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Impact of drafts on the damage survivability of cruise ships

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ABSTRACT

The prevailing probabilistic damage stability concept, as outlined within SOLAS 2009 for passenger ships, calculates the Attained Subdivision Index based upon three loading conditions which combine to form a theoretical draft range for a given vessel. To each of these loading conditions a weighting factor is then applied to account for the probability that a vessel will be operating at or near any of these drafts at the time of collision, should one occur. Currently the weighting factors are applied in a 'one-size-fits-all' manner, with the same weightings to be applied in the case of cargo and passenger vessels despite the fact that these ship types are known to have very different tendencies when it comes to the nature of their operation. This in turn, calls into question the suitability of these weightings concerning what degree they, in fact, reflect the operational profile of the vessels covered by the standard. With this in mind, the present paper aims to investigate the suitability and accuracy of the currently assumed draft weighting factors with regards to cruise vessels. This study is conducted using operational loading condition data sourced from 18 cruise ships and spanning up to a period of two years in some cases. On the basis of this data, draft probability distributions are derived and new weighting factors are formed specifically pertaining to cruise ships and the nature of their operation. Finally, an assessment is conducted looking into the impact of the newly derived weighting factors on the magnitude of the Attained Subdivision Index and recommendations are made on how best to implement them.

1. Introduction

The current IMO instrument for assessing the damage stability performance of passenger vessels and dry cargo ships is that which is outlined in SOLAS Chapter II-1, Res. MSC.216 (82) (IMO, 2009), referred to herein as SOLAS 2009. Upon entering into force this brought about an end to the age of deterministic requirements on passenger vessel subdivision based on what were widely considered to be anachronistic means of damage stability evaluation. This included such elements as the floodable length and margin line criteria, which had existed within the rules for well over half a century and were starting to show their age.

Instead, the more traditional deterministic requirements were cast aside in favour of the probabilistic approach to damage stability assessment. With regards to methodology this was nothing new and, in fact, rules based on this approach were already in place within the mandatory requirements for dry cargo ships in Chapter II-1, part B-1 from 1992 along with the seldom used though highly innovative alternative regulations for passenger ships, Res. A.265(VIII) from 1973. Instead, SOLAS 2009 had the effect of harmonising damage stability assessment under one common and rational methodology.

Unfortunately, however, a fully probabilistic approach has never been realised and there remains a requirement to supplement the criteria with a number of deterministic rules. In this respect, SOLAS 2009 is neither a design nor a performance-based standard, but instead a hybrid, relying on a combination of both probabilistic and deterministic elements. In addition, designers are still required to adhere to a number of prescribed modelling methodologies, many of which bring back some of the shortcomings of the deterministic approach.

One of the most predominant examples of this, concerns the assumptions made regarding the assumed draft range and respective weighting factors defined within SOLAS 2009. The underlying concept behind the probabilistic approach to damage stability is simple, and one that is based upon the probability of a vessel surviving collision damage in waves. This probability is then used as an objective measure of ship

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safety in the damaged condition and is represented within the rules by the Attained Subdivision Index, A (see eq. (2) later in the paper). This index is formed on the basis of three partial indices calculated with respect to three drafts assumed to be representative of the operational draft range of the vessel. To each of these indices a weighting factor is then applied which does not vary with regards to ship type and which is intended to account for the likelihood that the vessel will be operating near or at any of these drafts at the time of collision (see eq. (4) later in the paper). In this respect, the weighting factors can be viewed as a representation of the operational profile of the vessel and it is this deduction in combination with a number of other observations that present cause for concern.

Firstly, the means by which the current weighting factors were determined remain somewhat unclear, as there is little that can be found in literature on their derivation with regards to ship types assessed and the number of vessels considered. However, some discussion on this can be found in SLF 42/3/4 (IMO, 1998) and SLF 43/3 (IMO, 2000) with references made back as early as SLF 41, though this document was not found to be readily available. As such, some uncertainty surrounds these weighting factors with respect to how representative they are of the operational profiles of the vessels covered by the standard. In particular, the "one-size-fits-all" approach currently in place would appear to be a gross over simplification. The current regulation assumes in essence that RoPax, Dry Cargo and Cruise vessels are operated according to the same operational profile despite the fact that these ship types are known to have very different tendencies when it comes to the nature of their operation. In order to substantiate such an assertion, one must first be able to show that there is adequate correlation between the loading behaviours of each of these ship types, which intuitively speaking is unlikely to be the case. In this respect, even if it were found that these values are accurate for any one of the vessel types covered by the standard, confirmation of that fact would subsequently indicate that they were inaccurate for the others.

It is understood that within any technical standard there will always be elements of assumption, generalisation and simplification, particularly where there are areas of uncertainty stemming from either lack of information or knowledge, but also in an effort to achieve broad applicability. The latter gives rise to a somewhat paradoxical situation between what are two conflicting objectives, namely to achieve broad levels of applicability, whilst also ensuring that the standard sufficiently captures the complexities of scattered reality. As such, generalisation must be attained in a balanced way that ensures any simplifications made do not undermine the fundamental purpose of the regulation, which rests upon the ability to accurately assess and measure ship survivability. In fact, a number of studies have been conducted in which certain aspects of the current SOLAS 2009 regulation have been challenged with a view to improving the prescribed assumptions. This includes such studies as the Joint Industry Project eSAFE for which this work was conducted and where several proposals were made regarding more accurate calculation of cruise ship survivability. This included critical reviews of a number of SOLAS assumptions including the assumed tank permeabilities, sea state distribution and damage distributions, see Bulian et al. (2018) and Paterson et al. (2017). In addition, various damage stability calculation techniques were evaluated, including the application of the direct approach (Bulian et al., 2016), and the use of time-domain numerical simulations for survivability assessment (Atzampos et al., 2019) along with CFD for validation purposes. More information on the eSAFE project can be found in the summary reports Luhmann et al. (2018a) and Luhmann et al. (2018b). Building on this, it is important that where circumstances permit us to reduce uncertainty or to replace any of these simplifying assumptions with more accurate information, not only should we do so, but such efforts should be actively encouraged.

