GM limiting curve for operation in brackish water

Petri Pennanen, *NAPA,* petri.pennanen@napa.fi
Daniel Lindroth, *NAPA,* daniel.lindroth@napa.fi
Pekka Ruponen, *NAPA,* pekka.ruponen@napa.fi

ABSTRACT

Onboard a passenger or dry cargo ship, the statutory compliance related to intact and damage stability criteria is most conveniently determined by using GM limiting curves. The actual GM of the loading condition is compared to a required value, read from a curve for the actual draught/trim combination. The GM limit values are calculated for the full operating range of draught and trim. However, in practice the GM limiting curves do not cover draughts greater than the deepest subdivision draught or the maximum sea water draught of the ship. When the ship is operated on a sea area of brackish water, like the Baltic Sea, there is no common understanding on how to use the GM limiting curves, and it is not clear whether the ship is allowed to submerge the Plimsoll mark. Furthermore, the definition of the required GM value is not clear since the limit curve does not exceed to that draught. The problem affects many ships built according to different editions of the SOLAS. The authorities and classification societies have different approaches, but a common and well-grounded way is needed. The problems are highlighted by presenting real life practical examples.

Keywords: *damage stability, statutory compliance, loading computer, load line, sea water density.*

1. BACKGROUND

The GM limiting curves are very practical for determining the statutory compliance for passenger or dry cargo ships, especially onboard. These curves are calculated by the designer, and presented in the stability booklet of the ship. According to the SOLAS, the GM limit information shall be presented as consolidated data and encompass the full operating range of draught and trim. In practice, however, the curves do not cover draughts exceeding the deepest subdivision draught or the maximum sea water draught of the ship.

When the ship is operated on a sea area of brackish water, like the Baltic Sea, there is no common understanding on how to use the GM limiting curves. Brackish water is water having more salinity than freshwater, but not as much as seawater, and consequently density is between 1.0 and 1.025 t/m^3. This condition commonly occurs when fresh water meets seawater such as estuaries, where a river meets the sea. However, there are also brackish seas and large lakes, such as Baltic Sea, Black Sea and Caspian Sea.

When a ship arrives from the North Sea to the Baltic Sea, the draught of the ship increases, possibly exceeding the summer load line draught. In these cases, it is not clear, how to define the minimum required GM for the sea passage on the Baltic. Some classification societies have not approved the calculation of the curves beyond the summer load line draught, whereas some require separate "fresh water limiting curves" to be used. Some classification societies request the use of the equivalent draught, calculated in sea water, to be used instead of the actual draught in brackish water.

This paper discusses the problems by presenting four real life cases related to the use of a loading computer applying GM limiting curves in brackish water navigation. In addition, the relevant damage stability calculations are briefly referred with examples.

2. REGULATORY ASPECTS

International Convention of Load Lines (ICLL)

The International Convention of Load Line (ICLL), as amended, declares limitations to how much a ship can be loaded based on freeboard, and was signed on April 5th 1966, ICLL (1966). The convention received a significant update in the Protocol of 1988, ICLL (1988), and in Resolution MSC.143(77) in 2003, IMO (2003). Use of basic freeboard tables, as is done in the convention, dates back more than a century, and regardless of the latest amendments, the convention would still benefit from further revision, as is discussed in Kobylínski (2006).

The requirement not to submerge the Plimsoll mark in Article 12 is part of the original text of ICLL from 1966. Unfortunately, still today the convention does not provide a clear answer to if it is acceptable to submerge the Plimsoll mark, for example in the Baltic Sea. The original intention in the convention was likely to allow a temporary submersion of the mark when sailing into, or from, sheltered estuaries, rivers and lakes. However, brackish water areas, like the Baltic Sea, are not sheltered, and the operating conditions can be very harsh, FMI (2019).

Ships designed to be operated solely in the Baltic Sea traffic, like the cruise ferries between Finland and Sweden, have their stability documentation done for sea water with a density of 1.005 t/m^3, and are not allowed to submerge the summer load line.

Ships designed for unrestricted service and oceans, like international cruise ships, are however typically allowed to "slightly" submerge the summer load line mark in the Baltic Sea since their visit is considered "temporary". However, these cruise ships may be operating in the Baltic Sea for the whole summer season, which can last over three months.

From a loading computer point of view, "slightly" is not a precise enough definition to be applied in a software that is used for confirming statutory compliance. Therefore, a clearer definition, or at least a common interpretation, is needed.

