GOALDS – Goal Based Damaged Stability: Collision and Grounding Damages

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ABSTRACT

The present paper outlines the current status of work of the EU funded, FP7 project GOALDS (Goal Based Damaged Stability, 2009-2012), which aims at addressing shortcomings of SOLAS 2009 with respect to the survivability assessment of passenger ships by state of the art scientific methods, formulating a rational, risk-based regulatory framework, properly accounting for the damage stability properties of passenger ships. The paper is herein focusing on the presentation of project results regarding the update of statistics of collision and grounding damages and the conclusions on the way ahead in this respect.

KEYWORDS

Grounding and collision; risk-based regulation; SOLAS 2009

INTRODUCTION

The new probabilistic damaged stability regulations for dry cargo and passenger ships (SOLAS 2009), which entered into force on January 1, 2009, represent a major step forward in achieving an improved safety standard through the rationalization and harmonization of damaged stability requirements. There are, however, serious concerns regarding the adopted formulation for the calculation of the survival probability of passenger ships, particularly for ROPAX and vary large cruise vessels; thus eventually of the Attained and Required Subdivision Indices for passenger ships. Furthermore, present damaged stability regulations account only for collision damages, despite the fact that accidents statistics, particularly of passenger ships, indicate the profound importance of grounding accidents.

Responding to the above shortcomings, the research project GOALDS is addressing the above issues by:

- Improving and extending the formulation introduced by MSC 216 (82) for the assessment of probability of survival of ROPAX and cruise ships in damaged condition, based on the extensive use of numerical simulations and physical model experiments; for ROPAX ships, water on deck effects are considered.
- Elaborating damage statistics and probability functions for the damage location, length, breadth and penetration in case of a grounding accident, based on a thorough review of available information regarding grounding accidents worldwide.
- Revisiting most recent damage statistics for collision damages and concluding on the necessity of likely update of probabilistic damage distributions laid down in latest SOLAS regulations for passenger ships.
- Formulating a new probabilistic damage stability concept for ROPAX and cruise ships, incorporating collision and grounding

damages, along with an improved method for calculation of the survival probability.

- Establishing new risk-based damage stability requirements of ROPAX and cruise vessels based on Formal Safety Assessment (FSA) and a cost/benefit analysis (CBA) to establish the required subdivision index in terms of acceptable risk levels.
- Investigating the impact of the developed new formulation for the probabilistic damage stability evaluation of passenger ships on the design and operational characteristics of a typical set ROPAX and cruise vessel designs (case studies).
- Preparing and submitting a summary of results and recommendations for consideration to IMO (end of project, year 2012).

The present paper is focusing on the presentation and discussion of project results regarding the update of statistics of collision and grounding damages, with emphasis on the groundings.

OVERVIEW OF GOALDS DATABASE

One of the tasks within the GOALDS project focuses on updating and developing all components of a probabilistic model of collision and grounding characteristics, respectively, and its ensuing impact on ship stability. Based on a thorough review of available information from all possible sources regarding collision and grounding accidents worldwide, appropriate functions for the probability distributions of collision and grounding damage location, length, breadth and penetration were generated or updated when deemed necessary.

As basis, the casualty database of the HARDER project (HARDER project, 1999-2003) was used and amended by including casualties from 2000 to 2009. To identify the casualties, the Lloyd's Register Fairplay database was used, but data were also collected from the 3 classification societies taking part in the project (GL, DNV and LR).

Finally, 1527 damage cases were identified for collision, grounding and contact of all ship types within the database (see Table 1). This data set was used for the initiation of the statistical analysis.

Table 1: Overview of data sample

	Collision	Grounding	Contact
HARDER	832	312	35
GOALDS	184	160	4
database	**1016**	**472**	**39**

In the below Figure 1, the distribution of the GOALDS database ship types is shown.

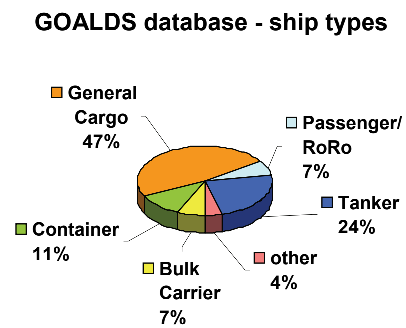

Fig. 1: GOALDS Database - Ship types

The analysis of the updated collision damage data of the GOALDS database did not lead to significant changes in the resulting probabilistic distributions for the collision damages, as laid down in SOLAS 2009. We focus therefore herein our attention on the new findings related to the grounding damages.