It is with this in mind that the present paper investigates to what degree the currently assumed draft weightings reflect the true operational profile of cruise vessels, which is a particular class of vessel for which the suitability of SOLAS 2009 has already previously come under question (Vassalos, 2015). This is achieved through analysis of operational loading condition data sourced from a total of 18 cruise vessels and over a time frame spanning in some cases up to two years which has been utilised in order to derive a number of draft probability distributions. Such derivation of draft distributions has been conducted in the past, as in the cases of Meng et al. (2014), Hollenbach et al. (2007), and Rusaas et al. (1996), where draft probability distributions have been derived for various types of cargo vessels along with Ro-Ro passenger vessels. However, in contrast there does not appear to be any work of this kind publically available that has been conducted for cruise vessels. Drawing on this analysis, a further study is conducted in which weighting factors more representative of the manner in which cruise vessels are operated are derived and their impact on the magnitude of the Attained Index is measured. This is undertaken with a view to satisfying two objectives. Firstly, an attempt is made in order to provide a more appropriate means of assessing cruise vessel survivability within the design stage and with the understanding that uncertainty at this stage calls for certain assumptions to be made. Secondly, proposals are made in order to provide a simplified assessment for vessels that are already in operation and where sufficient data is available in which to constrain the assessment, allowing for a more straightforward approach to be taken.

2. Background

The survivability of a vessel following collision damage that has led to hull breach and subsequent flooding is dependent on a number of factors, none more so than the loading condition of the vessel. The manner in which a vessel is loaded greatly effects its ability to withstand the effects of flooding, with draft and trim influencing important parameters such as freeboard and reserve buoyancy, and the centre of gravity affecting the vessel's restoration properties. As touched upon within the introduction, SOLAS 2009 assumes a draft range based on three values defining the lower and upper limits of an assumed draft range along with consideration of an intermediate condition, each of which are defined as follows:

- Light service draft - dl: service draft corresponding to the lightest anticipated loading and associated tankage, including ballast as required for adequate stability and immersion. In the case of passenger ships, dl also includes a full complement of passengers and crew on board.
- Deepest subdivision draft - ds: corresponds to the Summer Load Line draft of the ship.
- Partial subdivision draft - dp: this is estimated by the service draft with the addition of 60% of the difference between the light service draft and the deepest subdivision draft.

$$dp = dl + 0.6 \cdot (ds - dl) \quad (1)$$

A partial Attained Index is then calculated at each of these draft values and the Attained Subdivision Index is formed as the weighted sum of these indices according to the formula below:

$$A = 0.2 \cdot A_{dl} + 0.4 \cdot A_{dp} + 0.4 \cdot A_{ds} = \sum_{j=1}^{J} \sum_{i=1}^{I} w_j \cdot p_i \cdot s_i \quad (2)$$

where.

j = The loading condition under consideration.

J = The total number of loading conditions considered in the calculation of A, usually three drafts covering the operational draft range of the vessel.

w_j = A weighting factor applied to each initial draft.

i = Represents each compartment or group of compartments under consideration for loading condition j.

I = The total number of all feasible damage scenarios involving flooding of individual compartments or groups of adjacent compartments.
p_i = The probability that, for loading condition j, only the compartment or group of compartments under consideration are flooded, disregarding any horizontal subdivision.
s_i = Accounts for the conditional probability of survival following flooding of the compartment or group of compartments under consideration for loading condition j weighted by the probability that the space above a horizontal subdivision may not be flooded.

The weighting factors represent the time, t, spent in each loading condition, T, as provided below.

$$w_{dl} = P(T_{dl}) = 0.2 \quad (3a)$$

$$w_{dp} = P(T_{dp}) = 0.4 \quad (3b)$$

$$w_{ds} = P(T_{ds}) = 0.4 \quad (3c)$$

$$\sum_{j=1}^{3} w_j = w_{dl} + w_{dp} + w_{ds} = 1 \quad (3d)$$

$$A = 0.2 \cdot A_{dl} + 0.4 \cdot A_{dp} + 0.4 \cdot A_{ds} \quad (4)$$

The Required Subdivision Index, R, which is determined predominantly by the passenger and lifeboat capacity of the vessel and to a lesser extent by the subdivision length, dictates the mandated level of safety. So long as a vessel possesses an Attained Index greater than or equal to the Required Index it is deemed safe from a regulatory perspective.