International Convention for the Safety of Life at Sea (SOLAS)

A practical way for the master to check compliance with the intact and damage stability requirements is to compare the current loading condition to a limiting GM curve. This information is required to be supplied to the master by the current Chapter II-1 Part B-1 Reg. 5-1 of the International Convention for the Safety of Life at Sea (SOLAS), as amended, IMO (2006).

The limiting GM curves are, for damage stability compliance, calculated for a draught range from the lightest service condition up to the deepest subdivision draught, at different trims if needed. SOLAS Chapter II-1 Part A Reg. 5-1.4 further explains that for draughts in between the calculated ones, the limiting values are to be obtained by linear interpolation, IMO (2006). Regulation 5-1.5 right after continues that if the curve could be considered not appropriate for a condition, possibly for situations when the operating condition falls outside of the limiting curve range, the master is required to operate using an already studied condition or to verify by calculation that the condition is acceptable.

According to the definition in SOLAS Chapter II-1 Part A Reg. 2.10, the deepest subdivision draught is *the waterline which corresponds to the summer load line draught of the ship*, IMO 2006. Deadweight, on the other hand, is according to SOLAS Chapter II-1 Part A Reg. 2.20 defined as "*the difference in tonnes between the displacement of a ship in water of a specific gravity of 1.025 at the draught corresponding to the assigned summer freeboard and the lightweight of the ship*". Following these definitions, ships operating in waters with a smaller density than 1.025 t/m^3, like the Baltic Sea, cannot be loaded with their full deadweight, without submerging the summer load line mark.

Looking a little deeper into SOLAS, Chapter II-1 Part A-3 Reg. 18.5 states for passenger ships that: *"In no case shall any subdivision load line mark be placed above the deepest load line in salt water as determined by the strength of the ship or the International Convention on Load Lines in force".*

Additionally Reg. 18.6 immediately after states that: *"Whatever may be the position of the subdivision load line marks, a ship shall in no case be loaded so as to submerge the load line mark appropriate to the season and locality as determined in accordance with the International Convention on Load Lines in force".* Consequently the interpretation of if or how much the mark can be submerged is here passed to ICLL.

Looking a little into the future, the most recent amendments for SOLAS Resolution MSC.421(98), IMO (2017a), and the corresponding Explanatory Notes Resolution MSC.429(98), IMO (2017b), do offer some guidance to this situation. According to the new Explanatory Notes for SOLAS 2020 Reg. 5-1.4 Paragraph 5: *"Ships may be permitted to sail at draughts above the deepest subdivision draught ds according to the International Convention on Load Lines, e.g. using the tropical freeboard. In these* *cases, for draughts above ds the GM limit value at ds is to be used"*. The Baltic Sea is, however, defined to be a normal winter or summer load line seasonal area according to Annex II Reg. 51 in ICLL, ICLL (1966).

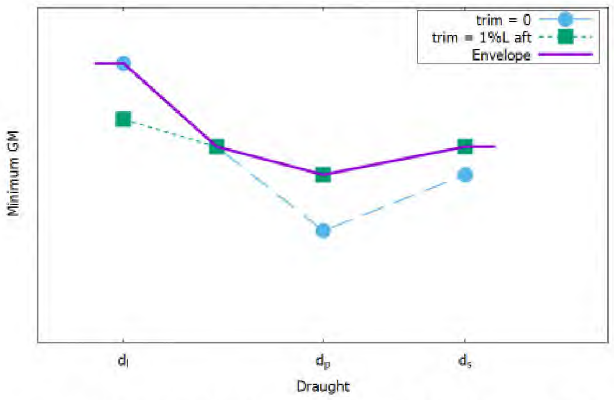

Figure 1: Illustration of envelope GM limit curve with SOLAS 2020, including the extensions of the draught range

3. DAMAGE STABILITY CALCULATIONS AND WATER DENSITY

Calculation of a damage case

When the initial condition before flooding is defined as the floating position (draught and trim) and center of gravity (or metacentric height), and the final condition is calculated with the lost buoyancy method, the water density has no effect at all. The results are solely dependent on the hull form, damaged compartments and the center of gravity. For intermediate flooding stages, a common practice is to consider constant volumes of floodwater in the calculation of the righting lever, see Ruponen et al. (2018).

Let us consider a single degree of freedom model for the transverse stability and heel angle ϕ of the ship, Figure 2. The static righting moment is:

$$M_{st}(\phi) = -\Delta\overline{GZ}(\phi) = -\rho g \nabla \overline{GZ}(\phi) \qquad (1)$$

where ρ is density of water, g is gravitational acceleration, ∇ is volume of displacement and $\overline{GZ}$ is righting lever.

