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Evaluation of risk from raking damages due to grounding. Interim report

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Task and objective:

To provide an extensive analysis of the work performed towards:

a. The identification of historical raking damages and modelling of damages due to grounding
b. The amendment of the regulatory framework to include the assessment of survivability due to grounding

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0	2014-11-11	First draft			
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1 PREFACE

This report is a deliverable according to the Framework Service Contract Number EMSA/OP/10/2013. This is the third study commissioned by EMSA related to the damage stability of passenger ships. The previous studies focused on ro-ro passenger ships.

This study aims at further investigating the damage stability in an FSA framework in order to cover the knowledge gaps that have been identified after the finalization of the previous EMSA studies and the GOALDS project.

The project is separated in to 6 studies:

- Identification and evaluation of risk acceptance and cost-benefit criteria and application to risk based collision damage stability
- Evaluation of risk from watertight doors and risk based mitigating measures
- Evaluation of risk from raking damages due to groundings and possible amendments to the damage stability framework
- Assessment of cost effectiveness or previous parts, FSA compilation and recommendations for decision making
- Impact assessment compilation
- Updating of the results obtained from the GOALDS project according to the latest development in IMO.

The project is managed by DNV-GL and is established as a joint project which includes the following organisations:

Shipyards/designer:

Euroyards representing: Meyer Werft, Meyer Turku, STX-France and Fincantieri SpA

Knud E. Hansen AS

Operators:

Royal Caribbean Cruises

Carnival Cruises

Color Line

Stena Line

Universities:

National Technical University of Athens

University of Strathclyde

University of Trieste

Consultants:

Safety at Sea

Software manufacturer:

Napa OY

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4 ABBREVIATIONS

B00	damages to the ship's bottom, with a principally vertical direction of penetration (see § 8.3.1 for a detailed definition)
CDF	Cumulative Distribution Function
CN	Collision Accident
CONTIOPT	Formal Safety Assessment and Multi-objective Optimization of Containerships, NTUA-GL bilateral project, 2011-2013
CT	Contact Accident
DWT	Deadweight
EEDI	Energy Efficiency Design Index
GOALDS	"GOAL based Damage Stability", an EU funded research project
GISIS	Global Integrated Shipping Information System
GR	Grounding Accident
GRT	Gross Registered Tonnage
HARDER	"Harmonization of rules and design rationale", an EU funded research project
HSCC	High-Speed Craft Code
IACS	International Association Of Classification Societies
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
Marsden Grid	A system of 100 "squares" bounded by meridians and parallels at intervals of 10^{o} dividing the surface of the earth
MEPC	Marine Environment Protection Committee
MSC	Marine Safety Committee
NAPA	Naval Architectural Package
NTUA-SDL	National Technical University of Athens – Ship Design Laboratory
PDF	Probability Density Function
PMF	Probability Mass Function
RoPax	RoRo Passenger Ferry

S00	damages to the ship's side, with a principally horizontal direction of penetration (see § 8.3.2 for a detailed definition)
SIS Zone	The surface of the earth has been divided into thirty-one zones which broadly correspond to major areas of interest
SOLAS	International Convention for the Safety of Life at Sea

5 EXECUTIVE SUMMARY

Grounding accidents are traditionaly associated with bottom damages. While the risk from collision accidents has been the subject of extensive research and rigorous regulations over the years, the risk from grounding to conventional passenger and cargo vessels seems to have received less attention, assuming that fitting of a double bottom of ample height would be enough to provide protection and to ensure safety. Historical data, however, indicate that this design countermeasure can be, in some cases, insufficient, since a series of grounding accidents resulted in ship losses and a significant number of fatalities. As a matter of fact, in case of passenger ships the impact of grounding accidents to human life seems much more severe in comparision to that of collisions. A common characteristic of a series of severe grounding accidents (the most recent of them is the accident to Costa Concordia on the 13th of January 2012) is that the area of the hull breach is not at the bottom, where the double bottom could offer protection, but at the side. This is the reason why from the very beginning of the elaboration of Task 3 it was decided that it was imperative to take this type of damages into consideration. A proposal for a possible regulatory framework assesing survivability of passenger ships in damaged condition due to a grounding or contact accident has been formulated, based on the probabilistic approach. In this respect, considering the particular characteristics of hull breaches resulting from groundings or contacts in comparison to those from collisions, a new methodology is adopted for the evaluation of the probability of a particular damage case (the so-called p-factor) in contrast to the zonal approach used in SOLAS 2009 regulations for the collision damages. Since this type of damages (side damage due to grounding) was not considered in previous studies of grounding accidents, a thorough review of past accidents has been performed to develop/update relevant accidents databases. The collected data has been used for the elaboration of probabilistic model for side damage characteristics. Based on the developed formulation, a dedicated software tool has been developed within the NAPA package, facilitating the evaluation of survivability of passenger ships considering both types of damages (i.e. bottom and side damages).