The partial Attained Index values, A_d, are also used in order to form the vessel GM limit curve, Fig. 1. GM limits are determined as those required in order to ensure that the Attained Index is greater than or equal to the Required Index (A ≥ R) with the additional requirement that each partial index must satisfy the following conditions at each calculation draft:

- A_{ds}, A_{dp} and $A_{dl} \geq 0.9R$ in the case of passenger vessels
- A_{ds}, A_{dp} and $A_{dl} \geq 0.5R$ in the case of dry cargo ships

These conditions have been set in order to ensure a certain level of safety is maintained across the entire draft range. However, the question remains as to why this was not set as Ad ≥ R? Currently, the partial Attained Index for a given loading condition can fall short of the requirements by 10% in the case of passenger vessels and more shockingly by 50% in the case of dry cargo vessels, so long as the deficit in Attained Subdivision Index is compensated for by another loading condition. If we consider this with regards to the GM limit curve, it enables the limits to be manipulated in such a manner as to apply a more stringent limit on a draft at which the vessel will rarely operate or that is limited by intact stability requirements, such as the lower draft often is. This then allows a relaxation on the GM limitation around the design draft where the vessel is likely to be more vulnerable to damage and where GM margins are tighter. Ideally, the condition A ≥ R would be set for each calculation draft, thus removing the requirement for draft weighting factors all together as recommended in (Jasionowski, 2011). Instead, the use of draft probability distributions could find their place for use in direct approaches where sampling across the draft range could be conducted.

3. Weighting factor derivation methodology

In the development of new draft weighting factors that are more reflective of the manner in which cruise vessels are operated, loading condition data from a total of 18 cruise vessels has been sourced. This data contains in some cases up to two years of operational loading information from a range of cruise vessels that provide ample coverage of the fleet demographic both with regards to size and age, as demonstrated in Fig. 2 below which highlights the sample vessels assessed in relation to the world cruise ship fleet and expected new-buildings.

The information obtained has been processed accordingly in order to yield draft probability distributions, both ship-specific and in a generalised format with consideration of all vessel data.

Due to the large variance in size between the vessels contained within the test group, it was necessary to process the data in a uniform way through non-dimensionalising the draft distributions. Two sets of results are obtained; in the first, the data is normalised with respect to the actual operational draft range of the vessels (maximum and minimum draft values obtained from operational data), whilst in the second, with regards to the SOLAS 2009 assumed draft range (maximum and minimum draft values according to ds and dl). The generalised formula for the max-min normalisation is indicated below.

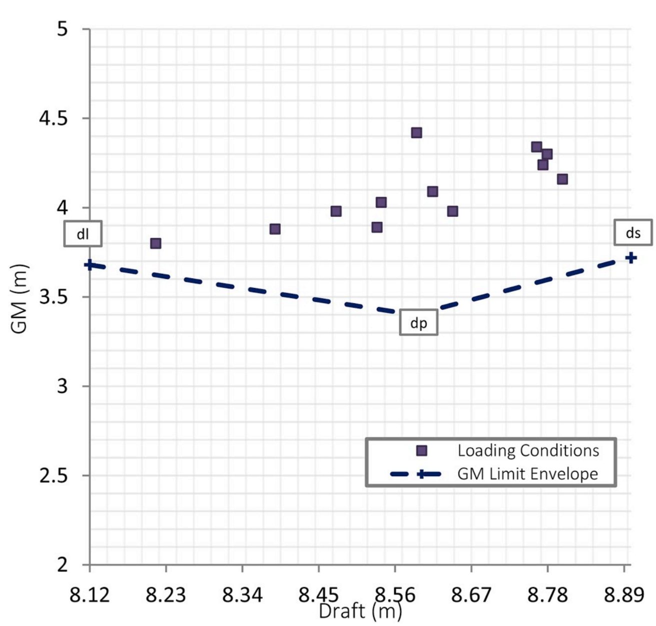

Fig. 1. Limiting GM curve, three loading conditions (typical example for cruise ship).

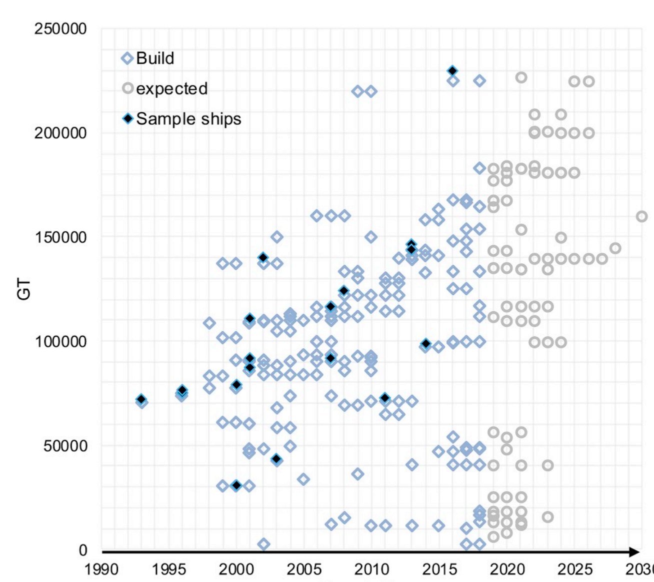

Fig. 2. Sample ships relative to world fleet (size and age).

$$\hat{x}_i = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)} \quad (5)$$

where, x_i is taken as the mean value $(\overline{x_i})$ between the respective aft and fore draft of each vessel according to operational data readings. This was essential as the sample data varied largely with regards to operational trim. Translating equation (5) with respect to draft yields the following:

$$T_{ND} = \frac{\overline{T_i} - \min(\overline{T_i})}{\max(\overline{T_i}) - \min(\overline{T_i})} \quad (6)$$

where, $\max(\overline{T_i})$, $\min(\overline{T_i})$ represent the maximum and minimum operational drafts, $\overline{T_i}$ the mean draft and T_{ND} the non-dimensional draft value.

