as presented in Heinvee et al. (2013). The updated structural resistance coefficient function for $\bar{c}_T^i$ takes the form (Fig. 8a)

$$\bar{c}_T^i = f_{C_T}(L) = \begin{cases} 137.5 \cdot L + 176709.1, & \text{if } 50 \leq 190 \text{ [m]} \\ 10676.7 \cdot L + 31932.2, & \text{if } 190 \leq 300 \text{ [m]} \end{cases}.$$  \hspace{1cm} (4)

In Fig. 8 the structural resistance coefficients $\bar{c}_T^i$ are presented for the tankers used in this paper (Fig. 8a) and for those used in Heinvee et al (2013) (Fig. 8b) and about 1.6 times increase in recognized. Reasons for that are analyzed in the next section, where the structural resistance coefficient is connected to the volume steel material.

The updated form for the pressure polynomial was derived based on average forces $F_{B/4}^2$ and is as follows

$$\bar{P}(a) = 2.64 \cdot 10^{-3} a^2 - 6.1 \cdot 10^{-2} a + 1.16.$$  \hspace{1cm} (5)

The contact force in grounding can now be calculated using Eq. 3. If the rock is positioned directly under the longitudinal bulkhead then Eq. 3 is to be multiplied with the term given by Eq. 1 giving the average grounding force under the longitudinal bulkhead as

$$F_H = \bar{c}_T^i \cdot \bar{P} \cdot A \cdot (0.105 \delta + 1.04).$$  \hspace{1cm} (6)

Structural resistance coefficient as a function of material volume

The difference of structural resistance coefficients in Fig. 8 is due to the different design criteria used for the ships- the tankers in the current paper meet all the strength criteria according to HCSR-OT rule while the tankers in Heinvee et al. (2013) only satisfy the minimum rule scantling requirements and thus, present very conservative approach in means of structural resistance. Clearly, the latter tankers contain less steel. To determine their differences, we calculate the volume of deformed material $V_{def}$ (material where plastic strain $\varepsilon_p > 0.01$) for four numerical simulations: two conducted with T190 tankers and two with T260 tankers, see Table 2.

Table 2: Ratios of $V_{def}$ and $\bar{c}_T^i$ for different tankers.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\delta$ [m]</th>
<th>$V_{def}$ [m$^3$]</th>
<th>Ratio ($V_{def}$)</th>
<th>Ratio ($\bar{c}_T^i$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T190, rock A</td>
<td>2.5</td>
<td>4.05</td>
<td>1.5</td>
<td>1.63</td>
</tr>
<tr>
<td>T190, rock A**</td>
<td>2.5</td>
<td>6.05</td>
<td>1.44</td>
<td>1.61</td>
</tr>
<tr>
<td>T260, rock A</td>
<td>2.5</td>
<td>5.55</td>
<td>1.4</td>
<td>1.61</td>
</tr>
<tr>
<td>T260, rock A**</td>
<td>2.5</td>
<td>7.75</td>
<td>1.92</td>
<td>1.61</td>
</tr>
</tbody>
</table>

* tanker used in Heinvee et al. (2013); ** tanker used in the current study.

The results given in Table 2 show that the volume of deformed material for the current tankers is 1.5 and 1.4 times higher for T190 and T260 tankers, respectively. This indicates a possible correlation between the structural resistance coefficient and the volume of deformed steel material. If such correlation exists, the $\bar{c}_T^i$ values presented by Eq. 4 can be used as a basis to evaluate a $\bar{c}_T^i$ value for any ship $i$ once the steel volumes $V_{mat}^i$ and $V_{mat}^j$ are determined:

$$\frac{\bar{c}_T^i}{c_T^j} = \frac{\bar{V}_{mat}^i(a, \delta)}{\bar{V}_{mat}^j(a, \delta)} \rightarrow \frac{\bar{c}_T^i}{\bar{c}_T^j} = \frac{\bar{V}_{mat}^i(a, \delta)}{\bar{V}_{mat}^j(a, \delta)},$$  \hspace{1cm} (7)

where $\bar{V}_{mat}^i(a, \delta)$ and $\bar{V}_{mat}^j(a, \delta)$ are approximations.
for the steel volume to be deformed per unit length in a certain grounding scenario defined via rock size \( a \) and penetration depth \( \delta \). A routine to approximate this volume is presented in detail in Appendix A, which also presents the \( \bar{V}_{\text{mat}}^i \) values for the tankers (Table A1) used in the current paper. In the calculation procedure the volume \( \bar{V}_{\text{mat}}^i \) includes the contributions from the double bottom structural members, which are in direct contact with the rock.