ANALYSIS OF GROUNDING DAMAGE CHARACTERISTICS

The statistical analysis of grounding damage data collected in the GOALDS database had originally two main objectives, namely first the development of a probabilistic model for grounding damage characteristics (position and dimensions) and secondly to review, in parallel, present SOLAS requirements for minimum double bottom height and bottom damage dimensions (Ch. II-1 Part B-2 Regulation 9 in IMO SOLAS Consolidated Edition 2009). Statistical analyses and post-processing of the obtained results were carried out in line with the above objectives by DINMA

(Bulian & Francescutto, 2010, 2011a,b); herein a brief overview of some of the main achievements is provided.

A Probabilistic Model For Grounding Damage Characteristics

One of the main objectives of GOALDS is the rational consideration of grounding damages in the damage stability assessment of passenger vessels. In the GOALDS database, however, the number of accidents involving specifically passenger vessels was found to be, in absolute value, extremely limited (22 cases out of a total of 359 cases). Thus, it was impossible to develop reliable models for grounding damage characteristics using only data specific to passenger vessels. Considering similar limitations in relation to the analysis of collision damages, for which damages for all types of ships were included in the construction of relevant probabilistic models, an alternative way was followed: ships were separated in two main categories, containing a statistically meaningful number of samples, namely on one side full type ships (bulk carriers and tankers, 138 cases) and on the other side more slender type of ships (to which, also passenger ships belong, 221 cases). For these two categories, different models were developed, accounting for the significant differences of the damage characteristic between these two groups. At the end, it was verified, considering the limits of the available data, that the behavior observed for passenger vessels is in line with the behavior observed for the non full sample ships.

A first exploratory data analysis led to the following observations and early conclusions:

- There were no data available for what concerns the transversal position of damage.
- The longitudinal position of the damage can be effectively described by the distribution of the forward end of damage normalized by the ship length (nondimensional model). It seems acceptable to consider this model as independent of the ship size. However, two different models should be used for the full and non full type of ships (including passenger ships), due to the fact that full ships have a tendency to show damages shifted significantly more forward with respect to non full ships (see later elaboration).
- The distribution of the vertical damage extent (damage penetration) did not show significant differences between full and non full ships and therefore the same model could be used for both categories. Neither a simple purely dimensional nor a simple purely nondimensional approach to the distribution of the damage penetration seems to be fully satisfactory.
- For what concerns the observed longitudinal extent of damage (damage length), full and non full ships do not show significant differences. Hence, the same modeling could be applied to both categories. In view of the observed behavior of data, such model could be developed in nondimensional form, i.e. by developing a distribution, independent of the actual ship size, for the damage length normalized by the ship length. Data for ships below about 80m in length show, however, some different behavior, with a tendency towards shorter damages. On a conservative basis, it is suggested to develop the model for the distribution of the dimensionless damage length by neglecting data for ships below 80m in length (which are anyway not addressed by the SOLAS Ch. II-1 damage stability provisions);
- The distribution for the recorded damage width (transversal damage extent) should be different between full and non full ships, with full ships showing in general wider damages than non full ships. A model for the distribution of the damage width normalized by the ship breadth (nondimensional model), which is ship-size-independent, but ship-type-dependent, can reflect the overall behavior of this data.

The observed major difference between full and non full type ships with respect to the distribution of the longitudinal position of damage is evidenced in the following. Figure 2 provides a comparison, between full and non full ships, of the cumulative distribution (CDF) of the longitudinal position of the forward end of damage normalized by the ship length ($X_{F,dam}/L_{pp}$). For sake of comparison, data of passenger vessels are also reported to show that they are in line with those associated with non full ships. It can be seen that a very significant part of damages have a forward end very close to the ship bow. For instance, for non full ships, about 41% of observed grounding cases have a forward end in a region extending from the bow up to 0.2Lpp aft of the forward perpendicular. This percentage increases to 63% in case of full ships. As a result of the discussion among GOALDS partners, it was conjectured that the observed differences between full and non full ships could be associated with the fundamental difference in the geometry of typical bottom shapes for these two categories, as shown in Figure 3 (Mains, 2010).

