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Floodable length of a bulk carrier

Elwira Kałkowska

Maritime University of Szczecin
1-2 Wały Chrobrego St., 70-500 Szczecin, Poland
e-mail: elwira.kalkowska@wp.pl

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Abstract

With regards to safety, the International Maritime Organization (IMO) and the International Association of Classification Societies (IACS) regularly issue regulations and technical standards for the design and construction of ships in order to safeguard the crew and people on board. In light of these regulations, three issues concerning the properties of a bulk carrier are investigated. Initially the floodability of a bulk carrier is researched to investigate the largest possible volumes of compartments which can be flooded without causing a bulk carrier to capsize. The results are determined by means of a marine design software, *Maxsurf Enterprise*.

Introduction

According to Ole Skaarup, the designer of the modern version of a bulk carrier, "…the most practical ship should have wide, clear cargo holds. Thus, it would require machinery aft, wide hatch openings to ease cargo handling and a hold configuration that could eliminate the need for shifting boards."

Due to the loss of bulk carriers at sea, a new regulation was added to the International Convention for the Safety of Life at Sea (SOLAS) regarding their damage stability. SOLAS Chapter 12, Regulation 4 (IMO, 2009) states that all bulk carriers over 150 metres long and built after July 1999 must, when loaded to the summer load line, withstand the flooding of any one cargo hold in all loading conditions and remain afloat (IMO, 2014b).

The floodable length is the length of a ship, disregarding any transverse watertight bulkheads, that, when flooded, causes the ship to sink or trim to the margin line. The margin line is taken to be a minimum of 76 millimetres (3 inches) below the bulkhead deck. The bulkhead deck refers to the highest point of the transverse bulkheads at which a watertight deck is situated (Rawson & Tupper, 2001).

Floodable length

Figure 1 represents the floodable length of longitudinal position A. The floodable length can be