In Fig. 9 averaged steel volume \( \bar{V}_{\text{mat}}^i \) is presented for all the simulated scenarios with position \( B/4 \). Two patterns can be recognized. First, for each ship the averaged volume increases proportionally with the penetration depth. This holds for all the rocks. This indicates that the ratio of average volumes at each penetration depth is constant between any two ships. This is also presented in Table 3, where the averaged steel volumes are normalized with respect to the volume of the largest tanker T260. The Table 3 reveals that the normalized values are constant for each tanker, except for T150 at \( \delta=1.5 \) [m] for which the normalized value is 0.93. This is due to rapid and local increase in steel volume as the penetration slightly above the double bottom height \( (h_{db}=1.4 \text{ m}) \) for T150. This effect diminishes as the penetration increases further. Thus, it is suggested to use \( \delta \geq h_{db} \) for the evaluation of the \( \bar{V}_{\text{mat}} \) in Eq. 7.

### Table 3: Normalized material volumes.

<table>
<thead>
<tr>
<th>Ship</th>
<th>( \bar{V}<em>{\text{mat}}^i / \bar{V}</em>{\text{mat}}^{T260} ) for penetration ( \delta ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T150</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>2…3</td>
</tr>
<tr>
<td>T190</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>0.85</td>
</tr>
<tr>
<td>T260</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

In Fig. 10 the normalized volumes from Table 3 and the \( c_i^s \) values from Fig. 8 are presented as a function of ship size. All the values are normalized with respect to the corresponding value of the largest tanker T260. The comparison shows that the average volume behaves similar to the structural resistance coefficient. Thus, the structural resistance coefficient can be determined via the steel volumes by using Eq. 7. It should be noted, that for the comparison in Eq. 7, the same \( a \) and \( \delta \) values should be used both for \( \bar{V}_{\text{mat}}^i(a, \delta) \) and \( \bar{V}_{\text{mat}}^j(a, \delta) \) and for \( \delta \geq h_{db} \).

Moreover, as the link between the \( \bar{V}_{\text{mat}}^i \) and the structural resistance exists, there should also be a relationship between the steel volume and the deformation energy. This relationship is studied in the next section.

### Relationship between the dissipated energy and volume of deformed material

It was shown by Minorsky (1959) that there is linear correlation between the volume of the deformed material and the energy dissipated during the ships collision. In Luukkonen (1999) the performance of Minorsky’s equation together with several other simplified models was analyzed with respect to real grounding accidents. Although the correlation between the deformed material...
and the dissipated energy was recognized, significant variations occurred for all the models. Obviously, the differences were partly due to poor reporting of the real accidents, e.g. the grounding velocity and the description of the grounding scenario. Here the aim is to develop linear relationship between the steel volume \( V_{\text{mat}} \) and the absorbed energy based on numerical simulations, where the grounding scenario is well defined.

Fig. 11: Averaged energy vs volume of deformed material per unit damage length in case of B/4: (a) \( \varepsilon_p > 0.01 \); (b) \( \varepsilon_p > 0.1 \).