The heeling moment, caused by the floodwater, depends on the water density:

$$M_w(\phi) = \rho g V_w(\phi)\big(y_w(\phi) - y_G(\phi)\big) \qquad (2)$$

where V_w is the volume of floodwater and y_w and y_G are the centre of floodwater and centre of gravity in a global coordinate system.

At equilibrium heel angle ϕ, the sum of these two moments is zero:

$$M_w(\phi) + M_{st}(\phi) = 0 \qquad (3)$$

Substituting equations (1) and (2) results in:

$$\rho g V_w(\phi)\big(y_w(\phi) - y_G(\phi)\big) - \rho g \nabla \overline{GZ}(\phi) = 0 \qquad (4)$$

Or simply:

$$V_w(\phi)\big(y_w(\phi) - y_G(\phi)\big) = \nabla \overline{GZ}(\phi) \qquad (5)$$

Obviously, the solution is not dependent on the density of the water.

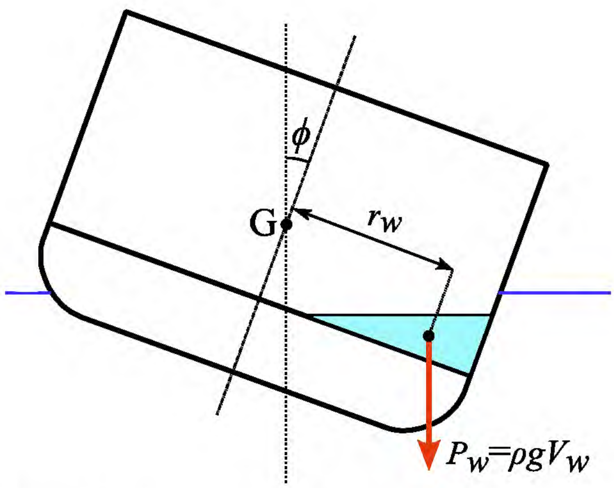

Figure 2: Heeling moment due to floodwater

Calculation of GM limiting curve

When evaluating the minimum GM at given draught (and trim), the form stability lever is unchanged, and only the center of gravity KG is iterated so that the stability requirements are passed.

The s-factor in SOLAS depends on the characteristics of the righting lever (GZ) curve, in particular:

- heel angle
- immersion angle of unprotected openings
- range of positive stability
- maximum righting lever

In principle, all of these are geometric quantities, dependent on the hull form and the center of gravity. The density of water does not have a direct effect on the righting lever values. Naturally, the displacement, and subsequently the static righting moment, are directly proportional to the density. The only exception is the s-mom factor that is used for passenger ships since the external heeling moments (passenger, wind and survival craft) are independent of the water density, but in fresh water the displacement that corresponds to the same draught value is smaller than in salt water.

4. PRACTICAL EXAMPLES

SOLAS 1992 (Reg. 25-1) ro-ro ship in Baltic and North Sea operation

This ship has been built in the early 2000s, and is operating between ports at the northern end of the bay of Bothnia in the Baltic Sea and the North Sea. All the loading conditions presented in the original stability booklet have been calculated using 1.005 t/m^3 as the sea water density. Also the maximum displacement has been defined at the summer draught in that density.

After installation of a scrubber, the cargo capacity of the ship was naturally decreased. In order to compensate this, a new stability booklet was suggested, with one full load loading condition calculated in fresh water. Also the maximum deadweight would be defined based on this loading condition. The idea was to be able to load the ship at the FW load line, when departing from the Bay of Bothnia, where the water is brackish, although not completely fresh. The owner requested the loading computer to be updated in order to show this as a legal departure loading condition. However, the flag administration could not deliver a clear answer, whether this would be such a case.

The new stability booklet still presented the original GM limiting curve, calculated up to the maximum summer draught (in density 1.025 t/m^3). Even in case it would be allowed to submerge the Plimsoll mark for a voyage of several days on the Baltic Sea, there would not be a value of required GM to compare the actual GM with, at that draught.

The owner even had damage stability calculations performed at the fresh water maximum draught and in fresh water. However, these calculations did not provide required GM value for that draught – only a confirmation of a sufficient A-index

Finally, the class advised that the Plimsoll mark may be submerged at the Baltic, according to ICLL and that the SOLAS 2020 method could be used for the required GM at the draughts above the maximum summer load line.