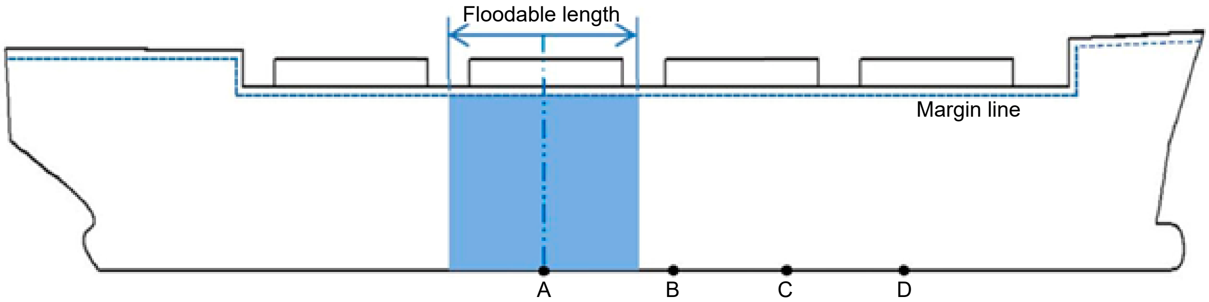

Figure 1. Floodable length of point A

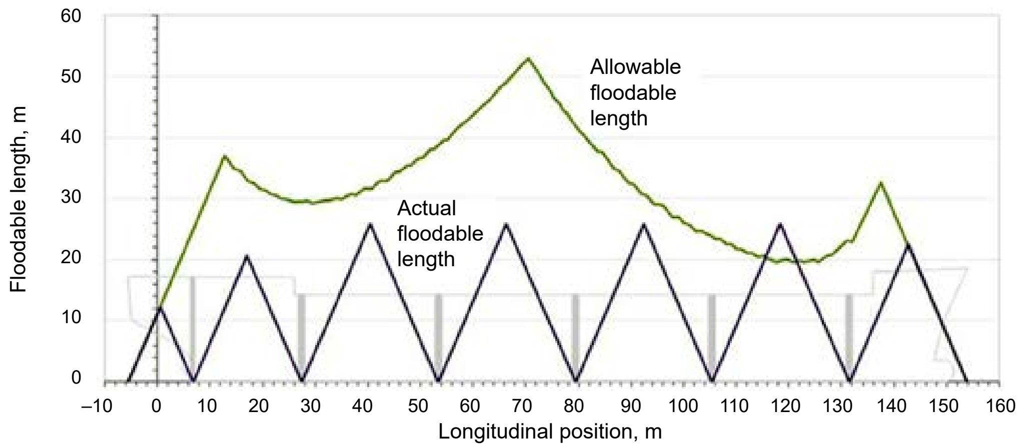

Figure 2. Floodable length curve

calculated for different points longitudinally, such as points B, C and D, and the results are plotted in a Floodable Length Curve where the *x*-axis represents the longitudinal length of the ship and the *y*-axis represents the allowable floodable length.

A ship is subdivided into compartments by watertight bulkheads, which limit the floodable length at some locations along its length. Taking this concept into consideration and bearing in mind that only one compartment can be flooded, another graph can be plotted on the same axis showing the actual floodable length, as shown in Figure 2. The bases of the triangles in the graph represent the locations of the watertight bulkheads. The peaks of the triangle represent the actual floodable length in the corresponding compartment. The actual floodable length can therefore be immediately drawn on a graph if the bulkhead locations are known since the height of each triangle is equal to the distance between the respective bulkheads.

If the upper points of the actual floodable length's triangles exceed the allowable floodable length, as shown by the sixth triangle from the left in Figure 2, the waterline exceeds the margin line and the ship is considered lost.

Allowable floodable length curves can be calculated for different ship displacement values. A greater displacement, which is relative to a ship having a higher draught, tends to lower the allowable floodable length values for the whole graph, whilst less displacement raises the allowable floodable length, meaning that more water volume is needed for the vessel's margin line to reach the waterline (Rawson & Tupper, 2001; Tupper, 2004).

Furthermore, the compartments' permeability (μ) plays an important role in calculating the floodable length. The permeability is the ratio of the floodable volume (υ_t) to the total compartment volume (υ_c):

$$\mu = \frac{\upsilon_t}{\upsilon_c} \tag{1}$$

According to SOLAS Chapter II Part B Regulation 25-7 (IMO, 2014a), the permeability for different cargo ships' compartments should be taken as shown in Table 1.

Table 1. Permeabilities of different compartments according to SOLAS Chapter II (IMO, 2014a)

Space	Permeability
Accommodation	0.95
Machinery	0.85
Void Space	0.95
Dry Cargo Spaces	0.70
Liquid Compartments	0.95

Allowable Floodable Length Calculation

The following procedure was proposed by Dipl. Ing. F. Shirokauer (1928) (Lewis, 1988). Supplementary information is included to clarify Shirokauer's method.

The allowable floodable lengths at various positions along the ship's length are obtained by considering the bulk carrier at different trims, and with a draught at which the margin line touches the water line. The seawater which floods a compartment is called damage water, and every trim is caused by having a mass of damage water with its centre of gravity (COG) a distance away from amidships. The weight of the damage water causes a moment about the ship's longitudinal centre of gravity (LCG), causing the ship to trim. The floodable length is therefore the length of flooded compartment needed at a particular longitudinal position to cause the vessel to heave down and trim until the margin line touches the waterline.

The first part of this method involves finding:
- the volume of the damage water; and
- the distance between a vessel's COG and amidships.
- The second part entails finding:
- the length of the compartment which holds the volume of damage water, i.e. the floodable length; and
- the location of the compartment's midpoint.

Each trim line will therefore result in one floodable length value and its corresponding longitudinal position. A variety of trim lines must be tested in order to get a sufficient number of points to plot a graph such as Figure 2.

The third and final part of this method involves finding the floodable length curve's aft and forward endpoints.