The non-dimensional draft range is then discretised across the range [0, 1] in increments of 0.1 and the frequency in which each vessel has operated within each interval is calculated with respect to the operational data. This provides appropriate weightings for each interval of the draft range. Following this, an inverse normalisation can then be conducted in order to identify the actual draft values for a given ship (eq. (7)) which, in turn, can then be used in combination with the newly derived weightings in order to provide a more accurate means by which to calculate the Attained Index.

The following formulation is obtained by the inverse of equation (eq. (6)):

$$\overline{T_i} = T_{ND} \cdot (\max(\overline{T_i}) - \min(\overline{T_i})) + \min(\overline{T_i}) \quad (7)$$

4. Operational distribution of drafts

4.1. Ships in operation

The operational loading condition data from a range of cruise vessels has been utilised in order to generate a number of different draft probability distributions. In the first case, the data from each vessel has been non-dimensionalised with respect to their operational draft range. Through doing so it is possible to assess the manner in which cruise vessels behave in operation as opposed to the manner in which SOLAS 2009 assumes. The distribution yielded in this case is presented in Fig. 3 below. Here we see that cruise vessels have a tendency to operate towards the upper region of their draft range with limited time having been spent towards the lower end. It should also be noted that, in the majority of cases, the vessels' operational draft range was found to be much narrower than that assumed within SOLAS 2009. As such, it is important to consider that the distribution shown below corresponds to

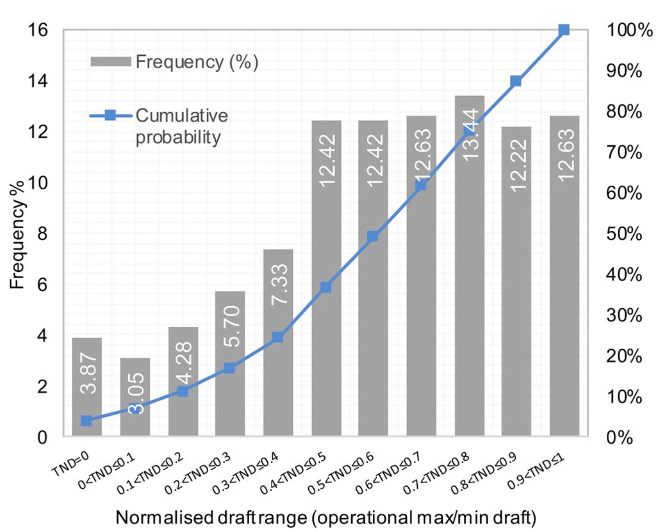

Fig. 3. Draft distribution non-dimensionalised by operational draft range and based on all sample vessel data.

minimal variation in draft and is over a draft range that is, relatively speaking, towards the upper portion of the assumed SOLAS 2009 draft range.

In light of the above, it has been found that as a simplified means of assessing/monitoring survivability once a vessel has entered operation, a one draft approach to calculating the Attained Index could be taken. In such a case, the Attained subdivision Index would be calculated using the highest recorded draft value within the vessels' loading condition history, weighed by a factor of 1 and using actual trim, fluid GM and respective KG values, as shown in the following:

$$A = w \cdot A(T_{ds}) \quad (8)$$

$$A = 1 \cdot A_{ds} \quad (9)$$

Such a simplified approach is made possible due to two reasons. Firstly, the availability of information within the operational phase, which would otherwise be an unknown within the design stage, enables the problem to be substantially constrained. During the design stage the actual operational profile of the vessel is unknown, and so, certain conservative estimations of the lower and upper bounds of the draft range have to be made in order to account for this uncertainty. When the vessel enters operation, this is no longer the case and the true lower and upper bounds of the draft range are known. Secondly, as cruise vessels operate within a narrow draft range, the magnitude of the Attained Index has been found to demonstrate little variation with regards to the number of draft values considered within its calculation. The reason for this comes as a result of the small difference found between the lower and upper bounds of the operational draft range of cruise vessels, which yields almost identical Attained Index values at each of these bounds. This, in turn, means that any Attained Index calculated based on the weighted sum of any number of drafts sampled across this range would yield an almost identical Attained Index to that calculated with consideration of just one draft. Ultimately, this allows for only one draft to be considered whilst producing accurate results. The alternative to this approach would be to simply calculate the Attained Index in real time using the draft at the moment of calculation and the associated loading condition information and this would certainly be effective. However, the results would seem to indicate that the operational draft range of cruise vessels is, in fact, so narrow that such an approach may be superfluous. This last point is further substantiated within the next section where sensitivity analysis is performed demonstrating less than 1% variation in the magnitude of the Attained Index when considering just one draft as opposed to ten drafts sampled at equally spaced intervals across the vessel draft range.

Such an approach could foreseeably be used as a simple monitoring tool, in line with such proposals as outlined in (Vassalos et al., 2018) for measuring operational risk and allowing risk information to be used in order to guide decision making for safe operation and in emergencies.

4.2. Ships during the design stage

Unlike vessels that are in operation, those during the design stage suffer from a lack of operational data which produce a greater amount of uncertainty and call for a number of assumptions to be made. However, steps can be taken in order to ensure that the draft weighting factors are more representative of the way cruise vessel are operated in general. With this in mind, an additional draft distribution has been generated, this time having non-dimensionalised the draft data of each vessel with regards to their respective SOLAS 2009 assumed draft ranges. The resultant distribution, shown in Fig. 4, illustrates more predominantly the tendency of cruise vessels to operate towards the upper portion of their draft range, though there are, however, incidents, albeit infrequently, where the lower end of the draft range is also utilised.