The present report outlines the work performed in Sub-tasks 3.a and 3.b of the project. The structure of the main part of this report consists of the following sections:

- Regulatory Framework: This section considers the two alternative approaches for the assesment of survivability of passenger ships in damaged condition due to a grounding or contact accident, i.e. the deterministic and the probabilistic approach, and presents the reasoning behind the selection of the probabilistic approach as the adequate basis for the development of a new regulatory framework. Furthermore, this section reports information from some existing IMO regulations (SOLAS, HSC Code, MARPOL) with reference to the way of addressing the risk from grounding.

- Modelling of damages: In this section the description of the two types of damages considered in this study (i.e. bottom – B00 - and side – S00 - damages) is given in detail. Damages are assumed to have either vertical (for bottom damage) or transversal (for side damage) penetration. Two sets of parameters specifying the location and extend of the breach for each damage type are specified. In case of damages resulting to multiple breaches an artificial envelope damage is used, which corresponds to the region enclosing all the breaches.

- Development of accidents databases: This section presents the databases of accidents to passenger ships and containerships that have been collected in order to provide the basis for the development of the probabilistic model.
- Probabilistic model for bottom damage characteristics: This section describes a probabilistic model, developed in the GOALDS project and adapted in this study for the damage characteristics to passenger ships, as a result of a grounding accident resulting in bottom damages. Distribution functions for the characteristic values describing the location and extend of bottom damage are reported.
- Probabilistic model for side damage characteristics: This section describes a probabilistic model, developed in the framework of this study for the damage characteristics to passenger ships, as a result of a grounding or contact accident resulting in side damages. Based on the statistical analysis of the available data from past accidents, appropriate distribution functions for the characteristic values describing the location and extend of side damage are developed and discussed.
- Probabilistic framework: This section describes the probabilistic framework envisioned in this study. The framework aims at determining an attained subdivision index associated with survivability to grounding and contact accidents resulting in hull breach and water ingress. To this end, two factors are necessary: the probability of flooding a (group of) compartment(s), and the conditional probability of surviving to the specified "damage case". With reference to the probability of survival, the so-called "s-factor" from SOLAS 2009 is employed. With reference to the probability of flooding a certain (group of) compartment(s), the so-called "p-factor", the envisioned approach is based on a "direct" evaluation of p-factors. The "direct approach" for the evaluation of "p-factors" is based on the random generation of a large number of breaches, each one with an associated probability of occurrence, according to the underlying statistics of the breach characteristics, in order to identify the potential "damage cases" and to determine the probability of occurrence associated with each specific damage case (i.e. the "p-factor"). Combining "p-factors" with associated "s-factors" allows the determination of an attained subdivision index.
- Development of the Software Tool: A dedicated Software Tool, developed in the course and for the purpose of this study within the NAPA package, is described. The tool can treat both type of damages (bottom damages and side damages). These two types of damages are treated sequentially, resulting in two different A-indices. An option has been added, allowing the use of SLF 55 proposal for the calculation of the "s-factor" for the case of RoPax ships. Two different alternatives have been implemented: the software tool generates automaticaly the required number of hull breaches or reads them from a special input file. User instructions and modelling considerations before using the tool are presented. The alternative ways of using damage stages, openings, cross-flooding connections, up-flooding connections and A-class bulkheads are presented.