Part 1: Damage Water

1) The vessel is divided longitudinally into a number of transverse sections between the aft perpendicular (AP) and forward perpendicular (FP). Figure 3 shows a vessel split into ordinates 0 to 10 having a spacing found by equation (2).

$$S = \frac{L_{BT}}{10} \tag{2}$$

2) The initial draught at which the floodable length is investigated is drawn and denoted by T_0. The underwater transverse cross-sectional areas at each ordinate are read from the vessel's Bonjean curves. Simpson's rule, thus equation, is applied to calculate the ship's initial displaced volume at the initial waterline, and is denoted by ∇_0.
3) A trim line is drawn parallel to the initial water line at the lowest point of the margin line. It is denoted as PAR in Figure 3. This trim line represents the ship on an even keel, and having the deck almost touching the waterline.
4) Points on the AP and FP are marked at distances $H/3$, $2H/3$, $5H/6$ and H away from the parallel trim line, as shown in Figure 3. According to Shirokauer (Lewis, 1988), the value is given by equation (3):

$$H = 1.6\,D_m - 1.5\,T_0 \tag{3}$$

where: D_m – depth from keel to margin line (m).

5) From these points, trim lines tangent to the margin line are drawn. The forward trim lines are named 1F, 2F, 2.5F and 3, while the trim lines having a trim by the aft are named 1A, 2A, 2.5F and 3A, as displayed in Figure 3.
6) For each trim line:
   i. The cross-sectional area at each ordinate up to the trim line is found using the vessel's Bonjean curves.
   ii. The volume of damage water is the volume of water which is added to the ship at the initial waterline. It is, therefore, the difference between the displaced volume of the trimmed ship and the initial volume displacement:

$$\upsilon_t = \nabla_t - \nabla_0 \tag{4}$$

   iii. The moment of the area about amidships is calculated using Simpson's rule. Section 5 is the amidships; therefore, the application of Simpson's rule are taken about Section 5. The distance between the LCG of the ship and amidships is denoted by $\bar{x}_t$.
   iv. The damage water causes the ship to trim, causing the initial LCG (G_0) to move to a new position (G_1), as shown in Figure 4. Taking moments about, the distance can be found by:

$$\upsilon_t x_\upsilon = \nabla_0 (G_0 G_1)$$
$$x_\upsilon = \frac{\nabla_0}{\upsilon_t}(G_0 G_1) \tag{5}$$
$$x_\upsilon = \frac{\nabla_0}{\upsilon_t}(\bar{x}_t - \bar{x}_0)$$

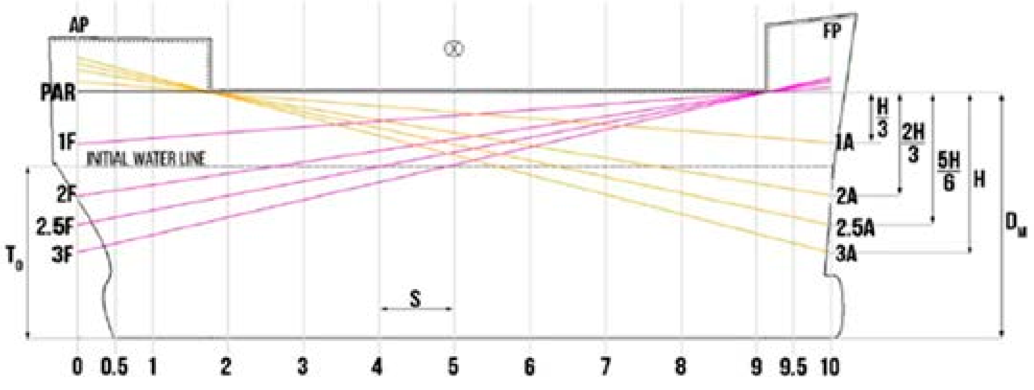

Figure 3. Vessel split into sections 0 to 10. Various trim lines are drawn on the ship's profile

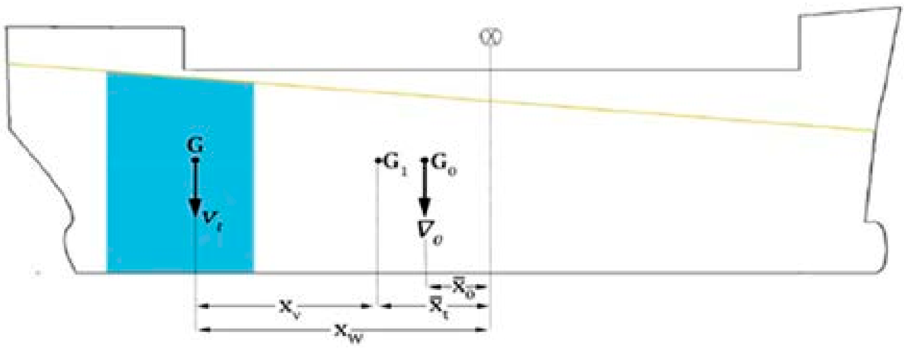

Figure 4. Moment caused by damage water

Figure 4 indicates that the distance between the COG of damage water and amidships is:

