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FLOODING ACCIDENT RESPONSE

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List of symbols and abbreviations

A	Attained Subdivision Index
CDF	Cumulative Distribution Function
eSAFE	Enhanced Safety After Flooding Event
GT	Gross Tonnes
IMO	International Maritime Organisation
ND	Non-Dimensionalised
RoPax	Roll-on/Roll-off Passenger Vessel
SOLAS	Safety of Life at Sea

1. EXECUTIVE SUMMARY

1.1 Problem definition

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 despite these vessels having different operational characteristics. This in turn, calls into question the suitability of these weightings concerning what degree they, in fact, reflect the true operational nature of passenger vessels and questions arise as to how this may ultimately impact the assessment of damage stability risk. As such, there is a requirement to critically evaluate these weighting factors by assessing firstly to what degree they accurately reflect passenger vessel operation, and secondly, by exploring the potential for deriving passenger vessel specific weighting factors that account for the unique operation of these vessel types.

1.2 Technical approach and work plan

In order to critically assess the suitability of the currently assumed calculation drafts and associated weighting factors, operational loading condition histories from a total of 36 passenger vessels (27 cruise ships, 6 RoPax vessels and 3 cruise ferries) are utilised in order to derive ship specific draft distributions. These ship-specific distributions are then combined in order to yield generalised draft distributions accounting for all ship data and also for cruise vessels and RoPax independently, thus enabling any ship type specific operational tendencies to be identified. The draft distributions are derived using two separate approaches, firstly, with respect to the sample vessels’ operational draft range, and secondly relative to their currently assumed SOLAS draft ranges. The generalised draft distributions are then used in order to yield optimal calculation drafts and associated weighting factors for both vessels in operation and those within the design stage. Finally, the operational data is further assessed in order to determine the influence of other factors on the vessel operational profile including vessel age, seasonal variations and ship type.

In addition the collected loading condition data is also used in workpackage 2.3 for the assessment of loading for cargo holds and stores.

1.3 Findings & Conclusions

The results have shown that passenger vessels, in general, operate within a much narrower draft range than that presently assumed within SOLAS. Furthermore, it was found that the calculation drafts currently considered within SOLAS should be taken at intermediate locations within the vessel draft range, as they rarely operate at the extremities. The resultant optimal non-dimensional calculation draft values were found to be 0.35-0.45 on the basis of a vessel’s operational draft range and at 0.45-0.75 relative to the currently assumed SOLAS draft range. In both cases, the optimal weighting factors to be applied to the calculation drafts was identified as a common weighting of 0.5. This stems from the nature of the draft distribution CDFs which were found to take on the form of a sigmoid curve, resulting in an optimum of two calculations drafts located equidistant from the inflection point of this curve.

2. INTRODUCTION

2.1 Task/Sub-task text

The main purpose of this task is to collect information on how passenger ships are operated with focus on stability. It is a continuation from the eSAFE project (Luhmann et al, 2018), but the analysed fleet is to be extended and also to cover RoPax ships. The actual operating conditions will be recorded for a significant number of ships for the duration of 1 to 2 years in some cases. For the selection of ships, the variety of the fleet of cruise ships and RoPax should be covered, which means that the data of younger and older ships should be included as well as different operational profiles and areas. The collected data will be statistically analysed and proposals be made on how real operational patterns can be used in the assessment of flooding risk.

2.2 Background

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. This approach is predominantly probabilistic in nature, with the exception of some deterministic elements, and aims to assess the average probability of a vessel surviving collision damage in waves. This probability is then used as an objective measure of ship safety in the damaged condition and is represented within the rules by the Attained Subdivision Index, A.

This index is formed on the basis of three partial indices, calculated with respect to three drafts intended to represent the operational draft range of the vessel. To each of these partial indices, a weighting factor is then applied which accounts for the likelihood that the vessel will be operating near or at any of these drafts at the time of collision. In this respect, these weighting factors can be viewed as a representation of the operational profile of the vessel. Currently, the same weighting factors are applied to all vessels covered by the standard in a “one-size-fits-all” manner, with no differentiation made on the basis of ship type. This assumes in essence that vessels such as cruise ships, dry cargo ships and RoPax share the same operational profile, which defies logic given that these ship types are known to have very different tendencies when it comes to the nature of their operation. Furthermore, there are a number of other operational factors liable to affect a given vessel’s draft range and operational profile that are presently unaccounted for and their influence on damage stability risk remains unclear. This includes, but is not limited to, factors such as the vessel area of operation, age, seasonal variations, route etc.

In light of the above, the present work package aims to assess the true operational loading behaviour of passenger vessels in order to derive draft weighting factors that better represent this category of vessels and their operation. In addition, the impact of factors such as vessel age and type (cruise vessel, RoPax, cruise ferry etc.) will be assessed in order to identify the degree to which these factors influence vessel operation and thus damage stability risk.

3. METHODOLOGY

The development of the draft weighting factors has been achieved through the analysis of operational loading condition data sourced from a total of 36 passenger vessels. This consists of 27 cruise ships, 6 RoPax vessels and 3 cruise ferries, which range between 2 and 38 years in age and 19,800 GT - 227,000 GT in size. This provides ample coverage of the fleet demographic, as demonstrated in Figure 1 below.

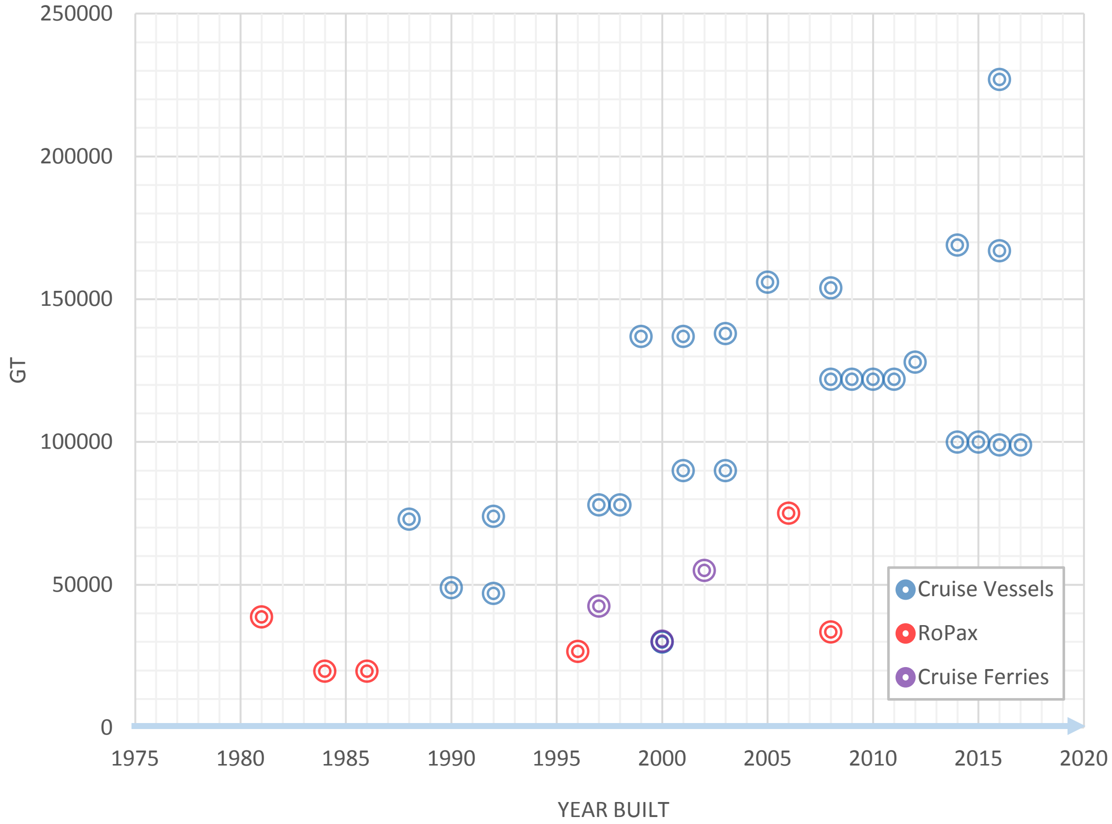

Figure 1 - Basis ship overview

The data comprises ship-specific loading condition histories, recorded over a time-span ranging from 1-2 years of operation. Through sourcing draft readings from this data, draft probability distributions have been derived for each vessel and then combined to generate a global distribution, accounting for all vessels. This has been conducted in two manners, the first of which derives the draft distributions with respect to each vessels assumed SOLAS draft range (ds-dl), which serves to provide a picture of how the vessel is operated relative to the assumptions made in SOLAS. Within the second approach, the draft distributions have been derived on the basis of each vessels operational draft range, allowing the operational nature of passenger vessels within their true draft range to be assessed. Such analysis subsequently allows new calculation drafts and associated weighting factors to be derived that best reflect the draft distributions. To this end, the information obtained has been processed 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 non-dimensionalise the draft data. 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). In both cases this is conducted in accordance with Eq.1.