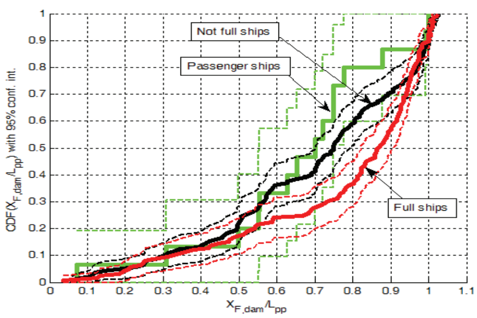

Fig. 2: Distribution of dimensionless longitudinal position of forward end of damage.

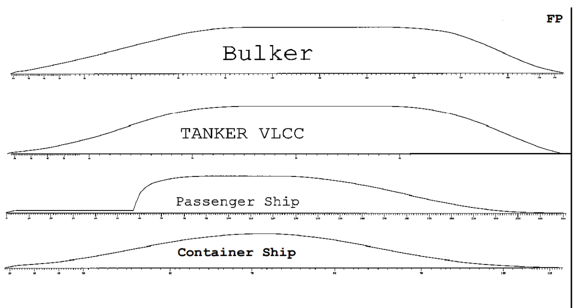

Fig. 3: Typical bottom lines for different ship types (Mains, 2010).

For what concerns the longitudinal extent of damage, it was found acceptable to describe it by means of a ship-size and ship-type independent distribution for the dimensionless damage length, i.e. for the damage length normalised by the ships length, to be obtained from data associated with ships having length not less than 80m. Such distribution, as estimated from the available data, is shown in Figure 4. It is interesting to note that data from passenger vessels are in line with the distribution of the dimensionless damage length observed for all ships. It is also worth underlining that there are a significant number of cases showing large dimensionless damage lengths. For instance, about 12% of cases are associated with a damage length in excess of 0.5Lpp. However, it must be reminded that the damage length, referred to herein, is the length of the entire damage extent, thus, in the frequent case of grounding accidents leading to *multiple holes*, it is the length of the "equivalent damage"[1].

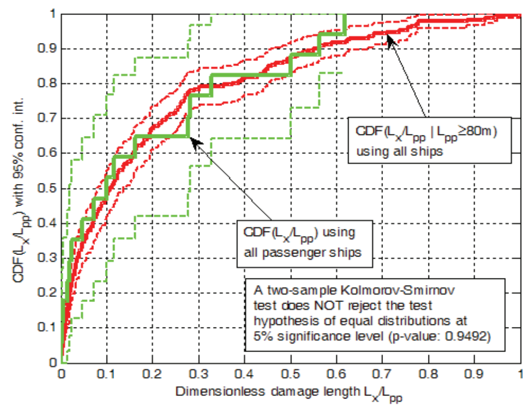

Fig. 4: Distribution of observed dimensionless damage length.

Regarding the vertical damage extent (damage penetration), Fig. 5 shows how the mean dimensionless damage penetration $E\{L_z/B\}$ depends on the ship breadth. It can be seen that there is a tendency towards a decrease of the mean dimensionless damage penetration, as the ship breadth, and thus the overall ship size, increases.

On the basis of the described exploratory data analysis (Bulian & Francescutto, 2010), explicit mathematical models for the distributions of grounding damage characteristics were developed (Bulian & Francescutto, 2011-a). In developing such models, particular attention was given to the theoretical background laid down by Pawlowski (2004, 2005) for what concerns the proper handling of random variables defined in non rectangular domains. Accordingly, the idea of the

[1] An *equivalent damage* covers the entire extent of the damaged area and has a mean width (considering all individual damages), this modelling ensures that recorded small damage lengths will not be overestimated within the statistical analysis.

"potential damage" was made explicit, i.e. the idea of a damage which can also partially extend outside the ship, but such that the distributions of the characteristics of that part of damage actually involving the ship are in accordance with the observed data from the GOALDS database. To do so, a box-shaped ship geometry needed to be assumed. In addition, box-shaped internal volumes needed to be assumed to develop a "p-factor-like" formulation for the flooding probability (Bulian & Francescutto, 2011-b). It is worth underlining that also the distributions behind the present SOLAS formulation for flooding probability due to collision implicitly, though not explicitly, refer to such "potential damage" and also assume a box-shaped ship with box-shaped compartments.