$$x_w = \bar{x}_t + x_\upsilon \quad (6)$$

Substituting (5) for (6):

$$x_w = \bar{x}_t + \frac{\nabla_0}{\upsilon_t}\left(\bar{x}_t - \bar{x}_0\right) \quad (7)$$

7) υ_t and x_w for each trim line are plotted on a graph against the respective trim.

Part 2: Floodable Lengths

The following method is repeated for every trim line in the test.

1) Taking permeability into consideration, the flooded compartment volume is found by:

$$\upsilon_c = \frac{\upsilon_t}{\mu} \quad (8)$$

where μ – permeability of the compartment.

2) The COG of the damage water is represented in Figure 5. An arbitrary value is taken between the damage water COG and the midlength of the flooded compartment, and is denoted by x_{m1}.
3) x_{c1} is found by:

$$x_{c1} = x_w - x_{m1} \quad (9)$$

4) The compartment volume (υ_c) is divided by an approximate mean section area to find an assumed floodable length (l_1). The length is subdivided into five ordinates, which are represented by numbers 0, 1, 2, 3 and 4, as seen in Figure 5.
5) Using Simpson's rule with five ordinates:

i. The spacing (S) of the ordinates is found by equation $S = l/n$.

ii. The five section areas at each ordinate are read from the vessel's curve of areas at that specific trim and draught. The curve of areas may be obtained using the Hydrostatics module of *Maxsurf's Stability*.

iii. The volume of this compartment, denoted by υ_{c1}, is calculated by equation:

$$\text{volume} = \frac{S}{3}\left(A_0 + 4A_1 + 2A_2 + \cdots + 4A_{n-1} + A_n\right).$$

υ_{c1} may not be equal to the volume of damage water because the floodable length was calculated using an assumed mean section area.

iv. An improved estimation of the floodable length, denoted by l_2, can be found by simple proportion where:

$$\frac{l_2}{\upsilon_c} = \frac{l_1}{\upsilon_{c1}}, \qquad l_2 = \frac{l_1}{\upsilon_{c1}}\upsilon_c \quad (10)$$

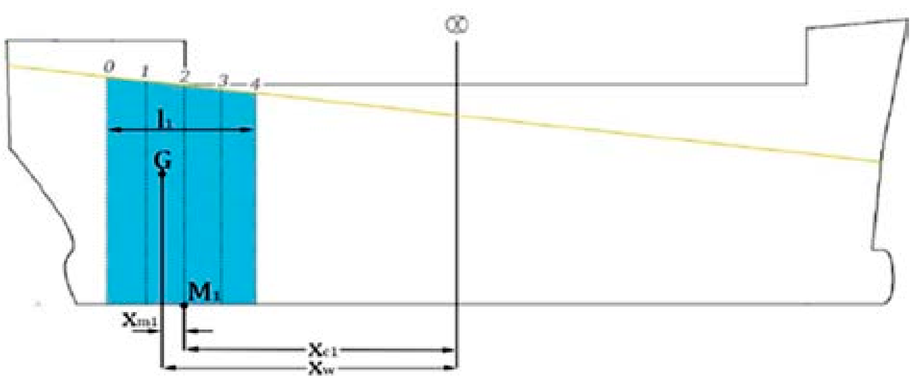

Figure 5. Flooded compartment at a specific trim by the aft

v. An improved estimation of x_{m1}, denoted by x_{m2}, is calculated by finding the location of the compartment's COG, denoted by G_1 in Figure 6. The compartment's COG should fall on position G but, since the value of x_{m1}, was an assumption, the compartment's COG – i.e. the damage water COG – might not fall exactly on G.