$$T_{ND} = \frac{\overline{T_i} - \min\left(\overline{T_i}\right)}{\max\left(\overline{T_i}\right) - \min\left(\overline{T_i}\right)} \qquad (1)$$

Where,

- $\max\left(\overline{T_i}\right), \min\left(\overline{T_i}\right)$ are the lower and upper limits of the draft range (m)
- $\overline{T_i}$ is a given mean draft reading sourced from the data
- T_{ND} is the resultant non-dimensional draft value.

In order to derive a given draft distribution, the non-dimensional draft range is 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 in accordance with the operational data, as demonstrated within Figure 2. This is a similar process to that adopted in the cases of (Meng et al, 2019) and (Hollenbach et al, 2007) where draft probability distributions have been derived in this manner for various types of cargo vessels along with Ro-Ro passenger vessels.

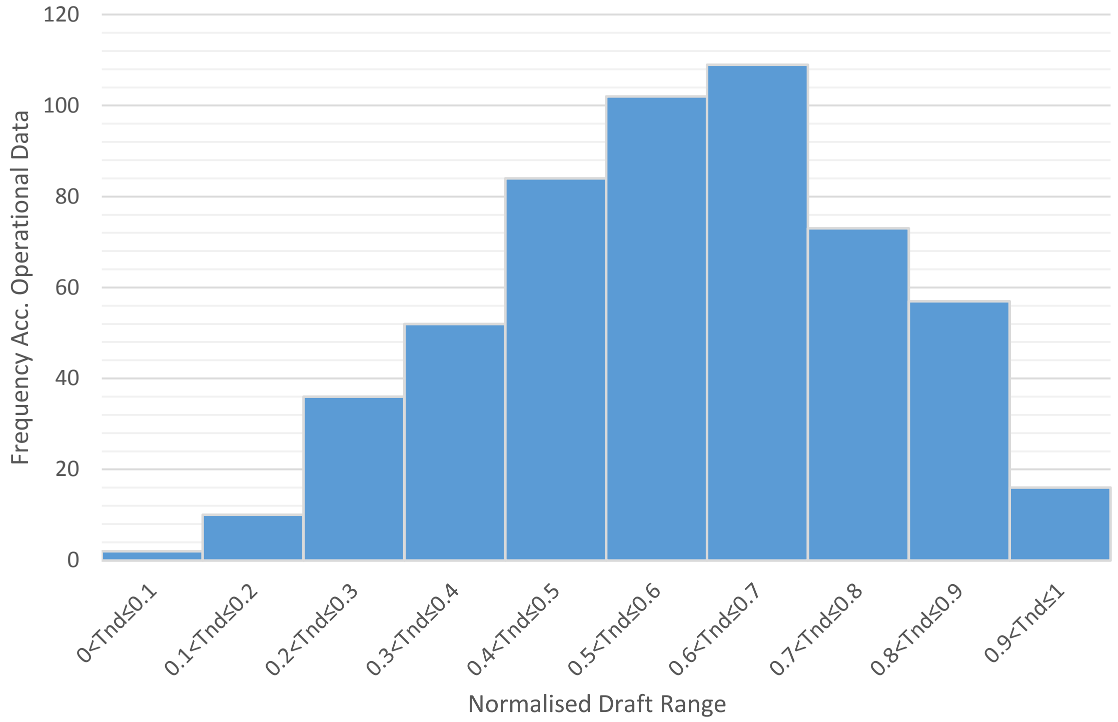

Figure 2 - Example of ND draft distribution

Following this process, the cumulative distribution function (CDF) of the vessel draft distribution can be derived which facilitates the identification of the following parameters:

- The appropriate number of calculation drafts to be considered.
- Which location within the vessel draft range the calculation drafts should be situated.
- The magnitude of the weighting factors to be applied to each calculation draft.

The above is achieved by fitting a simplified CDF to the existing CDF of the vessel draft distribution that is representative of the calculation drafts and their respective weightings, see Figure 3. In this example, the original CDF of the draft distribution is shown in grey and the stepped blue curve is the fit according to arbitrary non-dimensional drafts 0.25 and 0.6, weighted at 0.4 and 0.6 respectively. The optimal fit is identified by varying the location of the calculation drafts and their weightings such to minimise the fitting error, thus providing the most appropriate calculation drafts and weighting factors.

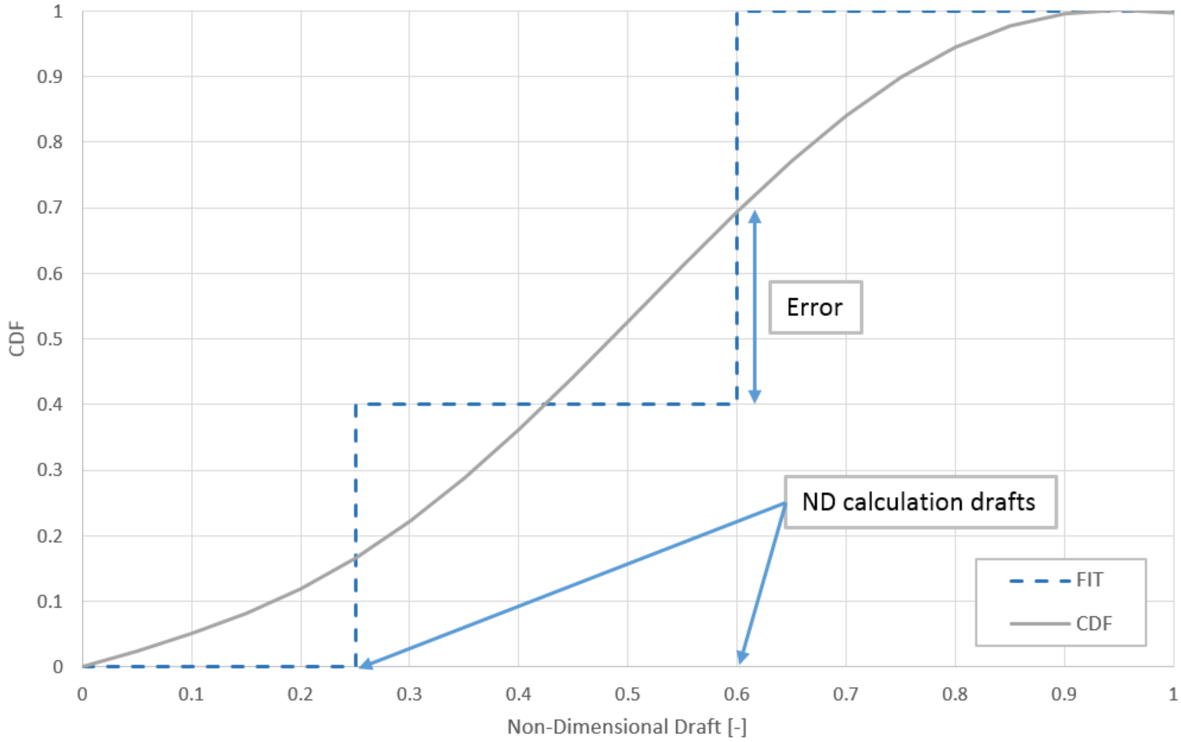

Figure 3 - Example of curve fitting to CDF of operational draft

Following this, an inverse normalisation can then be conducted in order to identify the actual draft values for a given ship (eq.2) which, in turn, can then be used in combination with the newly derived weightings in order allow the Attained Index to be calculated.