We use the steel volume \( V_{\text{mat}} \) (Appendix A) to approximate the volume of the deformed material \( V_{\text{def}} \). For each grounding simulation the volume of deformed material \( V_{\text{def}} \) was calculated for two different levels of equivalent plastic strains: \( \varepsilon_p > 0.01 \) and \( \varepsilon_p > 0.1 \), which are plotted against the dissipated energy in Fig. 11 for the position B/4. The dissipated energy includes the contribution from friction. In the figure, both the energy \( \bar{E} \) and the steel volumes are presented per unit length. For that the deformation energy \( E \) absorbed during the rock travel over the horizontal distance \( L_h \) (Appendix A) was divided with \( L_h \) to obtain \( \bar{E} \). For both plastic strains a strong linear correlation can be noticed. Clearly, the amount of deformed material depends how one defines the deformed material. It is interesting to note that for \( \varepsilon_p > 0.01 \) the obtained dependency is very similar to the one shown by Minorsky (1959). To maintain the similarity to Minorsky’s classical relationship, we derive the relationships based on \( \varepsilon_p > 0.01 \), giving the deformation energy \( \bar{E} \) per unit length as:

\[
\bar{E} = \begin{cases} 
38.11(1.07\bar{V}_{\text{mat}} + 0.021) + 3.85 \text{ [MJ/m]} \\
38.11(1.26\bar{V}_{\text{mat}} - 0.016) + 3.85 \text{ [MJ/m]}
\end{cases}
\text{for rock at B/4}
\]

where \( \bar{V}_{\text{mat}} \) unit is \([m^3/m]\).

Fig. 12: Average force calculated with Eq. (3) and Eq. (8), \((\varepsilon_p>0.01)\).

It should be noted, that the energy per unit length, \( \bar{E} \) given by Eq. 8, has a unit of [MJ/m] and actually represent the average grounding force. Thus, it can be direct-
ly compared to the average grounding force given by numerical simulations and with Eq. 3 and Eq. 6. For the position B/4, this comparison is given in Fig. 12, where empty circles present the average grounding force from numerical simulations, filled circles present the energy per unit length from numerical simulations, solid lines present Eq. 3 and dashed lines present Eq. 8. Good correlation exists between the equations and the numerical simulations, except for Eq. 8 and tanker T260, where the deviation is about 15-20%.

Depending on the available information for grounding scenario either Eq. 3, Eq. 6 or Eq. 8 can be used for the calculation of the average grounding force. If the rock size, penetration depth and the ship scantlings are available then Eq. 8 can be used to take into account the resistance of the specific ship. However, if such detailed data for ship is not available then Eq. 3 or Eq. 6 can be employed using the penetration depth, rock size, ship length and double bottom heights as variables.

**Size of the damage opening**

In this chapter the effect of transverse and longitudinal bulkheads to the damage opening width is studied. The damage opening formulas developed in Heinvee & Tabri (2015) are updated accordingly. The damage opening formulas give the dimensions of the opening widths and should be used together with a criteria defining whether the failure in the inner bottom occurs. First, the formulas for the opening widths are updated following the updated criteria for critical penetration depth.

**Damage width in outer and inner bottom**

In each numerical simulation the average opening width was measured for the outer and inner bottom and the measurements are presented in Fig. 15. Fig. 15 presents the damage widths only for the position B/4. In B/2 the behavior and the damage dimensions were similar meaning that the effect of longitudinal bulkhead to the average inner opening width is modest. Moreover, observations from FE simulations showed that a noticeable increase in opening width in the inner bottom occurred locally at the vicinity of the transverse bulkhead and this has only minor effect on the average width. The numerical simulations showed that the grounding damages with respect to the ship size were relatively local and concentrated to the vicinity of the intruding rock, see Fig. 13b. In is interesting to notice that the damage width in the transverse and longitudinal bulkheads contributed to the localization of the damage. In the simulations without the bulkheads (Heinvee & Tabri, 2015) the stiffness of the double bottom was lower and, especially in the case of larger rocks, the resulting damage was global deformation of the whole double bottom, see Figure 11a. When the bulkheads are included, the dominating deformation mode is a combination from local tearing and global crushing in case of all three rocks.

**Fig. 13: Comparison of bottom damages:** (a) tanker without the bulkheads (Heinvee & Tabri 2015) (b) tanker with bulkheads.