When deciding upon which draft values and associated weighting factors would be most suitable for the calculation of the Attained Index it was recognised that both the upper and lower ends of the draft range

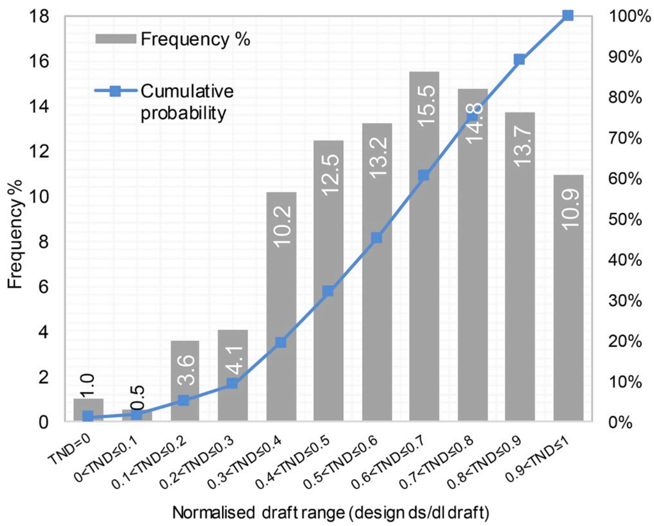

Fig. 4. Draft distribution – operational profile for all ships with regards to SOLAS drafts (global statistics).

would need to be catered for. This is despite the fact that, in theory, a one-draft approach similar to that proposed for vessels in operation would suffice with regards to accurate calculation of the Attained Index. However, in contrast with the operational phase, where the primary interest would be safety monitoring within the vessels permissible operational limits, during the design stage not only must the safety level be calculated but also the operational limitations defined. Furthermore, these limitations need to cover all foreseeable eventualities in order to account for uncertainty and as such must consider a wider, more versatile draft range than that found during operation. For this reason, it is proposed that during the design stage, a two-draft approach is utilised corresponding to the non-dimensional drafts 0.15 and 0.65 based upon the SOLAS 2009 assumed draft range. Both drafts 0.15 and 0.65 have been selected due to the nature of the draft distribution which shows approximate uniform probability for non-dimensional draft range 0–0.3 and near uniform probability from 0.3 to 1 with the calculation drafts taken at the centroid of these ranges. The weighting of these drafts is identified by summing the individual frequencies within each draft discretisation within these ranges, resulting in weighting factors of 0.1 and 0.9 respectively (Fig. 5).

Thus, the Attained Subdivision Index, equations (2) and (4), can be

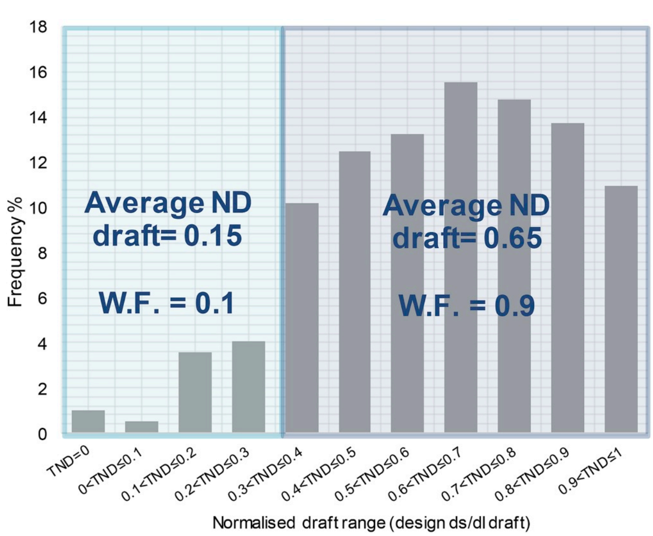

Fig. 5. Draft distribution based on SOLAS 2009 draft range and two draft approach.

translated to the following:

$$A = \sum_{j=1}^{2} w_j \cdot A(T_j) \tag{10}$$

$$A = 0.1 \cdot A_{0.15} + 0.9 \cdot A_{0.65} \tag{11}$$

where, $A_{0.15}$ and $A_{0.65}$ are the partial Attained Indices for the two normalised drafts. The calculation of the two draft values to be considered is achieved through re-dimensionalising the draft values 0.15 and 0.65 as shown next:

$$T_{Act} = (T_{ND} \cdot (d_s - d_l) + d_l) \tag{12}$$

where.

T_{Act} draft(s) to be considered in the calculation of the Attained subdivision Index.
T_{ND} non-dimensional draft values taken from the draft distribution, sampled at 0.15 and 0.65, respectively.
d_s the deepest subdivision draft as defined in SOLAS 2009.
d_l the lightest service draft as defined in SOLAS 2009.

With regards to the vessel GM limit curve, for draft values spanning below non-dimensional draft 0.15, it is recommended that the GM limit continue uniformly as this region is generally dominated by intact stability requirements. For non-dimensional drafts above 0.65, it is recommended that the GM limit be projected at the same slope formed between the two calculation drafts as shown in Fig. 6, which follows the general trend whereby the required damaged GM increases with draft. It should be noted, however, this form of extrapolation has its limitations in that the extremities of the draft range are not involved within the calculation and therefore the exact requirement at these drafts remains an unknown.