The following formulation is obtained by the inverse of equation (eq.1):

$$\overline{T_i} = T_{ND} \cdot \left(\max\left(\overline{T_i}\right) - \min\left(\overline{T_i}\right)\right) + \min\left(\overline{T_i}\right) \qquad (2)$$

4. RESULTS

4.1 Operational Draft Distributions

As a first assessment, draft distributions have been produced for each vessel that are representative of their actual operation. This is a process that has involved non-dimensionalising the loading condition histories of each vessel with respect to their operational draft range, following which, ship-specific draft distributions have been derived in the accordance with the process outlined in section 3. These distributions have then been averaged in order to yield generalised distributions accounting for:

- All vessel data
- Cruise vessel data only
- RoPax & Cruise ferry vessel data only

Through doing so, it has been possible to assess the manner in which passenger vessels operate within their actual operational draft range as opposed to that currently assumed within SOLAS. Furthermore, by considering ship types independently, it has been possible to identify any ship-specific operational tendencies and traits.

Firstly, the size of each vessel's operational draft range has been assessed relative to that assumed by SOLAS, as shown in Figure 4. Here, the ratio between these two draft ranges is presented for each vessel in relation to the year of their launch, with a ratio greater than one indicating that the operational draft range was found to be smaller than that assumed by SOLAS. The results of this process indicated that majority of the sample vessels, 62.5%, were found to operate within smaller draft ranges than those assumed by SOLAS, of which 50% were found to operate draft ranges over half the size of their SOLAS equivalent. This was found to be particularly true for younger vessels, where there is a more pronounced disparity between the magnitudes of the assumed SOLAS draft range and the actual operational draft range.

In such cases where the SOLAS draft range was found to be narrower than the operational draft range, the reason for this was found stem from the SOLAS definition of the "Light service draft" which entails that a full complement of passengers be on-board. In contrast, the operational data for a number of vessels contained loading conditions in which much fewer passengers were on-board yielding shallower drafts. It is important to note, however, that despite the draft range being wider in these cases, the frequency in which a given vessel was found to visit the lower end of this range was minimal (4.8% average operational time). This does, however, raise interesting questions with regards to damage stability risk and the current SOLAS regulations, where the Required Index, evacuation times and the passenger induced heeling moment is based on a full complement of passengers, which is not always the case.

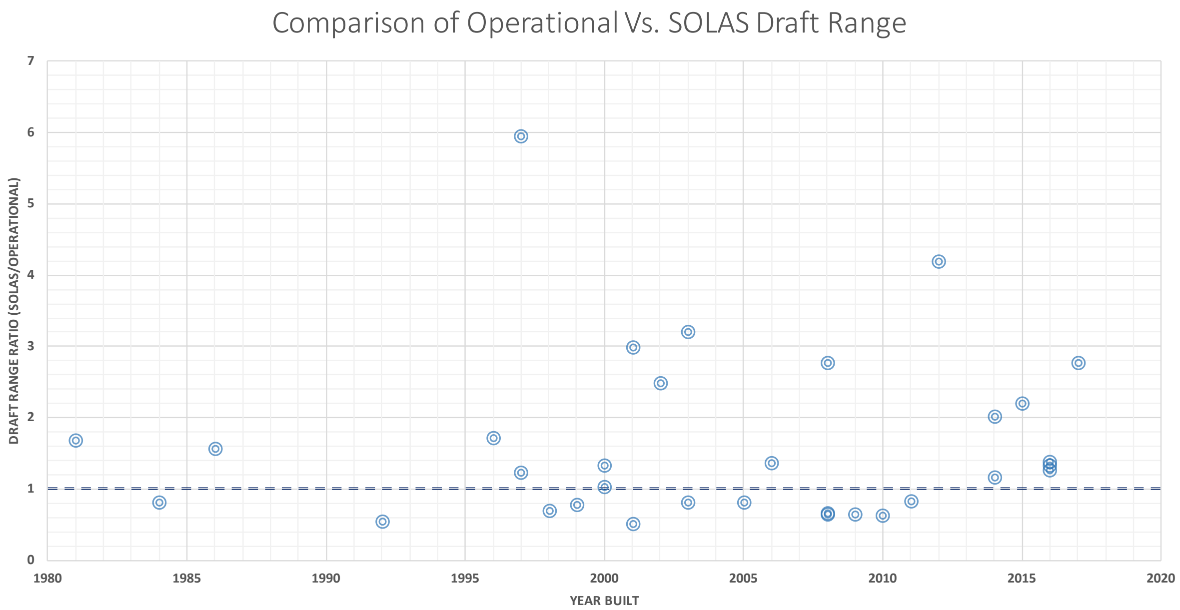

Figure 4 - Comparison of SOLAS and operational draft ranges with respect to ship age

As previously mentioned, three generalised draft distributions have been generated accounting for a.) All ship data, b.) RoPax vessels only and c.) Cruise vessels only, as presented in Figures 5-7. Here, it was found that, regardless of vessel type, the resultant draft distributions indicated that passenger vessels operate fairly uniformly within the middle 60% of their operational draft range. However, 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. As such, it is important to consider that the distributions shown within the figures below correspond to minimal variation in draft and are over a draft range that is, relatively speaking, towards the upper portion of the assumed SOLAS draft range.