In Heinvee & Tabri (2015) the equation for the damage opening widths were given separately for two rock size ranges due to the dominant global crushing modes in the case of large rocks (\(a \geq 12\)). Here, the deformation modes were similar for all the covered rock sizes and the equations can be presented for a single range covering all the rocks \(3 \leq a \leq 12\). Analysis revealed that within the range of penetration depths 1.0 to 3.0 [m] the behavior of the opening width in the outer bottom generally follows the rock width. Similar observations as in Heinvee & Tabri (2015) can be made:

i) the opening width in the inner bottom grows similarly to the opening width in the outer bottom;
ii) onset of failure in the inner bottom is delayed by \(\delta = b \cdot h_{ab}\) compared to that in the outer bottom, where constant \(b \equiv 0.75\).

Simulations revealed that the outer bottom failure was observed roughly at \(\delta \geq 0.5\) [m]. Thus, the simplified formulas for the prediction of opening widths in the outer and inner bottom are as follows:

**opening width in the outer plating**

\[
D_{out}(a, \delta) =
\begin{cases}
2\sqrt{a} \cdot \delta \cdot [1.6\delta - 0.8] & \text{for } \delta \leq 1\left[m\right] \\
0.8 \cdot 2\sqrt{a} \cdot \delta & \text{for } \delta > 1\left[m\right]
\end{cases}
\]
for $150 \, [m] \leq L \leq 260 \, [m]$, $3 \leq a \leq 12$

opening width in the inner plating

$$D_{in}(a, \delta, h_{db}) = \begin{cases} 2\sqrt{a(\delta - 0.75h_{db})}[1.6(\delta - 0.75h_{db}) - 0.8] & \text{for } \delta \leq 1 \, [m] \\ 0.8 \cdot 2\sqrt{a(\delta - 0.75h_{db})} & \text{for } \delta > 1 \, [m] \end{cases}$$

for $150 \, [m] \leq L \leq 260 \, [m]$, $3 \leq a \leq 12$.

Comparison between the measured opening widths and the calculations using the above equations are presented in Fig. 15. The figure shows that Eq. 9 slightly underestimates the width of the damage opening in the outer plating especially in the case of larger penetration depths. The deviation is about 20%. For the inner plating opening, the Eq. 10 alone, see dashed lines in Fig. 15, significantly overestimates the damage width for lower penetration depths, while for higher values the prediction is reasonable. Thus, a criterion is required to define the onset of the failure in the inner plating. This criteria is presented in the next section.

![Fig. 14: Fracture criterion for the inner bottom.](image)

**Critical penetration depth for the inner bottom failure**

The critical penetration depth $\delta_{f}$ defines whether the inner bottom is thorn open as Eq. 10 alone might predict inner bottom failure prematurely, see Fig. 15. Updated form for the critical penetration depth is derived in a similar manner to Heinvee & Tabri (2015). In the derivation, the simulations with the rock position $B/2$ are used. The critical penetration depth $\delta_{f}$ obtained from the numerical simulation was divided with the corresponding double bottom height $h_{db}$, providing the relative critical penetration depth. These ratios are presented in Fig. 14 as a function of the ratio between the rock size and the ship breadth - $a/B$. The regression line through the measured points forms the criterion as follows:

$$\frac{\delta_{f}}{h_{db}} = 0.75 \frac{a}{B} + 1.17$$

$$\Rightarrow \delta_{f} = \left(0.75 \frac{a}{B} + 1.17\right) h_{db}.$$ 

The inner bottom damage occurs once the penetration depth is higher than given by Eq. 11. After the critical penetration depth is reached, the width of the opening in the inner bottom can be evaluated using Eq. 10, see Fig. 15.

**Conclusions**

Simplified formulas for the calculation of average grounding force given in Heinvee et al. (2013) have been updated to consider the contribution from the transverse and longitudinal bulkheads. The contribution is studied via series of numerical grounding simulations. The analysis of numerical simulations showed that the longitudinal bulkhead substantially increases the average grounding force. If the intruding rock is directly under the longitudinal bulkhead the grounding force can be up to 50 % higher compared to the situation when the rock is between the bulkhead and the ship side. This influence is included in the simplified formulas via additional term depending on the penetration depth. Analysis also revealed that, in general, the transverse bulkhead has small influence to the average grounding force and thus its contribution in not explicitly included in the equations, while its influence is implicitly included in the structural resistance coefficient.