6 ABSTRACT

Grounding accidents are traditionaly associated with bottom damages. While the risk from collision accidents has been the subject of extensive research and rigorous regulations over the years, the risk from grounding to conventional passenger and cargo vessels seems to have received less attention, assuming that fitting of a double bottom of ample height would be enough to provide protection and to ensure safety. Historical data, however, indicate that this design countermeasure can be, in some cases, insufficient, since a series of grounding accidents resulted in ship losses and a significant number of fatalities. As a matter of fact, in the case of passenger ships the impact of grounding accidents to human life seems much more severe in comparision to that of collision. A common characteristic of a series of severe grounding accidents (the most recent of them is the accident to Costa Concordia on 13 January 2012) is that the area of the hull breach is not at the bottom, where the double bottom could offer protection, but at the side. This is the reason why from the very beginning of the elaboration of Task 3 it was decided that it was imperative to take this type of damage into consideration. A proposal for a possible regulatory framework assesing survivability of passenger ships in damaged condition due to a grounding or contact accident has been formulated, based on the probabilistic approach. In this respect, considering the particular characteristics of hull breaches resulting from grounding or contact accidents, in comparison to those from collision, an innovative methodology is adopted for the evaluation of the probability of a particular damage case (the so-called p-factor) in contrast to the zonal approach used in SOLAS 2009 regulations for the collision damages. Since this type of damages (side damage due to grounding) was not considered in previous studies of grounding accidents, a thorough review of past accidents has been performed to develop/update relevant accidents databases. The collected data has been used for the elaboration of probabilistic model for side damage characteristics. Based on the developed formulation, a dedicated software tool has been developed within the NAPA package, facilitating the evaluation of survivability of passenger ships considering both types of damage (i.e. bottom and side damage).These two types of damages are treated separately, resulting in two different A-indicies. An option has been considered, allowing the use of SLF 55 proposal for the calculation of the s-factor for the case of RoPax ships.

7 INTRODUCTION

Past and recent accidents have shown that grounding accidents can potentially result in catastrophic consequences; this being particularly true when speaking of passenger vessels, for which the risk to be accounted for is the potential loss of lives.

Present SOLAS probabilistic damage stability regulations for passenger and (dry) cargo vessels – so called SOLAS 2009 – are based on the assumption that a breach, resulting in the ship flooding, is created by a side damage due to collision. The underlying distributions of damage characteristics have been developed, originally, in the framework of the EU-funded HARDER project [25], and have been later been adapted as a result of discussion at IMO [18], [19], [20], [15] and [17].

The present SOLAS regulations for passenger and cargo ships do not specifically address the case of grounding damages within the probabilistic framework. Safety with respect to bottom grounding is addressed, instead, in a deterministic framework through Chapter II-1 - Regulation 9 "Double bottoms in passenger ships and cargo ships other than tankers". Regulation 9 [24], which was developed starting from statistics of grounding damages [21], provides minimum double bottom requirements and specifies deterministic bottom grounding damage characteristics to be used for survivability assessment in case of vessels with unusual bottom arrangements.

As a result, a dyscrasia exists in present SOLAS rules between the applied probabilistic framework for collision-related survivability, and the applied deterministic framework for grounding-related survivability. Furthermore, SOLAS Reg.9 only deals with grounding damages assumed to penetrate the vessel vertically, from the ship bottom. However, as both historical data and also recent accidents show, grounding damages can result also in a damage on the side of the vessel extending partially or totally above the double bottom. Damages on the side of the vessel can also be the result of the contact with fixed or floating objects. Such type of damages (i.e. side damages due to grounding) are presently not represented within the SOLAS regulatory framework for passenger vessels.

Since the year 2000, six cases have been recorded, resulting to the total loss of a passenger ship following a contact or grounding accident:

- Year 2000 – *EXPRESS SAMINA*: On Tuesday September 26, 2000, late afternoon, the Greek Passenger/Ro-Ro ferry *Express Samina* left the port of Piraeus heading to the island of Paros, the first on her route to the island of Lipsi. The vessel was reported carrying 533 persons on-board (472 passengers and 61 crewmembers), 17 trucks and 34 cars.

  While approaching the island of Paros, the ship deviated from the actual route and hit the rocks of Portes, located outside the entranceways to the port of Paros. The impact of the ship with the rocky islet was on the starboard side, resulting to three raking damages on the ship's outer shell, below and above the waterline level. Two of these damage openings were of particular significance for the flooding process, and the later sinking of the ship. The vessel sunk within half an hour, leading to death of 80 passengers and crewmembers. The impact to regulatory framework was an extension of Stockholm Regional Agreement to the South European Waters. EU Directive 2003/25/EC.

- Year 2007 – *SEA DIAMOND*: On April 5, 2007, the Passenger ship *SEA DIAMOND* ran aground on a volcanic reef east of Nea Kameni, within the caldera of the Greek island of Santorini. Because of the impact, there was loss of watertight integrity, resulting to ship's listing up to 12 degrees, starboard side. The accumulation of water led to the ship sinking after 27 hours from the initial hitting, leaving two passengers missing and presumed dead.