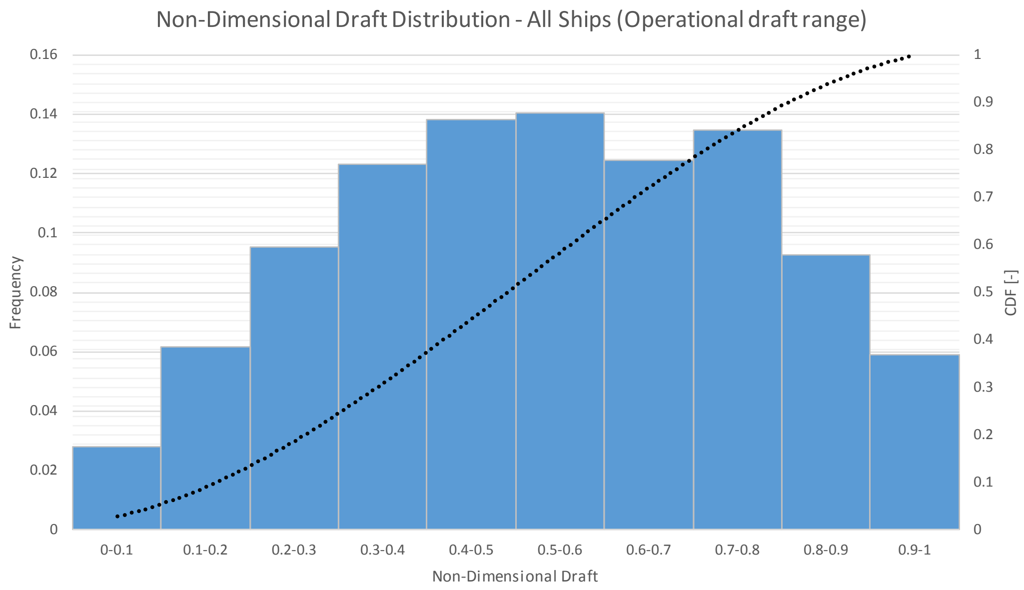

Figure 5 - Operational draft distribution for all ships

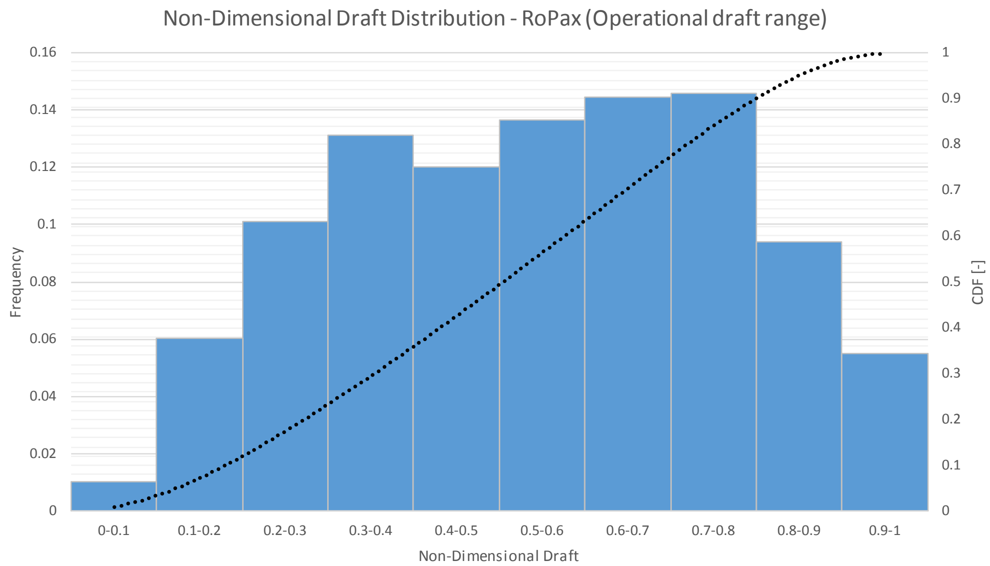

Figure 6 - Operational draft distribution for RoPax vessels only

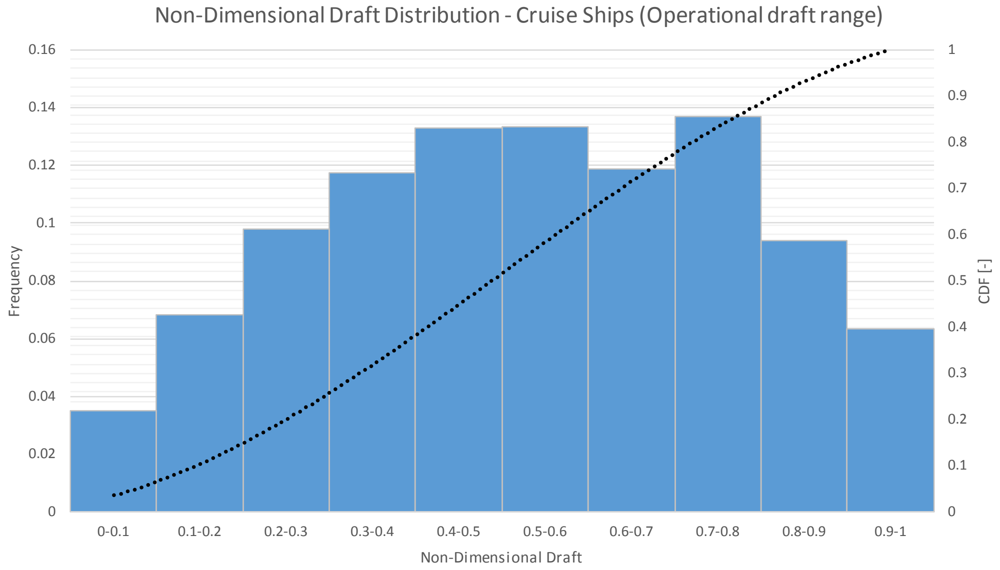

Figure 7 - Operational draft distribution for cruise vessels only

4.2 Derivation of calculation drafts and weighting factors

Following the above, optimal non-dimensional calculation drafts and associated weighting factors have been derived in order to provide a simplified means of assessing/monitoring survivability once a vessel has entered operation. This has been conducted in relation to the generalised operational draft distribution created with consideration of all ship data. The procedure adopted here is that which is outlined within Section 3, whereby a simplified CDF has been fitted to the operational draft CDF. Given that this CDF was found to take the form of a sigmoid curve, the optimal solution was found to be two calculation drafts situated equidistant from the CDF inflection point and with weighting factors 0.484 and 0.516. However, for ease of application, it is recommended to apply a weighting factor of 0.5 to each calculation draft, as this has minimal effect on the fitting accuracy but would enhance ease of implementation, as demonstrated within Table 1.

It is important to note here that, in the determination of the requisite number of calculation drafts, only the accuracy of the fit has been considered. Ideally, the sensitivity of the Attained Index to the number of calculation drafts considered would also be accounted for. For example, it may in fact be found that the consideration of two calculations drafts is superfluous as passenger vessels operate within such a narrow draft range as to produce little variation in Attained Index across the whole range.

Table 1 - Optimal calculation drafts and weighting factors

Parameters	Optimal Values	Practical Values
T_{ND1}	0.35	0.35
T_{ND2}	0.75	0.75
w_1	0.516	0.5
w_2	0.484	0.5
SSR	0.7316	0.736

Max Over	0.269	0.2687
Max Under	-0.268	-0.2680

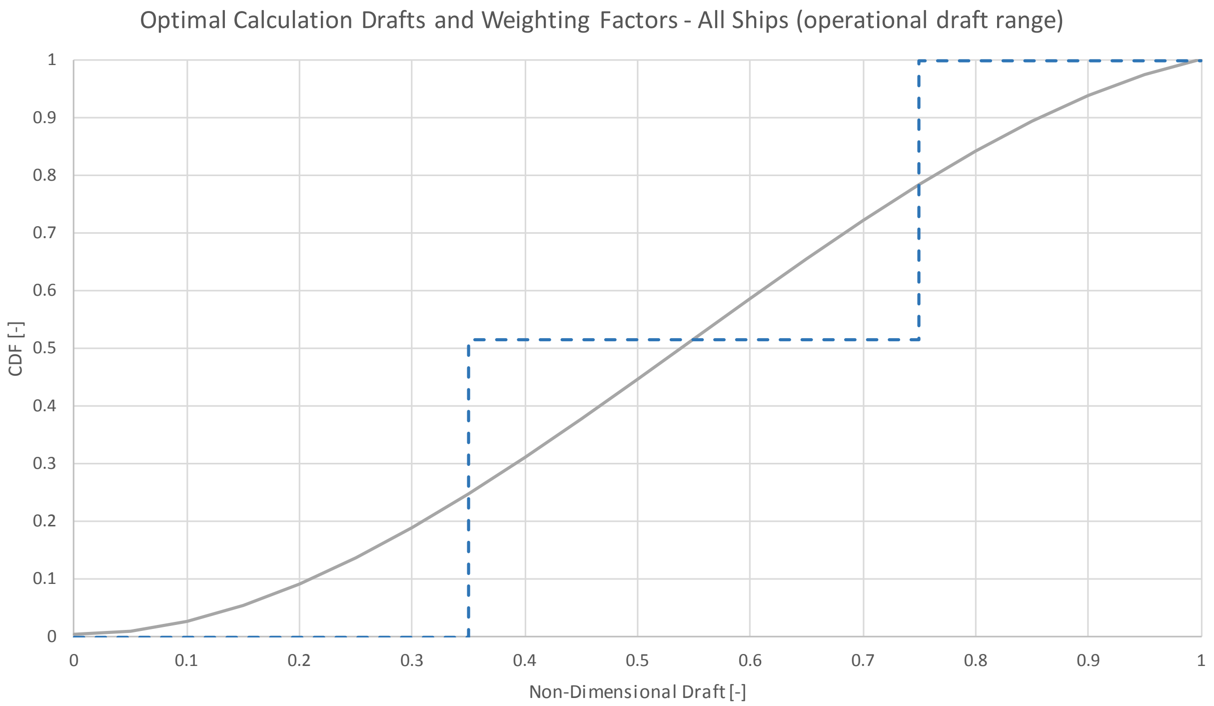

Figure 8 - Optimal operational calculation drafts & weighting factors

On the basis of the above, the resultant Attained Index calculation for a vessel in operation would be as follows:

$$A = \sum_{j=1}^{2} w_j \cdot A(T_j) \qquad (3)$$

$$A = 0.5 \cdot A_{0.35} + 0.5 \cdot A_{0.75} \qquad (4)$$

Where, $A_{0.35}$ and $A_{0.75}$ are the partial Attained Indices calculated according to non-dimensionalised draft values situated at 0.35 and 0.75 of the operational draft range. The alternative to this approach would be to calculate the Attained Index in real time using the draft at the moment of calculation and the associated loading condition information.