6) An improved value for x_c is found by:

$$x_{c2} = x_w - x_{m2} \tag{11}$$

7) Steps 4–6 may be repeated using l_2 and x_{c2} as l_1 and x_{c1} respectively. Iterations may halt when the values $\upsilon_{c1} \approx \upsilon_c$ and the compartment's COG fall approximately on point G, which is x_w away from amidships.

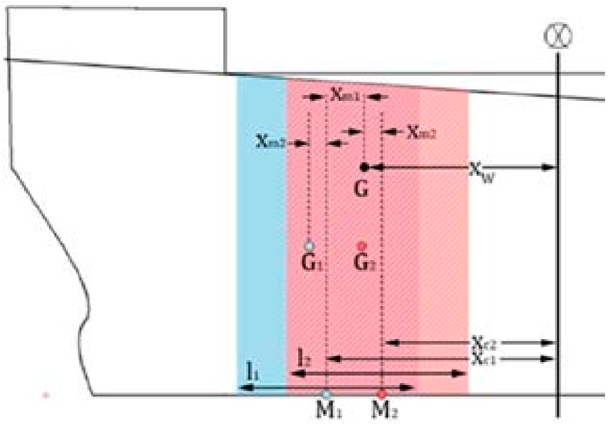

Figure 6. Floodable length calculation

Part 3: End Point Calculation

Generally, the floodable length for trim lines 3A and 3F cannot be found because the calculated compartment length will be partially outside the length of the ship. This condition implies that for a ship at the initial water line value, there exists no floodable compartment which makes the ship trim to 3A or 3F.

This is an indication that the aft endpoint on the graph corresponds to a trim line between 2.5A and 3A. Similarly, the forward endpoint occurs at a trim between 2.5F and 3F. The trims at which the endpoints fall are unknown, but close to 3F and 3A; therefore, Shirokauer (Lewis, 1988) suggests that the sectional areas considered in the endpoint calculations are those from trim lines 3F and 3A.

1) Considering the aft end of the ship, thus trim line 3A:
   Using the trend of the floodable length curve, a reasonably close estimate of the floodable length at the end points can be obtained. The estimated floodable length is denoted by l_a.

2) Two compartments, A and B, with length of ′ and ″ respectively from the AP are considered, as shown in Figure 7. Table 2 lists the compartments' properties.

Table 2. Assumed compartments A and B properties

Compartment	A	B
Length	l' ($< l_a$)	l'' ($> l_a$)
Volume	υ'_c	υ''_c
Distance from amidships to compartment's COG	x'_w	x''_w
Damage water volume in compartment	$\mu\upsilon'_c$	$\mu\upsilon''_c$

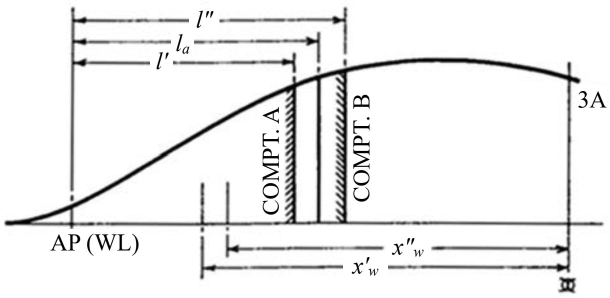

Figure 7. Endpoint calculation (Lewis, 1988)

3) The two compartments are sectioned into five ordinates and, using Simpson's rule with five ordinates, the COG of each compartment is calculated, thus finding the values of x'_w and x''_w.

4) On the graph plotted in the final step of *Part 1: Damage Water* which has the values of x_w and υ_t against their respective trimlines, the damage water volumes $\mu\upsilon'_c$ and $\mu\upsilon''_c$ are located on the damage water volume curve, and two vertical lines are drawn in order to find the respective trim values.

5) On the $\mu\upsilon'_c$ vertical line, a marker is drawn at the value of x'_w. Similarly, on the $\mu\upsilon''_c$ vertical line, another marker is drawn at the value x''_w.

6) The two marked points are joined by a straight line cutting the curve of the LCG of the damage water. The point of intersection corresponds to the trim line for the end point of the floodable length curve. The corresponding value of damage water volume, $\mu\upsilon_c$, is read from the graph, and is divided by the compartment's permeability to find the volume of compartment, υ_c.