For the purpose of assessing the impact of trim, it is deemed appropriate to conduct a trim sensitivity analysis. In this respect, the trim is assessed according to ±0.25%L and ±0.5%L along with level trim, with the final Attained Index taken as the lowest obtained in either case. This is only necessary however, if the operational trim is expected at any draft to exceed ±0.5%L, otherwise level trim should be assessed. Alternatively and perhaps more effectively, similar probability distributions for trim could be derived and calculation values could be

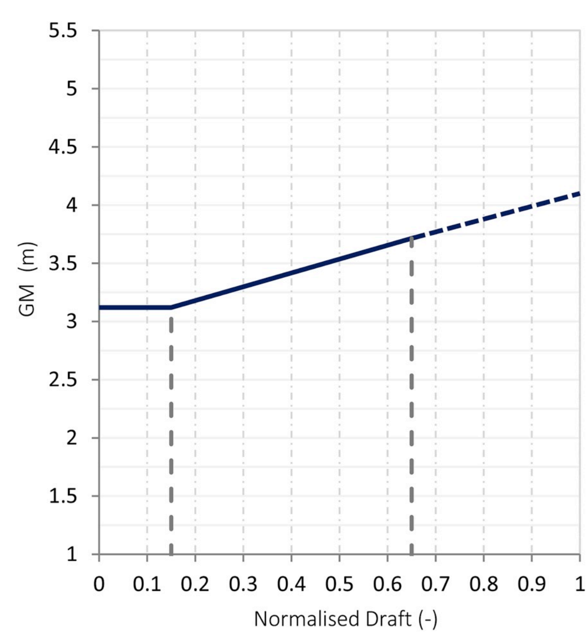

Fig. 6. Two draft approach GM limit curve example.

identified on this basis.

4.3. Ship-specific operational distributions

The third manner in which the data has been utilised is in order to generate ship-specific draft distributions. In this case, ship specific loading condition information was utilised in order to generate draft probability distributions for each vessel, an example of which is shown in Fig. 7. The reason for this was primarily to gauge the correlation between the trends witnessed for each vessel and in order to perform a sensitivity analysis on the Attained Index when using the ship-specific draft distributions in contrast to the more generalised approach previously outlined.

5. Sensitivity

Following on from the previous section, the sensitivity of the Attained Index has been assessed with regards to the draft distribution employed within its calculation. Focus in this case has been placed upon those distributions generated with respect to the vessels' actual operational draft range and with a view to gauge the variation in the magnitude of the Attained Index calculated with respect to the following:

- All draft increments within the draft distribution (T_{ND} = 0, 0.05, 0.15, 0.25 … 1) weighted according to the combined draft distribution of all basis ships (Fig. 3).
- The two-draft Attained Index calculation Approach as elaborated earlier for vessels during the design stage, T_{ND} = 0.1 and 0.65, weighted by factors 0.1 and 0.9 respectively (Eq. (11)).
- All draft increments within the draft distribution (T_{ND} = 0, 0.05, 0.15, 0.25 … 1) weighted according to ship specific draft probability distributions, i.e. consideration of ship specific operational data only in the derivation of the draft distribution but applied to one vessel only as opposed to each individual vessel.
- The one-draft approach suggested earlier for vessels during operation, specifically using only the highest recorded operational draft and associated GM and trim values for the specific sample vessel assessed.
- The current SOLAS 2009 drafts and applicable weighting values.

For each of the above conditions, the Attained Index of one of the vessels from which the operational data was sourced has been calculated. Where ship-specific draft distributions have been considered, the unique distributions and weighting factors pertaining to each vessel have been utilised in the calculation of the Attained Index. The Attained Index has, however, been calculated using just one sample ship, meaning that the only variable changed within the calculations has been the weighting factors applied to the partial indices in line with the various ship-specific draft distributions. The ship model utilised within the calculation has remained constant. In addition, the evaluation of the Attained Index has been calculated using GM values identified through interpolation of the vessel's existing GM limit curve which for the vessel utilised in the calculations has been defined based on the requirements of SOLAS 90. As a result of the latter, the Attained Subdivision Index calculated according to SOLAS 2009 falls short of the Required Index, but for the purposes of comparison this is not an issue. The results of this process are highlighted below in Fig. 8, where blue bars represent the Attained Index calculated and grey bars the maximum possible Attained Index based on damages up to five adjacent zones. Observation of the results demonstrates, firstly, that there is little sensitivity in the magnitude of the Attained Index with regards to using the generalised draft probability distribution over the ship-specific variant. In addition, there is also little sensitivity with regards to the number of drafts considered within the calculation of the Attained Index, having shown less than 1% variance in either case.

The primary reason for the observed lack of sensitivity is due to the fact that cruise vessels operate within a very narrow draft range and as such the change in condition of the vessel across its draft range is minimal. There is, however, a considerable difference between the results found using the newly derived weighing factors and those currently in place within SOLAS 2009. Here we observe that SOLAS 2009 appears to underestimate considerably the survivability of the vessel, which from a safety perspective is positive but it also indicates that operator/designer is being over penalised. This is highlighted further in Fig. 9 where the sensitivity of the Attained Index in relation to the number of calculation drafts considered and the type of draft probability distribution utilised is presented, with "Global Statistics" relating to distributions/weightings derived based on data sourced from all vessels and "Ship-specific draft distribution" relating to individual vessel distributions/weightings. In addition, a range of ± 1% of the Attained Index calculated with consideration of all draft intervals has been included in order to provide an indication of the magnitude of variation between the various approaches.