4.3 Draft distributions based on SOLAS

Unlike vessels that are in operation, those during the design stage suffer from a lack of operational data which produces a greater amount of uncertainty and calls for a number of assumptions to be made with regards to the size of the draft range to be considered. However, steps can be taken in order to ensure that the calculation drafts and associated weighting factors are more representative of the way passenger vessel are operated in general. With this in mind, additional draft distributions have been generated, this time having non-dimensionalised the draft histories of each vessel with regards to their respective SOLAS 2009 assumed draft ranges. As before, this has been conducted with consideration of all ships, cruise vessels only and RoPax vessels only with the resultant distributions provided within Figures 9-11. The resultant distributions show, in all cases, a tendency for passenger vessels to operate predominantly within the upper region of their draft range, with this tendency being more pronounced for cruise vessels in comparison to RoPax. In contrast, however, RoPax vessels were found to operate at the upper extremity of their draft range more frequently than cruise vessels, though the average age of the cruise vessels within the sample is 14 years in comparison to the RoPax average of 24 years, so it is reasonable to assume that the cruise vessels within the sample have a considerable growth margin yet to be utilised.

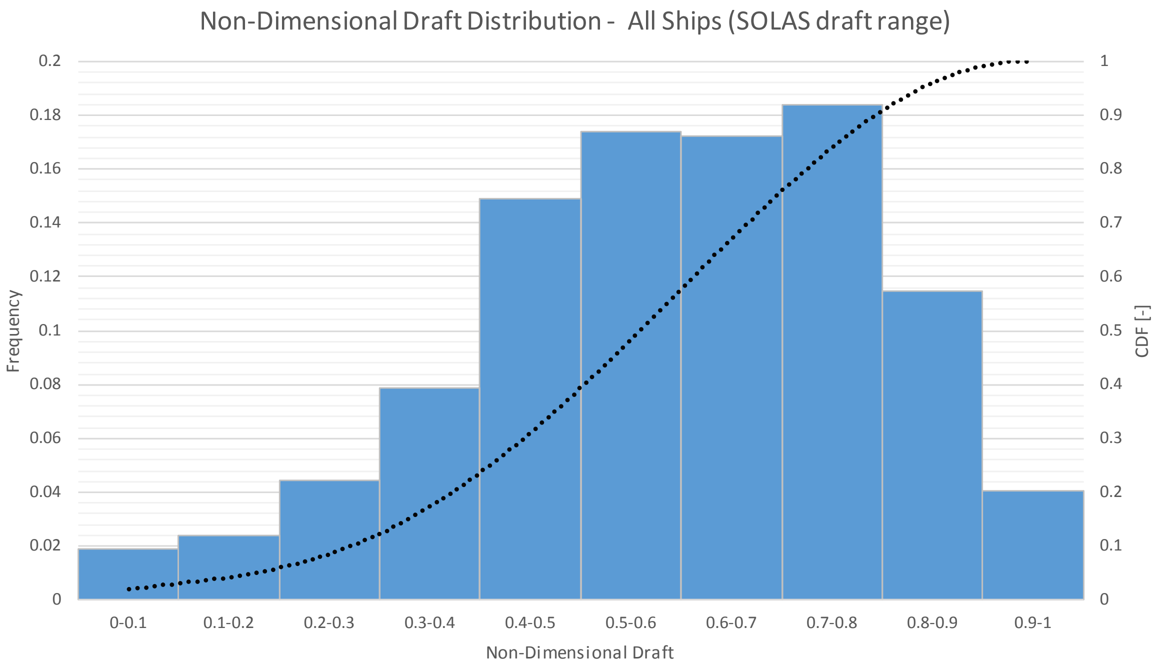

Figure 9 - Draft distribution relative to SOLAS range for all ships

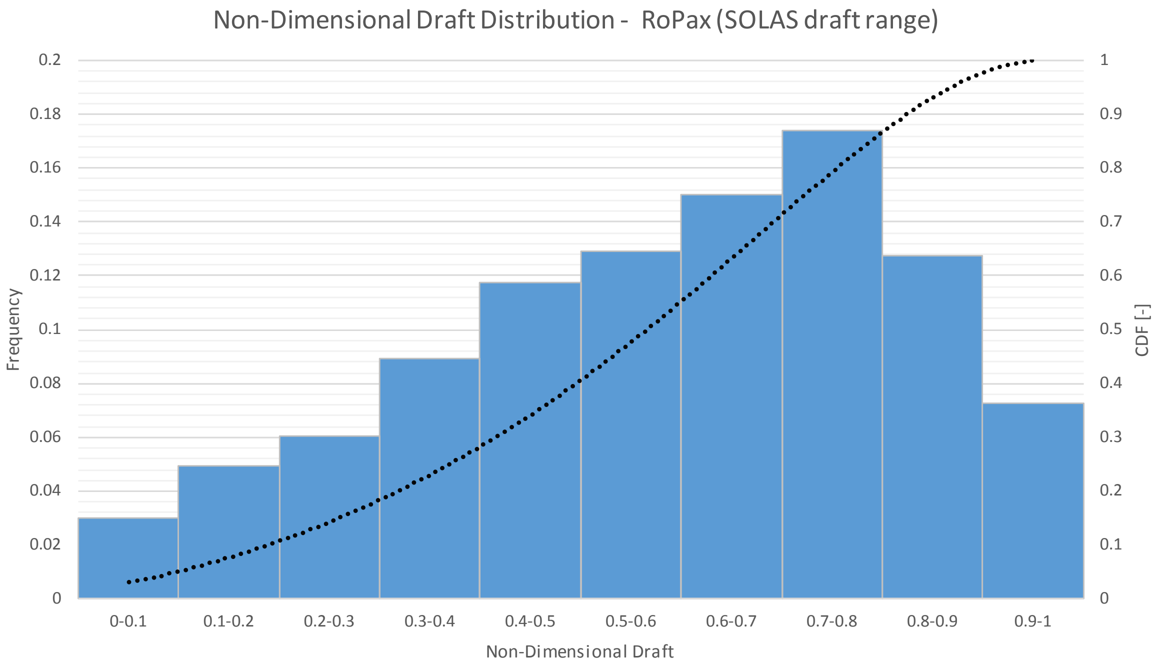

Figure 10 - Draft distribution relative to SOLAS range for RoPax vessels only

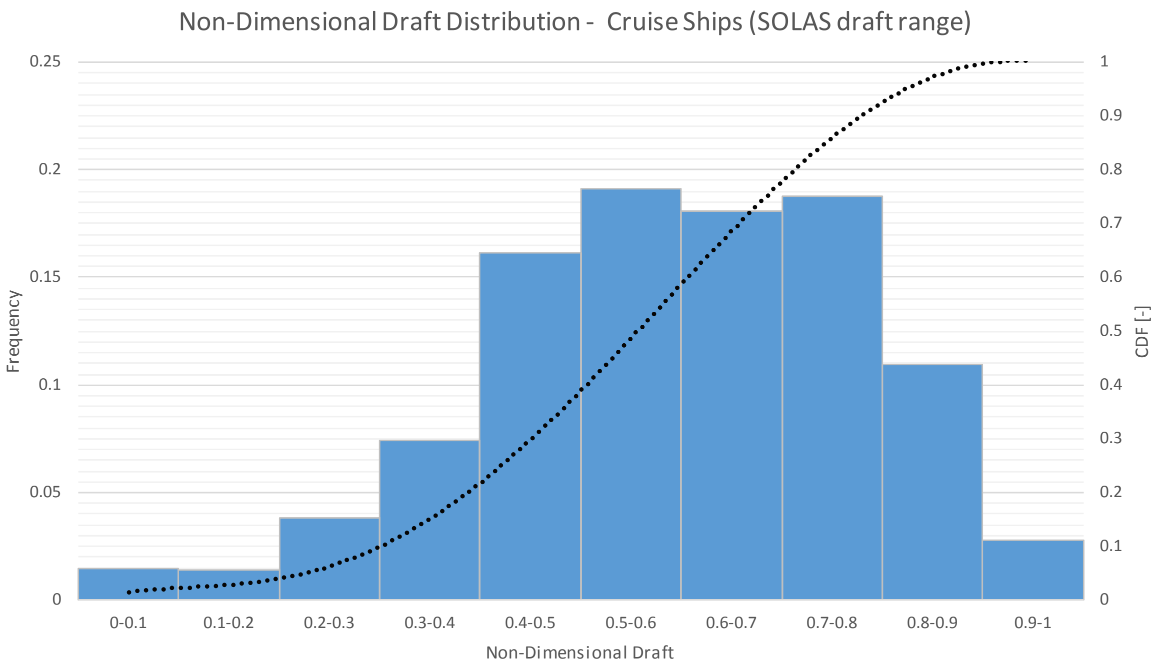

Figure 11 - Draft distribution relative to SOLAS for cruise ships only

4.4 Derivation of Weighting Factors