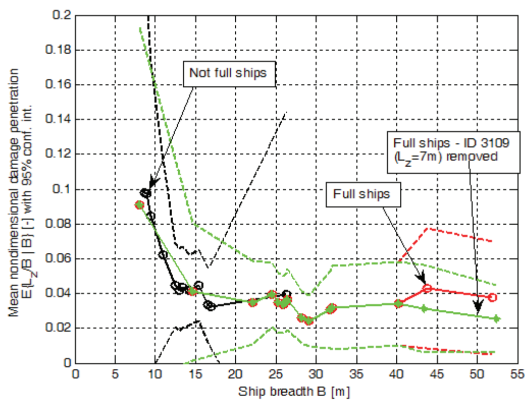

Fig. 5: Mean dimensionless damage penetration L/B as a function of the ship breadth.

Mathematical models for the distributions of damage characteristics were developed separately for three cases: full ships; non full ships; all ships. For each case, mathematical models were provided for the distributions of: the nondimensional longitudinal position of the forward end of damage, the nondimensional transversal position of the centre of the measured damage, the nondimensional potential damage length, the nondimensional potential damage width, the potential damage penetration. For the particular case of damage penetration, in accordance with the exploratory data analysis, the mathematical modeling has been assumed to be the same for all the considered cases, however two alternative models have been provided: a ship-size-independent and a ship-size-dependent model. All the details of the models and of their derivation can be found in (Bulian & Francescutto, 2011-a). Herein, we report only some typical example results.

Table 2 shows the modeling of the distribution for the dimensionless longitudinal position of the forward end of damage. The parameters of the mathematical model were obtained by a nonlinear least square fitting of the CDF estimated directly from the data. It is worth underlining, in particular, the change of the parameter α_2 between the group of full ships (6.042) and the group of non full ships (3.104). This difference reflects the fact that full ships, as already said, have a tendency to show damages shifted forward with respect to other ships.

Table 2 Models for the distribution of the nondimensional longitudinal position of the forward end of damage

Nondimensional longitudinal position of forward end of damage $\xi_{F,dam} = X_F / L_{ship}$, $\xi_{F,dam} \in [0,1]$			
Quantity	Full ships	Not Full Ships	All ships
$CDF(x)$	$\alpha_1 \cdot x + (1-\alpha_1) \cdot x^{\alpha_2}$		
$PDF(x)$	$\alpha_1 + \alpha_2 \cdot (1-\alpha_1) \cdot x^{(\alpha_2 - 1)}$		
α_1	0.303	0.325	0.382
α_2	6.042	3.104	5.054

Table 3 compares the modeling obtained for the distribution of the nondimensional potential damage length. It is worth underlining that, although the distribution of the actual (measured) damage length is the same between full and non full ships (in accordance with the exploratory data analysis), the models for the distribution of the potential damage length differ between the two groups due to the differences in the distribution of the longitudinal position of the forward end of damage. Table 4 reports the two proposed alternative models for what concerns the distribution of the potential damage penetration. The two models share the same functional form for the distribution of the potential damage penetration. However, in the ship-size-independent model, the maximum potential damage penetration $L_{z,p,max}$ has a fixed value of 4.5m, while in the ship-size-dependent model, the maximum potential damage penetration is considered to be dependent on the ship breadth and draught.

Table 3: Models for the distribution of the nondimensional potential damage length

Nondimensional potential damage length $\lambda_{x,p} = L_{x,p} / L_{ship}$, $\lambda_{x,p} \in [0,1]$			
Quantity	Full ships	Not Full Ships	All ships
$CDF(x)$	$\dfrac{\alpha_1 \cdot x^2 + \alpha_2 \cdot x}{x + (\alpha_1 + \alpha_2 - 1)}$		
$PDF(x)$	$\dfrac{\alpha_1 \cdot x^2 + (\alpha_1 + \alpha_2 - 1) \cdot (2 \cdot \alpha_1 \cdot x + \alpha_2)}{[x + (\alpha_1 + \alpha_2 - 1)]^2}$		
α_1	0.183	0.231	0.206
α_2	0.905	0.845	0.877

Assessment of SOLAS Regulation 9

The minimum height of double bottom for passenger ships and dry cargo ships is regulated in SOLAS through Regulation 9 in Chapter II-1, Part B-2. In addition, the ship must be able to withstand bottom damages, with specified dimensions, in those parts, if any, not fitted with a double bottom in accordance with the minimum double bottom height requirements. Moreover, the capability of withstanding bottom damages with specified dimensions must also be proved in case of unusual double bottom arrangements. Specific requirements are also provided for passenger ships fitted with large lower holds, by imposing an increased minimum double bottom height and an increased bottom damage penetration.