At the deeper end of the GM limiting curves, the governing values are derived from the intact stability criteria with an upwards trend. These should be extended by 0.12 m horizontal line in the loading computer, although not shown in the stability booklet.

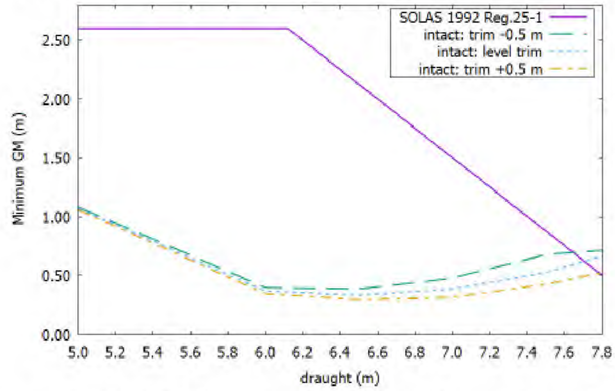

Figure 3: GM limiting curves for a ro-ro ship, ending at the maximum draught in sea water

SOLAS 2009 ro-ro ship in the Baltic Sea

The second example is also typical ro-ro ship in traffic between ports at the Baltic Sea, but designed according to the probabilistic damage stability requirements of SOLAS 2009. The ship has a typical GM limit curve for a ro-ro, Figure 4, with the damage stability results governing at the deeper draughts. The curve shows decreasing requirement for the GM as the draught is increased.

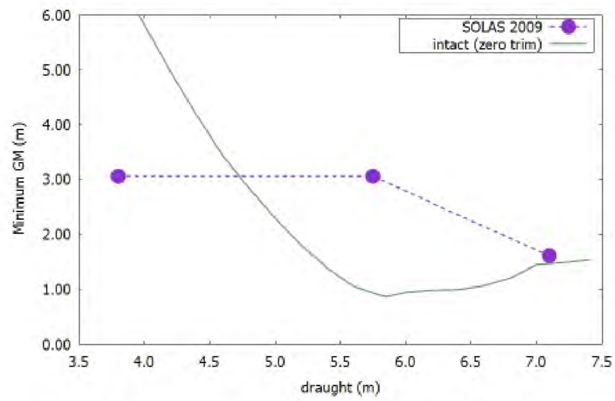

Figure 4: GM limiting curve of a Baltic ro-ro ship, according to SOLAS 2009

For some unknown reason, it was not allowed to use this curve in the loading computer in sea water densities below 1.025 t/m^3. Instead, it was requested that the GM should be compared using a draught corresponding to an equivalent loading condition in the density of 1.025 t/m^3 as a substitute of the actual draught in brackish water.

This suggested approach will result in a more conservative requirement, but based on the calculations shown earlier, this is not justified, since the density of the sea water does not affect the calculation of the GM limiting curve.

SOLAS 90 cruise ship in the Baltic Sea

The deterministic damage stability results are usually calculated for a set of trims covering the operational loading conditions. The required GM is found by interpolating between the curves. For deterministic damage stability requirements, it is easy to calculate the minimum GM at any combination of draught and trim.

An example of GM limiting curves, which has been calculated well beyond the summer load line draught of the ship is presented in Figure 5. This way it is possible to utilize the curves also in fresh water situations and the approach also gives flexibility for future draught increases based on weight growth over the life span of the ship.

The loading computer gives relevant warnings of possible overloading of the ship, based on summer load line draught and the set density of the sea water.

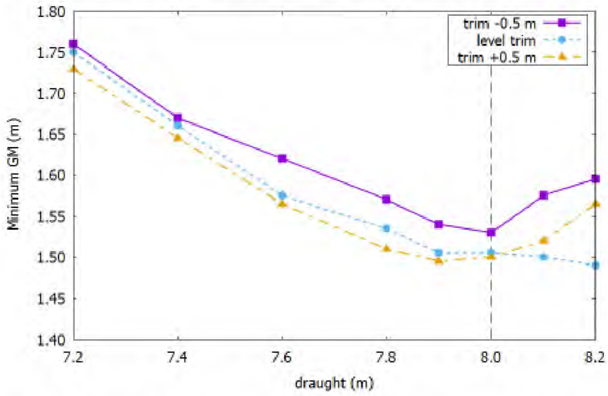

Figure 5: GM limiting curves of a SOLAS 90 cruise ship, the vertical line marks the maximum draught in sea water

SOLAS 2020 cruise ship in the Baltic Sea

For this kind of a ship, the single GM limiting curve is derived from the calculation of three draughts and compiled to cover the whole trim range. In addition to that, the explanatory notes of the rule state that the ship may be permitted to sail at draughts above the deepest subdivision draught according to the ICLL. In these cases, for draughts above ds, the GM limit value at ds is to be used.