As in the previous case, calculation drafts and their associated weighting factors have been derived by fitting a simplified CDF to the existing generalised draft distribution for all ships based on SOLAS draft range assumptions, Figure 12. Here, once again the CDF of the draft distribution took the form of a sigmoid curve, leading to an optimal number of two calculation drafts to be considered about the CDF point of inflection, located at non-dimensional drafts 0.45 and 0.75 respectively. The optimal weighting factors to be applied to these drafts were identified as 0.486 and 0.514, though it would be recommended to utilise a common weighting of 0.5 for practical purposes. The results of this fitting process are provided within Table 2.

Table 2 - Optimal calculation drafts and weighting factors

Parameters	Optimal Values	Practical Values
T_{ND1}	0.45	0.45
T_{ND2}	0.75	0.75
w_1	0.486	0.5
w_2	0.514	0.5
SSR	0.6004	0.6025
Max Over	0.247	0.260
Max Under	-0.270	-0.256

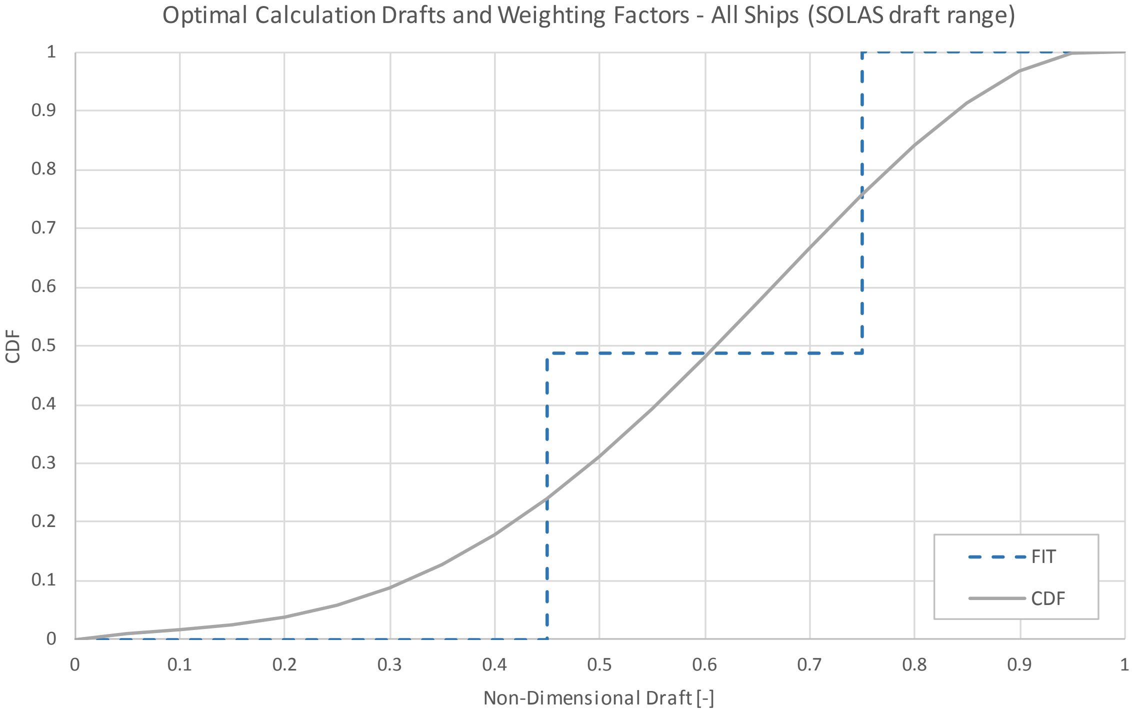

Figure 12 -Optimal calculation drafts & weighting factors based on SOLAS draft range

On the basis of the above, the resultant Attained Index calculation for a passenger vessel within the design stage would be as follows:

$$A = \sum_{j=1}^{2} w_j \cdot A(T_j) \qquad (5)$$

$$A = 0.5 \cdot A_{0.45} + 0.5 \cdot A_{0.75} \qquad (6)$$

Where $A_{0.45}$ and $A_{0.75}$ are the partial Attained Indices calculated according to non-dimensionalised draft values situated at 0.45 and 0.75 of the SOLAS draft range (ds-dl).

5. INFLUENCE OF OTHER FACTORS ON LOADING BEHAVIOR

In addition to the previously outlined assessment, a further study has been conducted in order to identify any trends that may exist in loading behaviours of the sample vessels and other pertinent factors. Firstly, the average non-dimensional draft of each vessel based on their loading histories has been compared to their age as shown in Figure 13. Here it can be observed that, in general, and as one would expect, with increased vessel age there is a tendency to operate towards the upper limit of the draft range. There is, however, quite a substantial scatter, with some younger vessels already operating in the upper region of their draft range. Ultimately, other determining factors will be at play in such cases relating to the owners requirements when the vessel was designed and the magnitude of the growth margin built into the vessel design along with operational influences.