Some background information associated with the original development of requirements in Reg. 9 can be found in SLF47/INF.4, (2004), in which use was made of grounding data collected, but not analysed in details, in the project HARDER. Herein, the enhanced GOALDS database was considered and data analysed aiming at: • The quantification of the probability that a bottom damage could penetrate the inner double bottom if constructed according to minimum standard;

- The quantification of the probability that bottom damage dimensions could be larger than those specified by SOLAS Reg.9;
- The obtained results were also (approximately) compared with known probability levels, and therefore to some extent agreed at IMO, in the process of development of Reg.9 (SLF47/INF.4, 2004).

Table 4 Alternative proposals for modeling the distribution of the vertical potential damage extent (potential damage penetration). B [m] is the ship breath and T [m] is the ship draught

Dimensional potential damage penetration $L_{z,p}$ [m] , $L_{z,p} \in [0, L_{z,p,\max}]$		
Quantity	Ship-size independent	Ship-size dependent
$CDF(x)$	$\dfrac{\alpha_1 \cdot x}{x + L_{z,p,\max} \cdot (\alpha_1 - 1)}$	
$PDF(x)$	$\dfrac{L_{z,p,\max} \cdot \alpha_1 \cdot (\alpha_1 - 1)}{[x + L_{z,p,\max} \cdot (\alpha_1 - 1)]^2}$	
Parameters	$\alpha_1 = 1.115$ $L_{z,p,\max} = 4.5m$	$\alpha_1 = 1.170$ $\alpha_B = 0.636$ $k_{MB} = 0.503$ $L_{z,p,\max}(B) =$ $= \min\{k_{MB} \cdot B^{\alpha_B}, T\}$ with B in $[m]$

Table 5 shows the estimated probability that, as a consequence of a grounding accident, the inner bottom is penetrated, if constructed according to minimum SOLAS standards. In the table, L_z is the vertical damage extent (damage penetration), DBH_{S2009} is the minimum double bottom height according to standard requirements (Reg. 9.2) and $DBH_{S2009\text{-}LLH}$ is the increased minimum double bottom height relevant for passenger ships fitted with large lower holds (Reg. 9.9).

Table 5: Probability of bottom damage penetration exceeding SOLAS minimum double bottom height

Event	Estimated probability with 95% confidence interval	Details of the sample of data
$\Pr\{L_z > DBH_{S2009}\}$	27.3% [16.1% , 41.0%]	Samples: 55 Exceeding: 15
$\Pr\{L_z > DBH_{S2009\text{-}LLH}\}$	14.5% [6.5% , 26.7%]	Samples: 55 Exceeding: 8

In both estimations all available data for ships different from tankers and fishing vessels have been used, although in principle for the estimation of the probability Pr $\{L_Z > DBH_{S2009\text{-}LLH}\}$ only passenger vessels should have been considered. This approach is however reasonable considering the fact that, in the exploratory data analysis, there was no evidence of significant differences in the distribution of bottom damage penetration between full ships and non full ships (representative of passenger vessels).

For what concerns the estimation of the probability of exceedance of bottom damage dimensions as specified by SOLAS Reg.9, the analysis considered different events. The probability was estimated that each single damage dimension specified in Reg.9 is exceeded in case of a grounding accident. In addition, the probability was estimated that all damage dimensions specified in Reg.9 could be exceeded as a consequence of a grounding accident. Finally, the probability was estimated that al least one damage dimension resulting from a grounding accident could exceed the values specified by Reg.9. Results from this analysis are reported in Table 6. In the table, L_X is the damage length, L_y is the damage width and L_Z is the damage penetration, while the subscript "S2009" indicates the same quantities as specified by SOLAS Reg.9.8. It can be seen that the SOLAS dimension with the highest probability of exceedance is the damage length, followed by the damage penetration and finally by the damage width. A probability of about 11% has been estimated that, in case of a grounding accident, all the actual dimensions exceed those specified by SOLAS. At the same time a probability of about 64% has been estimated that, as a result of a grounding accident, at least one damage dimension could exceed SOLAS specifications.