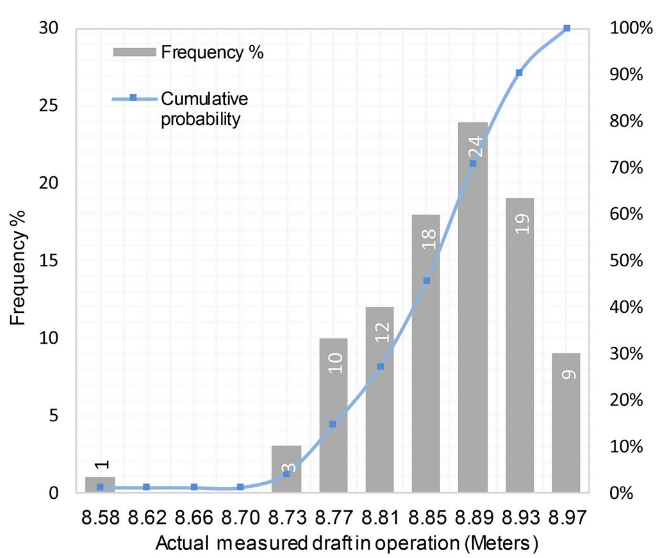

Fig. 7. Ship-specific draft distribution.

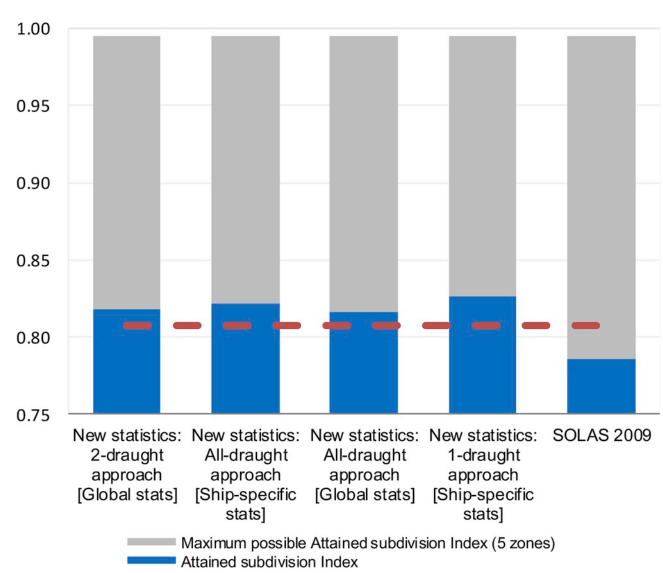

Fig. 8. Comparison of impact assessment on Attained subdivision Index for a typical cruise ship.

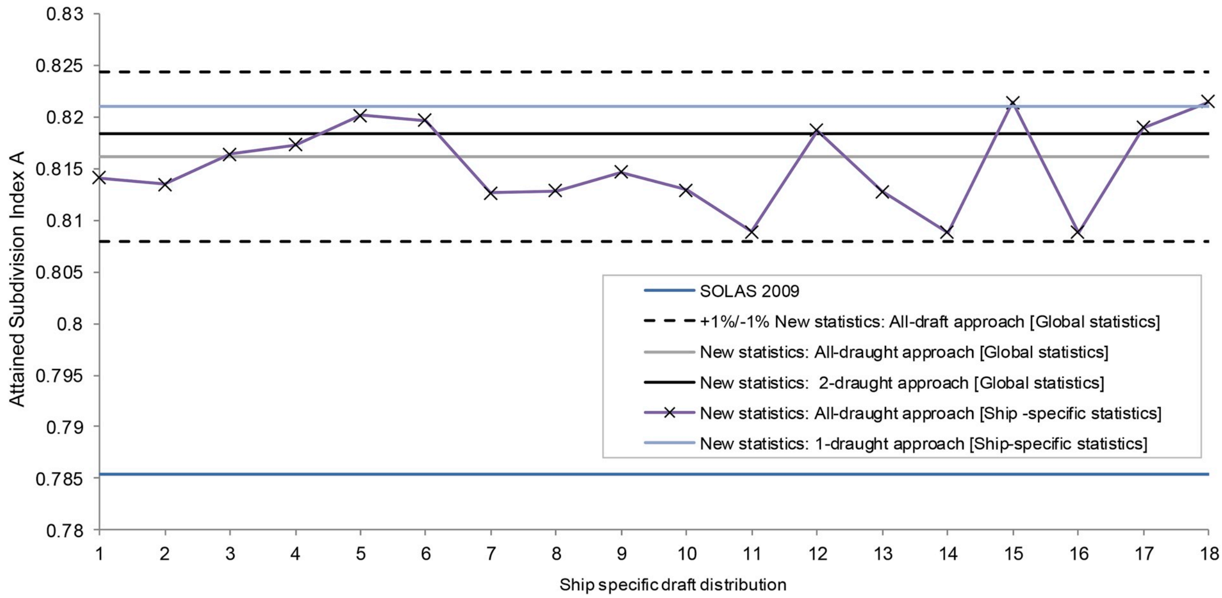

Fig. 9. Draft sensitivity analysis.