Rule-wise, it is clear how to handle the GM requirement at draughts above the summer load line draught, provided that it is clearly legal to exceed this draught because of the sea water density. An example of the limit curves is presented in Figure 6.

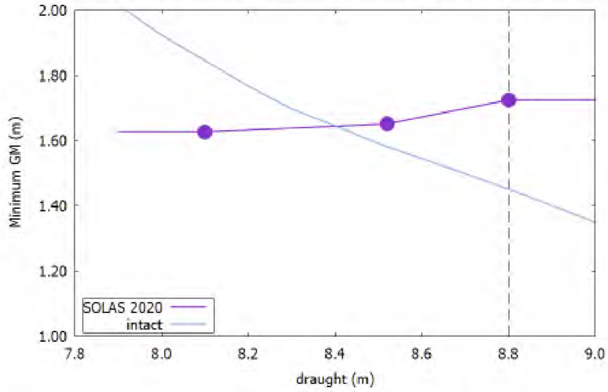

Figure 6: GM limiting curves of a SOLAS 2020 cruise ship, the vertical line marks the maximum draught in sea water

5. LIMIT CURVES WITH PROBABILISTIC DAMAGE STABILITY CALCULATIONS

In order to illustrate the effect of different sea water densities on the limiting GM curves, a case study calculation was performed using NAPA software for a generic ro-ro cargo ship ($L_S \approx 180$ m) and a cruise ship ($L_S \approx 300$ m).

In this study, for simplicity, it is assumed that the damage stability requirements are the governing ones, and the intact requirements are therefore left out. To simulate the effect of the ships entering or leaving brackish waters, draughts corresponding to a constant weight while the sea water density changes from 1.025 t/m^3 to 1.005 t/m^3, or 1.005 t/m^3 to 1.025 t/m^3 were used, and compared against the results from the actual draughts (constant density). The draughts calculated are presented in Table 1 and Table 2.

Table 1 - Draughts calculated for the ro-ro ship

Original draught	Draughts for δ: 1.005 t/m^3 → 1.025 t/m^3	Draughts for δ: 1.025 t/m^3 → 1.005 t/m^3
4.00 m	3.935 m	4.066 m
5.20 m	5.116 m	5.285 m
6.00 m	5.905 m	6.097 m

Table 2 - Draughts calculated for the cruise ship

Original draughts	Draughts for δ: 1.005 t/m^3 → 1.025 t/m^3	Draughts for δ: 1.025 t/m^3 → 1.005 t/m^3
8.10 m	7.975 m	8.227 m
8.52 m	8.390 m	8.651 m
8.80 m	8.666 m	8.936 m

For the probabilistic damage stability calculation according to SOLAS, IMO (2006), there is a global requirement that the attained subdivision index A shall be larger than the required subdivision index R. This requirement do however offer some freedom in choosing the GM values for the individual draughts, and is therefore not suitable to use when the actual limiting value at each draught is sought. The regulation on the other hand does also set a requirement for the individual draughts, that each partial attained subdivision index A_i shall be at least 0.5R for cargo ships, and at least 0.9R for passenger ships, IMO (2006). These criteria are more useful for an iteration searching to find the actual limit, and used in this case study as well.

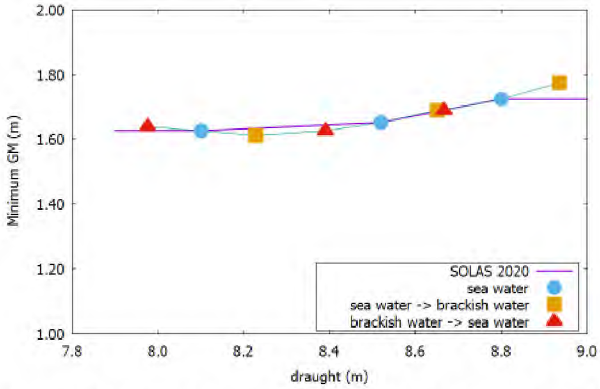

Figure 7: GM limiting curve for a cruise ship according to SOLAS 2020 and at actual draught changes due to water density