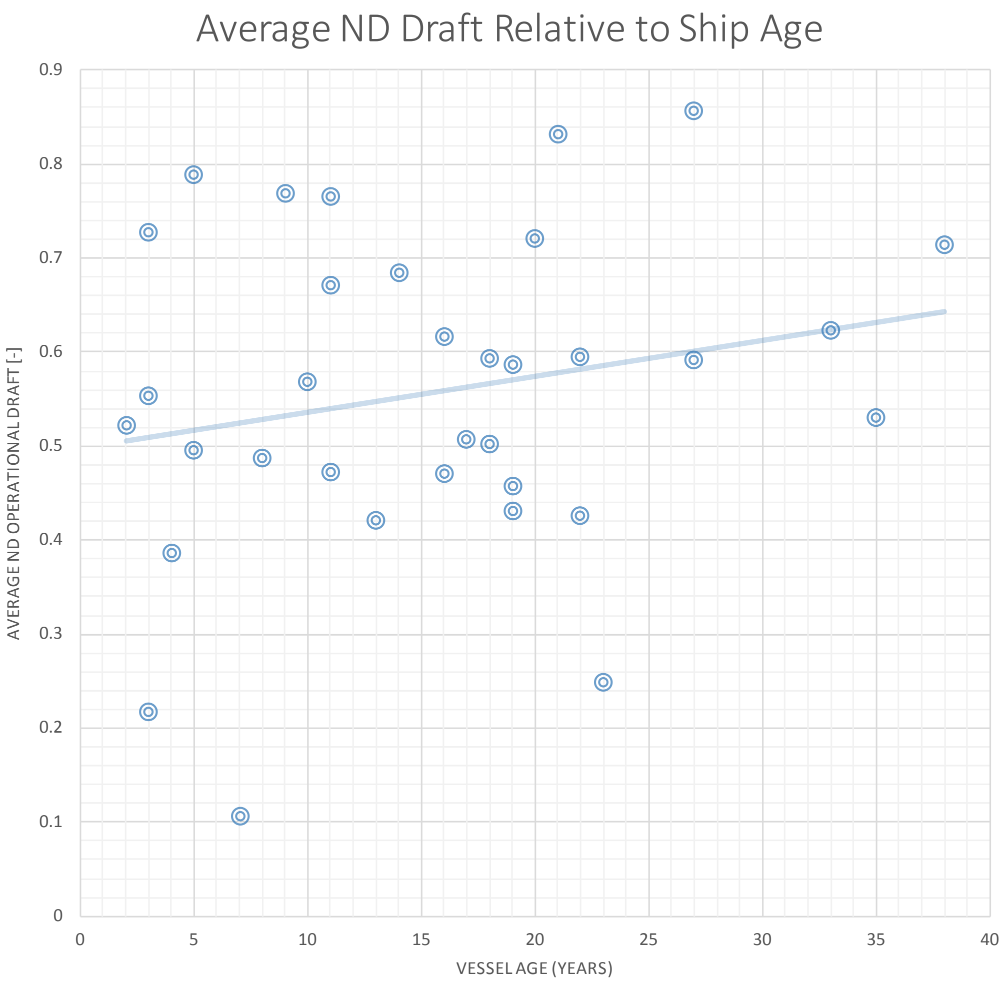

Figure 13 - Impact of ship age on average ND operational draft

The next aspect considered, was the magnitude of the operational draft range of each vessel relative to their year of construction, Figure 14. As in the previous example, there was considerable scatter found here, but in general it would seem that the draft range magnitude is independent of vessel age.

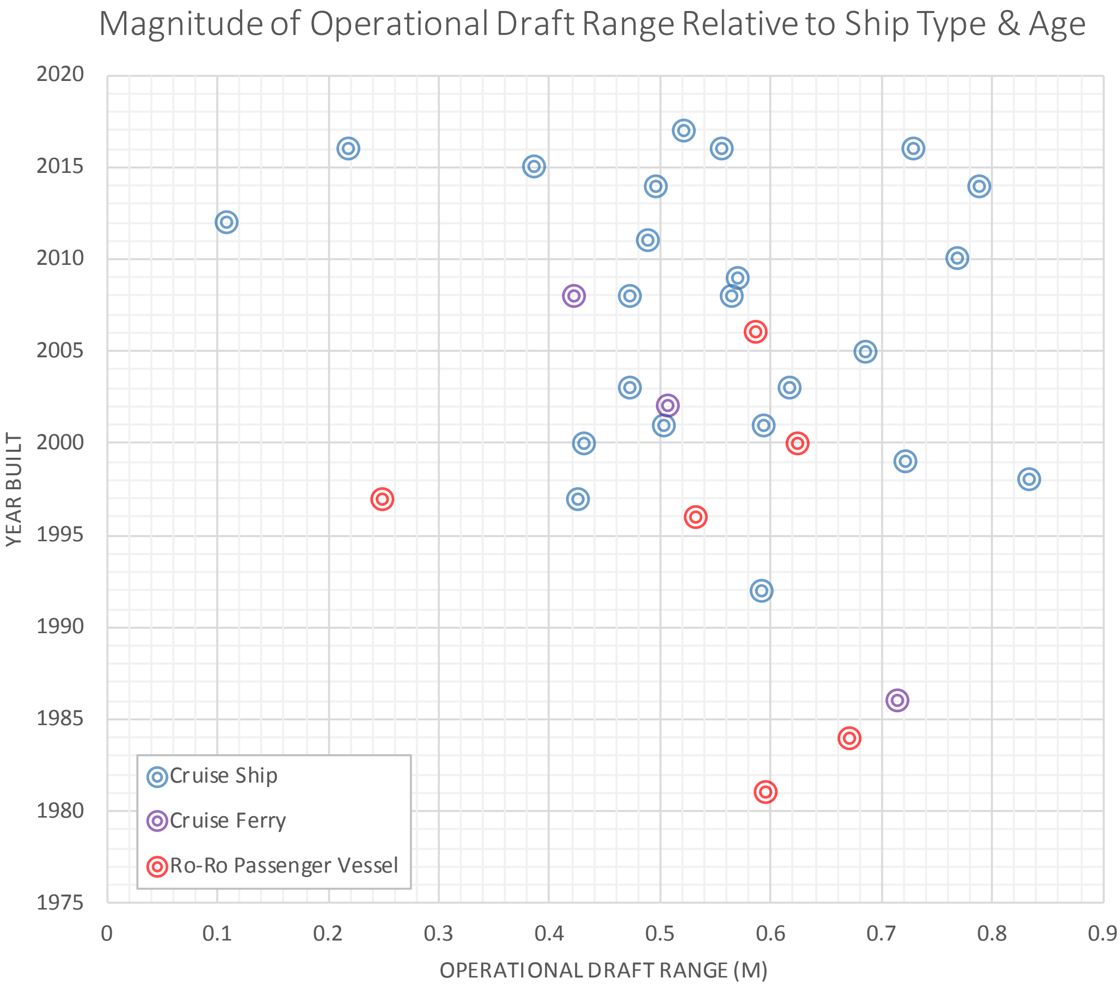

Figure 14 - Operational draft range size relative to vessel year of construction

In addition to considering the magnitude of the operational draft range with vessel age, a similar assessment has been conducted with respect to the SOLAS assumed draft range, shown in Figure 15, with the operational equivalent scaled for comparison in Figure 16. Here it can be observed, that with the exception of a few outliers, cruise vessels are generally designed to a much smaller draft range in comparison to the RoPax vessels within the sample. Furthermore, through comparison between Figures 15 and 16, the degree to which the operational draft ranges were found to be narrower than the SOLAS assumption can be clearly observed.