7) The correct floodable length, l, of the endpoint is found by linear interpolation:

$$l = l' + \frac{\upsilon_c - \upsilon'_c}{\upsilon''_c - \upsilon'_c}\left(l'' - l'\right) \tag{12}$$

8) All the calculations undertaken only take into consideration the longitudinal distance between

the AP and FP. However, the floodable length curve constitutes the whole length of the ship. Figure 8 shows the distance between the extreme aft end of the ship and the AP, denoted by α. The total floodable length of the aft endpoint is the calculated floodable length added to the extra length away from the perpendicular:

$$l_{\text{aft\_endpoint}} = l + \alpha \tag{13}$$

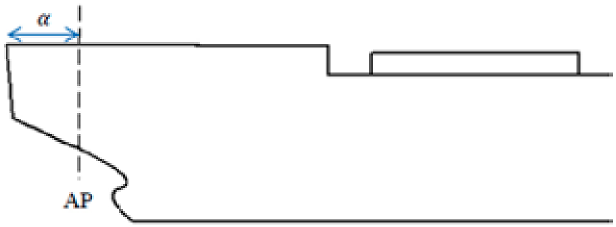

Figure 8. Aft section of a bulk carrier

The same procedure is repeated to find the endpoint at the forward end of the ship. Similarly, the corrected floodable length for the forward endpoint must be added to the distance between the FP and the forward extreme of the vessel, denoted by β, therefore:

$$l_{\text{fwd\_endpoint}} = l + \beta \tag{14}$$

Results

The two aft compartments, which consist of the aft peak and the engine room, can both be flooded without the vessel being considered lost. Similarly, cargo holds 4 and 5 can be flooded simultaneously, as can cargo holds 3 and 4.

The graph gives an indication of which compartment is the most dangerous to flood. The actual floodable length curve shows that the least floodable length is that of cargo hold 1; therefore, special attention should be given by a naval architect when designing the structure of this particular cargo hold.

An improvement to this design would be to split cargo hold 1 into two cargo holds separated by a watertight bulkhead. This design would ensure more safety since the allowable floodable length would be reduced by half, as shown in Figure 9.

Nowadays most bulk carriers are constructed with a double skin on their side and, according to IMO regulations, with a double bottom. It is therefore becoming more unlikely that a bulk carrier will be flooded because if a bulk carrier bilges its hull by hitting an obstacle, the tank on the bottom or the vessel's side will be flooded rather than the cargo hold, unless the hit is so severe that the damage manages to penetrate the double-sided hull (Kałkowska, 2017).

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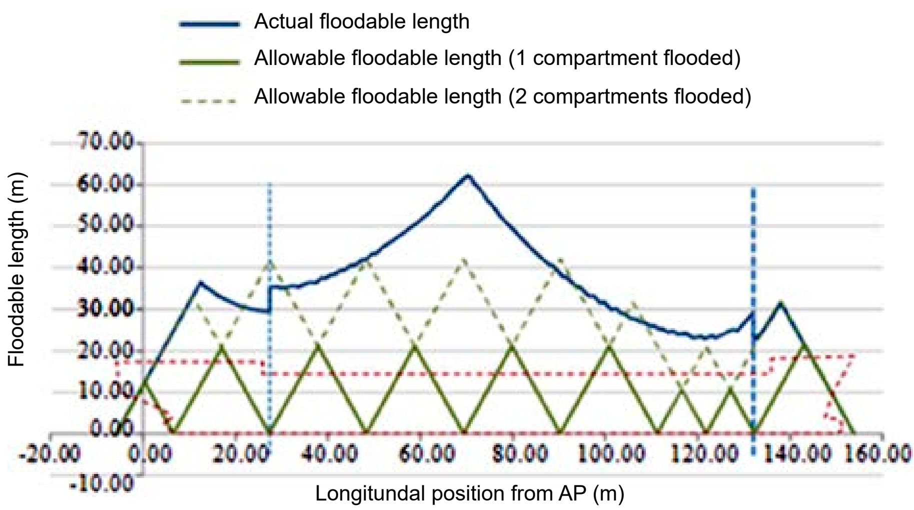

Figure 9. Allowable floodable length

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