A new approach was proposed for the prediction of resistance coefficient $c_{T}$ based on the approximation of the volume of the deformed material. It was shown that the structural resistance coefficient is proportional to the volume of deformed material. Even though the calculations require detailed information of ship’s double bottom structure, it provides an analytical measure to develop more ship-specific estimate for $c_{T}$. Moreover, simulations revealed that a linear relationship exists between the volume of the deformed material and the energy absorbed in grounding i.e. Minorsky’s relationship, though slightly modified, is applicable also for ship groundings. Equations to predict the volume of the deformed material in a certain grounding scenario were derived based on the structural configuration of the double bottom.

The longitudinal and transverse bulkheads influence also the damage opening size during the grounding over large rocks. In the case of smaller rocks, the influence of the bulkheads on the opening size was modest.

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Fig. 15: Opening width in the inner and the outer bottom: FE simulations vs. equations.

References


Appendix A

Procedure for the calculation of steel volume:

In transverse and longitudinal direction, the structural members contribute to the total steel volume only if in direct contact with the rock, see red area in Fig. A1. In longitudinal direction the steel volume is evaluated over the horizontal length $L_h$ that is the length of one tank compartment and is symmetric with respect to the transverse bulkhead.

The steel volumes are calculated with the following steps:

(i) Equivalent thicknesses for the inner and outer plate, girders and floors are calculated as follows

$$t_{eq} = t_{pl} + \frac{n \cdot A_{stiff}}{D},$$

where $t_{pl}$ is the plate thickness, $n$ is the number of stiffeners on the plate and $D$ is the plate width. If the plating consists of several plates with different thicknesses then the equivalent value for the $t_{pl}$ is calculated as
\[ t_{pl} = \frac{\sum_i d_i \cdot t_i}{D}, \]

where \( d_i \) is the width of \( i \)-th plate and \( t_i \) is the corresponding thickness.

(ii) Determine the length for the longitudinal members and the number for the transverse members:

The length of longitudinal members (inner and outer plate, girders) is taken as \( L_h \).

Number of the transverse members is equal to the number of floors inside the length \( L_h \).

(iii) Taking into account the position of the rock with respect to the structural members, calculate the total volumes for the structural members:

**Outer plate**

\[ V_{out,pl} = 2\sqrt{a} \cdot \delta \cdot t_{eq} \cdot L_h, \]

**Inner plate**

\[ V_{in,pl} = 2\sqrt{a} \cdot (\delta - h_{db}) \cdot t_{eq} \cdot L_h, \]

**Girders**

\[ V_{gir} = \sum_i \delta_a \cdot t_{gir}^i \cdot L_h, \]

where, \( t_{gir}^i \) is the equivalent thickness of a girder \( i \), \( \delta_a \) is the height of the “deformed” part of a girder which is given as:

\[ \delta_a = \delta - \frac{\Delta Y^2}{a}, \]

where, \( \Delta Y \) is the horizontal distance from the tip of the rock to the girder \( i \), see Fig. 1A. If entire girder is “damaged” then \( \delta_a = h_{db} \).

**Floors**

\[ V_{floor} = n \cdot t_{eq} \cdot A_{floor}, \]

where \( n \) is the number of floors, \( t_{eq} \) is equivalent thickness of the floor and \( A_{floor} \) is equal to the contact area \( A \) between the floor and the rock given by

\[ A_{floor} = A = \left\{ \begin{array}{ll}
\frac{4}{3} \sqrt{a} \cdot \delta^{(3/2)}, & \text{if } \delta \leq h_{db} \\
\frac{4}{3} \sqrt{a} \cdot \left[ (\delta^{(3/2)}) - (\delta - h_{db})^{(3/2)} \right], & \text{if } \delta > h_{db} \end{array} \right. \]

(iv) Total volume of material \( V_{mat} \) for a scenario is sum of all individual volumes of structural members

\[ V_{mat} = V_{out,pl} + V_{in,pl} + V_{gir} + V_{floor} \ [m^3]. \]

(v) Volume per meter is calculated as

\[ \bar{V}_{mat} = \frac{V_{mat}}{L_h} \ [m^3/m]. \]