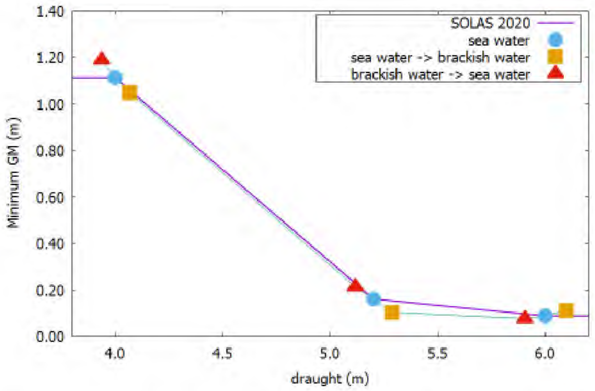

Figure 8: GM limiting curve for a ro-ro ship according to SOLAS 2020 and at actual draught changes due to water density

The calculation was set up in an iteration loop where new GM values were used to re-define the initial conditions until the difference for a new GM value was less than 2 cm and the A_i criteria for the ship type passed. In each iteration loop a new attained subdivision index for each draught was calculated.

The results of the GM limit iteration for the two calculated ships are presented in Figure 7 and Figure 8. Compared to the ro-ro ship, the original draughts for the cruise ship are closer to each other, and consequently, it operates with a smaller relative deadweight. This can also be one of the reasons for that the variation in limiting GM values is smaller for the cruise ship compared to the ro-ro ship. It is good to remember that as these GM limit values now represent the partial subdivision index requirements only, they do not as such comply with the overall attained subdivision index requirement of A being greater than R. It is also notable that the limiting GM values for draughts outside the original draught range are not exactly following the extrapolated values according to the Explanatory Notes for Reg. 5-1.4 of SOLAS 2020, IMO (2017b).

6. CONCLUSIONS

Based on the presented examples and underlying physics of damage stability, the most important finding of the study is that:

- The only relevant parameter when defining and applying the minimum GM values is the draught of the vessel in the sea water density of the operation area.

The big question for ships operating in sea areas with brackish water is whether it is allowed to submerge the Plimsoll mark. Provided that submerging the summer load line mark in brackish sea water areas is allowed by interpretation of the ICLL, the following conclusions can be drawn from the presented real life practical examples:

- Using the expanded GM limiting curves over the whole draught range, up to the maximum fresh water draught, with the draught (and possibly trim) as the only parameter would erase all problems related to the interpreting the effect of the sea water density
- SOLAS 2020 offers a solid rule-wise solution, which is easy to apply. The same could be expanded to cover SOLAS 2009 ships since the calculation methodology is the same
- However, this may not always be realistic, and alternatively a minimum GM curve could be extended based on calculations at additional

draught values. With this approach, the requirement for partial attained subdivision index must be met

- For SOLAS 90 ships with deterministic damage stability, it would be an easy task to expand the GM limiting curves, by calculating the requirements for one additional draught representing the maximum draught in fresh water

Finally, it should be noted that ships designed for operation at the brackish sea, like the Baltic Sea, should not be allowed to submerge the Plimsoll mark, since this operation cannot by any means considered to be a temporary situation.

REFERENCES

FMI 2019, "Wave height records in the Baltic Sea", visited March 20th, 2019, https://en.ilmatieteenlaitos.fi/wave-height-records-in-the-baltic-sea

IMO 2003, "Resolution MSC.143(77) – Adoption of Amendments to the Protocol of 1988 Relating to the International Convention on Load Lines, 1966", Adopted on 16 June 2003.

IMO 2006, "Resolution MSC.216(82) Adoption of Amendments to the International Convention for the Safety of Life at Sea, 1974, as Amended", Adopted on 6 December 2006.

IMO 2017a, "Resolution MSC.421(98) Amendments to the International Convention for the Safety of Life at Sea, 1974, as Amended", Adopted on 9 June 2017.

IMO 2017b. "Resolution MSC.429(98) Revised Explanatory Notes to the SOLAS Chapter II-1 Subdivision and Damage Stability Regulations", Adopted on 9 June 2017.

ICLL 1966, "International Convention on Load Lines, 1966", Adopted on 5 April 1966.

ICLL 1988, "Protocol of 1988 relating to the International Convention on Load Lines, 1966", November 11th 1988.

Kobylínski, L., 2006, "New Load Line Rules – Success or Failure?", EXPLO-SHIP 2006, ISSN 1733-8670

Ruponen, P., Manderbacka, T., Lindroth D., 2018, "On the calculation of the righting lever curve for a damaged ship", *Ocean Engineering* 148, pp. 313-324.