Table 7 shows the probability of exceedance of grounding damage dimensions (length L_X, width L_y and penetration L_Z) according to present estimations together with some reference values taken from the discussion in SLF47/INF.4 (2004). The comparison should be regarded as approximate, though perfectly meaningful, since the considered events for which probabilities have been estimated are not exactly the same. The reported reference values are shown in order to provide an order of magnitude of what, according to the discussion in SLF47/INF.4 (2004), was implicitly considered as "acceptable" in the rule making process eventually leading to the derivation of Reg.9. With respect to the reference values from SLF47/INF.4 (2004) the estimated probability that the damage dimension could exceed the SOLAS assumption is, according to Table 7: larger for the length, significantly smaller for the width, and comparable for the penetration. According to the comparison reported in Table 7 the present analysis would not call for strong revisions of Reg.9, unless different acceptable probabilities of exceedance are set.

Table 6 Exceedance probabilities for bottom damage characteristics as prescribed in SOLAS

Event	Estimated probability with 95% confidence interval	Details of the sample of data
$\Pr\{L_x > L_{x,S2009}\}$	54.6% $[47.6\%, 61.6\%]$	Samples:205 Exceeding:112
$\Pr\{L_y > L_{y,S2009}\}$	18.2% $[11.5\%, 26.7\%]$	Samples:110 Exceeding:20
$\Pr\{L_z > L_{z,S2009}\}$	29.1% $[17.6\%, 42.9\%]$	Samples:55 Exceeding:16
$\Pr\left\{\begin{matrix}(L_x > L_{x,S2009})\wedge \\ \wedge(L_y > L_{y,S2009})\wedge \\ \wedge(L_z > L_{z,S2009})\end{matrix}\right\}$	11.1% $[3.7\%, 24.1\%]$	Samples:45 Exceeding:5
$\Pr\left\{\begin{matrix}(L_x > L_{x,S2009})\vee \\ \vee(L_y > L_{y,S2009})\vee \\ \vee(L_z > L_{z,S2009})\end{matrix}\right\}$	64.4% $[48.8\%, 78.1\%]$	Samples:45 Exceeding:29

Table 7 Approximate comparison of probabilities of exceedance between present analysis and information from SLF47/INF.4 (2004)

Event	Present analysis with 95% confidence interval	Approximate reference value from SLF47/INF.4
$\Pr\{L_x > L_{x,S2009}\}$	54.6% $[47.6\%, 61.6\%]$	43 % (Ref: §4.3)
$\Pr\{L_y > L_{y,S2009}\}$	18.2% $[11.5\%, 26.7\%]$	about 38%-40% (Ref: §4.5)
$\Pr\{L_z > L_{z,S2009}\}$	29.1% $[17.6\%, 42.9\%]$	26% (Ref: §4.8)

CONCLUSIONS

On the basis of the findings from the analyses carried out so far it is possible to provide some recommendations on the way ahead. There are indeed, basically, two ways for implementing the results (with further refinements) obtained up to now for the groundings, i.e. by following a probabilistic approach or by following a deterministic approach.

In case the "probabilistic way" would be followed, this could mean a fully probabilistic model for grounding damage characteristics, conceptually similar to that presently in SOLAS2009 for collision (side) damages. Such an approach could be derived in the framework of research applications on the basis of available data. The quality of the database seems to be, however, not sufficiently high for deriving a robust detailed fully probabilistic approach for bottom damage for regulatory purposes at this stage.

In case the "deterministic way" would be followed, this could mean modifying Reg.9 assumptions. This “global” approach could be more robust than the fully probabilistic approach and less affected by the problems identified in the undertaken analyses. Probabilities of exceedance of SOLAS bottom damage characteristics have been found to be, overall, quite in line with those estimated at the time of development of Reg. 9. Hence, the present analyses would not call for immediate and significant revisions of Reg.9, unless different acceptable probabilities of exceedance are set. There are, however, some indications that the present Reg.9 requirements could be more conservative for large ships and less conservative for small ships, and this aspect deserves additional attention.

In general it seems that for research purposes, the probabilistic approach could be suitable and should be pursued in the framework of the GOALDS project, and possibly, in the long term, for regulatory implementation. The possibility of using direct Monte Carlo simulations in a probabilistic framework should also be considered as a step forward with respect to present formulations based on p-factors.

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