The reason for the disparity in the Attained Index value calculated according to SOLAS 2009, in contrast with those calculated using the newly derived weighting factors, stems from several reasons. Firstly, the weighting factors used within SOLAS 2009 overestimate the time cruise vessels operate within the lower to mid draft range. Secondly, the draft range assumed within SOLAS 2009 is too wide and, in fact, cruise vessels operate within a much narrower range.

Generally speaking, it has been observed that in the majority of cases the sample vessels were operating with a considerable GM margin, which would indicate that the actual risk in operation may in fact be much less than that calculated during design. This is, however, a matter that would require further investigation and operational GM values have not be considered within Fig. 9.

6. Conclusions

- On the basis of the foregoing study and the results presented, the following concluding remarks are made:
- The weighing factors used within the SOLAS 2009 framework appear not to reflect the nature of operation of cruise vessels, with the operation profile observed from the operational data sourced demonstrating a tendency to operate within the upper region of the draft range.
- The use of more realistic weighting factors, accounting for observed operational draught distributions, leads to an increase of the Attained subdivision Index compared to calculations based on standard SOLAS 2009. This means that the use of SOLAS 2009 draught weighting factors leads to an underestimation of the Attained subdivision Index (safety level) in case of cruise vessels.
- The use of real loading condition (draft) data can be employed to generate weighting factors based upon draft probability distributions that represent the true operational profile of vessels.
- In the case of existing ships, a one-draft approach to calculating the Attained Index has been identified, which will simplify calculations significantly whilst resulting in higher Attained Index that better reflects cruise ship operation.
- For assessment of cruise vessels during the design stage it is recommended to use a two draft approach with appropriate weighting factors formed on the basis of cruise vessel specific loading condition data and which is ultimately more reflective of the operational profile of cruise vessels.

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References

Atzampos, G., Vassalos, D., Cichowicz, J., Paterson, D., Boulougouris, E., 2019. eSAFE - cruise ship survivability in waves. In: Proceedings of the 17th International Ship Stability Workshop, pp. 265–274 (Helsinki, Finland).

Bulian, G., Cardinale, M., Francescutto, A., Zaraphonitis, G., 2018. Complementing SOLAS framework with a probabilistic description for the damage extent below water. In: Proceedings of the 13th International Conference on the Stability of Ships and Ocean Vehicles. Kobe, Japan, pp. 638–647.

Bulian, G., Lindroth, D., Ruponen, P., Zaraphonitis, G., 2016. Probabilistic assessment of damaged ship survivability in case of grounding: development and testing of a direct non-zonal approach. Ocean Eng. 120, 331–338.

Hollenbach, U., Klug, H., Mewis, F., 2007. Container vessels - potential for improvements in hydrodynamic performance. In: Proc. 10th International Symposium on Practical Design of Ships and Other Floating Structures. United States of America, Houston, Texas.

IMO, 2009. SOLAS - International Convention for the Safety of Life at Sea (London).

IMO, 1998. SLF 42/3/4 - Development of Revised SOLAS Chapter II-1, Parts A, B and B-1, 42nd Session, Agenda Item 3.

IMO, 2000. SLF 43/3 - Development of Revised SOLAS Chapter II-1, Parts A, B and B-1, 43rd Session, Agenda Item 3.

Jasionowski, A., 2011. Study of the Specific Damage Stability Parameters of Ro-Ro Passenger Vessels According to SOLAS 2009 Including Water on Deck Calculation, 2nd EMSA Study on Damage Stability of Ropax Vessels, Project No EMSA/OP/08/2009 (Glasgow, UK).

Luhmann, H., Bulian, G., Vassalos, D., Olufsen, O., Seglem, I., Pottgen, J., 2018. eSAFE-D4.3.2 – Executive Summary, Joint Industry Project "eSAFE - Enhanced Stability after a Flooding Event – A Joint Industry Project on Damage Stability for Cruise ShipsC, rev.2, 2018. Available from: https://cssf.cruising.org/projects.

Luhmann, H., Olufsen, O., Atzampos, G., Bulian, G., 2018. eSAFE-D4.3.1 – Summary Report, Joint Industry Project "eSAFE - Enhanced Stability after a Flooding Event – A Joint Industry Project on Damage Stability for Cruise Ships", Rev 4 , 2018.

Meng, Q., Weng, J., Suyi, L., 2014. Analysis with automatic identification system data of vessel traffic characteristics in the Singapore strait. In: Transportation Research Record: Journal of the Transportation Research Board, No. 2426. Transportation Research Board of the National Academies, Washington, D.C., United States of America, pp. 33–43.

Paterson, D., Atzampos, G., Vassalos, D., Boulougouris, E., 2017. Impact of wave statistics on ship survivability. In: Proceedings of the 16th International Ship Stability Workshop, pp. 73–80 (Belgrade, Serbia).

Rusaas, S., Jost, A., Francois, C., 1996. A new damage stability regulatory framework based upon probabilistic methods. In: Intl Seminar on the Safety of Passenger Ro-Ro

Vessels, Presenting the Results of the Northwest European Research & Development Project. RINA, London, UK.
Vassalos, D., Atzampos, G., Cichowicz, J., Paterson, D., Karolius, K., Boulougouris, E., Svensen, T., Douglas, K., Luhmann, H., 2018. Life-cycle flooding risk management of passenger ships. In: 13th International Conference on the Stability of Ships and Ocean Vehicles. STAB, Kobe, Japan.
Vassalos, D., 2015. Damage stability of cruise ships – evidence and conjecture. In: Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles. STAB, Glasgow, UK, pp. 1185–1196.