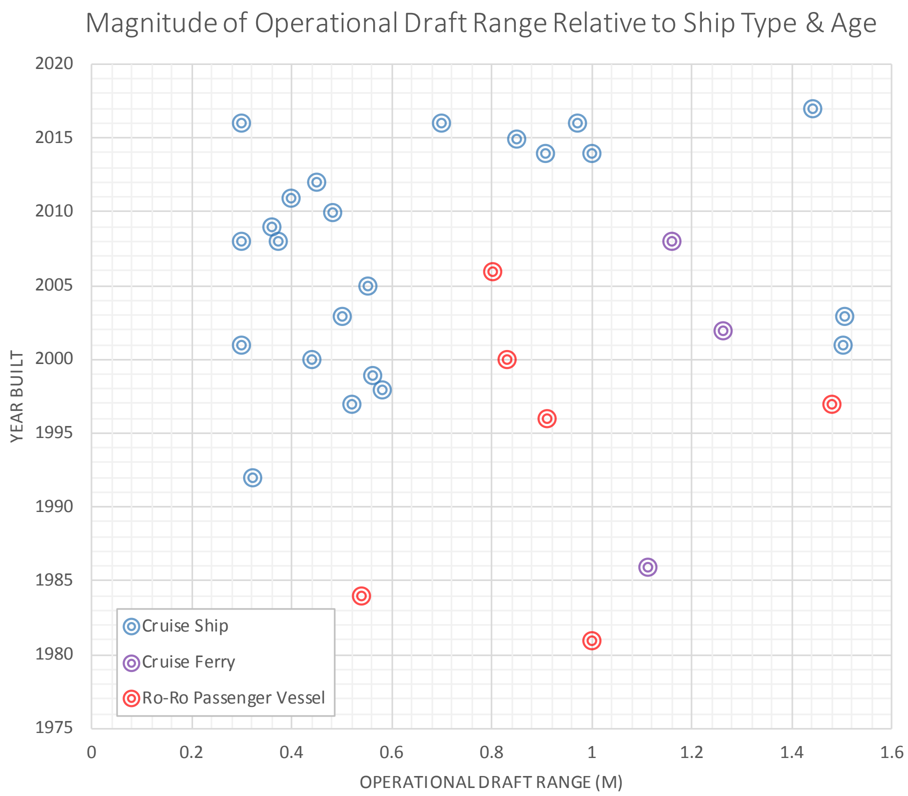

Figure 15 - Size of SOLAS draft range relative to vessel age and type

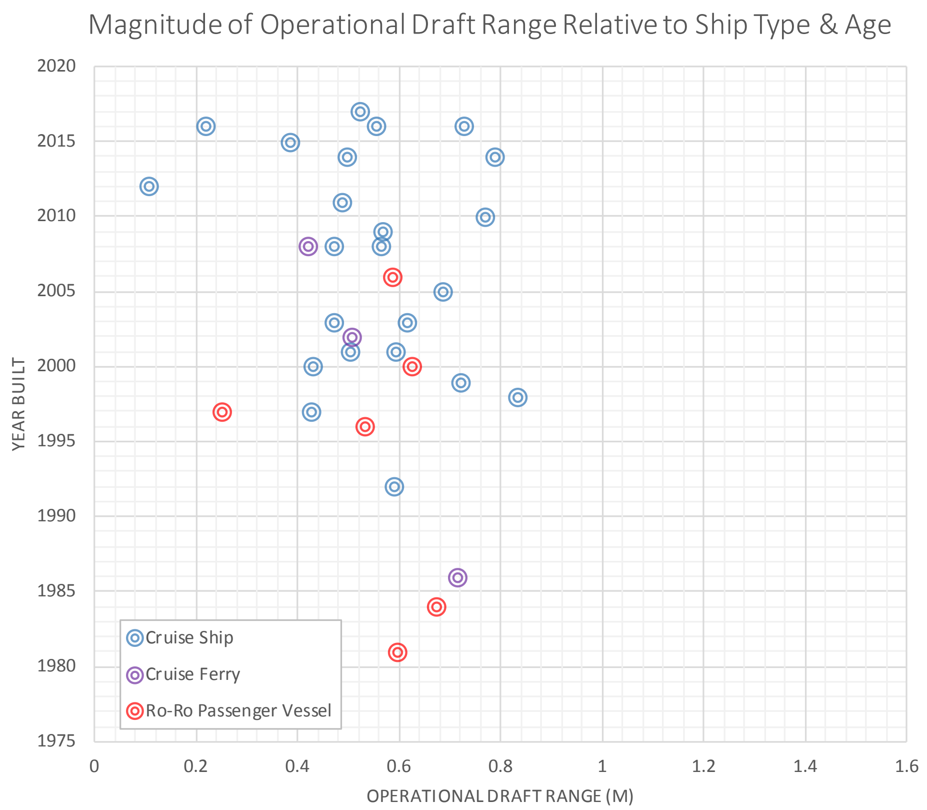

Figure 16 - Size of operational draft range relative to vessel age and type

The final manner in which the vessel loading histories were examined, was to look into seasonal variations in loading behaviour. This was found in some instances to quite pronounced (0.1m-0.15m), as in the example below. Such information would allow for the calculation of seasonal Attained Indices which could then be compared in order to assess the variation in damage stability risk between peak and off-seasons. Of course, such an assessment would also ideally account for variation in persons on-board and thus people at risk.

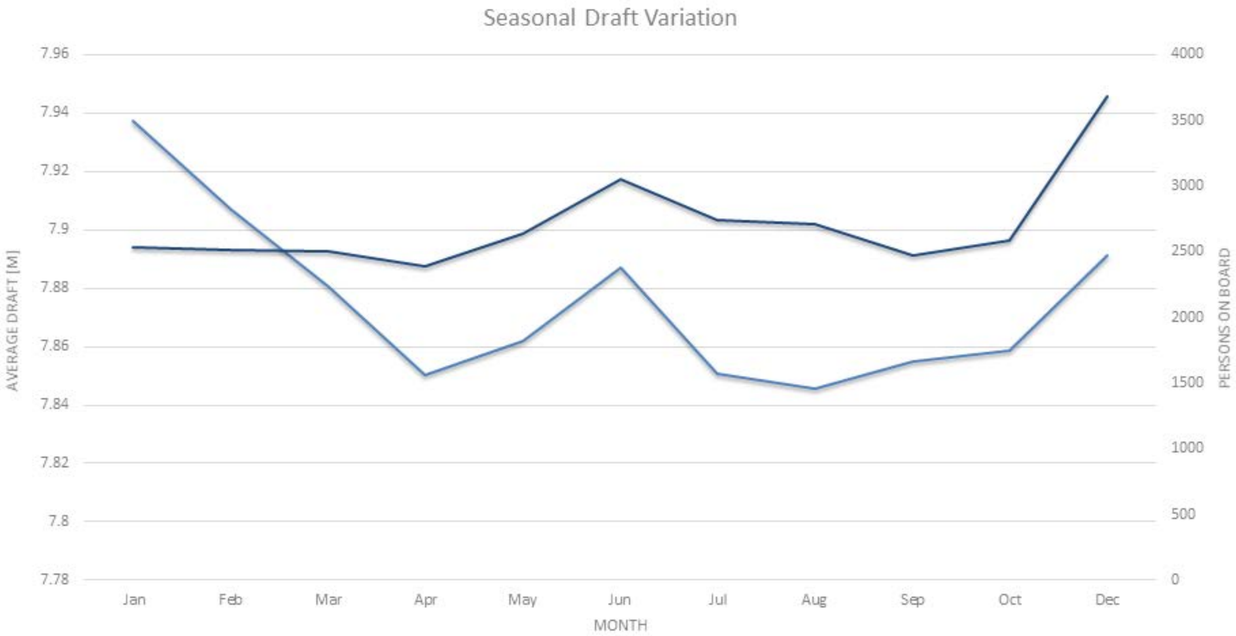

Figure 17 - Seasonal variation in average draft ship #xx

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the findings of this study, the following conclusions can be drawn:

- The results have shown that passenger vessels, in general, operate within a much narrower draft range than that presently assumed within SOLAS.
- It was found that the calculation drafts currently considered within SOLAS are not optimal with regards to the operation of passenger vessels. Instead, two calculation drafts should be considered at intermediate locations within the vessel draft range, as passenger vessels were found to rarely operate at the extremities of their draft range.
- The resultant optimal non-dimensional calculation draft values for vessels in operation and thus relative to the operational draft range, were found to be 0.35-0.45.
- With regards to vessels within the design stage, the optimal non-dimensional calculation drafts were found to be 0.45-0.75 relative to the currently assumed SOLAS draft range.
- In both cases, the optimal weighting factors to be applied to the calculation drafts was identified as a common weighting factor of 0.5.
- The magnitude of the vessel operational draft range was found to be insensitive to ship age and type.
- The average non-dimensional operational draft was found to increase with vessel age.
- Seasonal influences on the average operational draft were found to be considerable in some cases were variations up to 0.15m were found.

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