- Year 2007 – *EXPLORER*: On 23 November 2007, the Liberian registered, passenger vessel *EXPLORER*, sank in a position 25 miles southeast of King George Island. All 54 crewmembers and 100 passengers abandoned the ship safely. The vessel sank after striking ice and sustaining damage to the hull.

- Year 2008 – *PRINCESS OF THE STARS*: The RoPax ship *PRINCESS OF THE STARS* left the port of Manila on June 20, 2008, en route to Cebu City. While en route, the ship encountered the fierce winds and massive waves of Typhoon "Fengshen", which had been sweeping through the region, but were not expected to cross the ferry's path. The vessel sustained engine failure and stranded. As a result, there was a loss of watertight integrity below the waterline and the ship capsized in South China Sea, with 523 reported fatalities and 308 missing persons.

- Year 2009 – *ARIAKE*: The RoPax *Ariake*, travelling from Tokyo in high winds, developed a 22 degree list due to a large scale cargo shift induced by large rolling in stern quartering waves, ran aground and subsequently capsized at Mihama, Mie, Japan. All persons on board (7 passengers and 21 crewmembers) were safely rescued.

- Year 2012 – *COSTA CONCORDIA*: The Cruise vessel *Costa Concordia* struck a submerged rock in the Secca di Mezzo Canal, off the Isola del Giglio. It sustained severe damage to the port side of the hull near the engine room, took water, developed list to starboard side and partially capsized. Eventually, 32 lives were lost in the accident.

Considering the importance of grounding accidents for the safety of passenger ships, in the framework of the EU-funded (FP7) GOALDS project, an exploratory data analysis was carried out on historical data assumed to be associated with bottom grounding damages [27], [7]. As a result of this statistical analysis, a probabilistic modelling for grounding damage characteristic was developed [8]. Such probabilistic model was then used to develop a partially analytical formulation for "p-factors" [5]. However, concerns were expressed in [5] regarding the practical applicability of a zonal approach in case of bottom damages due to grounding. Citing, indeed, from [5]: "...concerns exist regarding the application of this approach *[the approach based on analytical p-factors]* to ship geometries and associated subdivisions which significantly differ from a box shell with internal box shaped volumes. As an alternative to the p-factor formulation it could be suggested to explore with more efforts the idea of a determination of probabilities of flooding of internal volume with generic shapes by means of direct Monte Carlo approaches. Such approach would be much more general, although it requires a careful definition of the domains of generation of the random damages and it suffers from sampling randomness". Some preliminary indications on how to proceed in this direction were given in the framework of the GOALDS project [6], but have not been practically applied during GOALDS.

At the same time, the GOALDS project did not address the case of damage due to grounding resulting in side damages extending partially or totally above the double bottom. However, such types of damages are actually occurring in real accidents and, in order to provide a sound regulatory framework, it is necessary to take them into account.

Starting from present SOLAS regulations, and considering the work carried out so far within the GOALDS project, results are reported herein regarding the work carried out towards the development of a fully practically applicable probabilistic methodology for the evaluation of risk due to grounding damages for passenger vessels. The work carried out is structured as follows:

- Development of a relevant database of grounding accidents and associated damage characteristics;
- Development of geometrical characterisations for grounding damages resulting in vertical (bottom damage type) or horizontal (side damage type) penetration;
- Adaptation and use of GOALDS probabilistic model for bottom damages;
- Development of a specific probabilistic model for side damages;
- Development of a procedure for the determination of the probability of flooding of (groups of) compartments;
- Determination of a procedure for the assessment of survivability using the s-factor from SOLAS 2009;
- Development of the software for the practical implementation of the developed procedure.

8 MAIN PART OF THE REPORT

8.1 Overview

Available accident statistics indicate an increase of risk from grounding to the safety of ships. The review, carried out in this study (Sec. §8.4), of accidents to passenger ships (RoPax, RoPax Rail, Cruise Ships and Pure Passenger ships exceeding 1,000 GT and 80 m in length) built on or after 1982, in the period from 1990 to 2013 resulted in 136 collisions and 126 groundings. Among them, 23 collisions (17%) suffered major damages, while there was no total loss or a ship being broken up as a result of the accident. In case of grounding, 56 ships (44%) suffered major damages, four ships were lost and one was broken up. Regarding the impact on human life, collision accidents resulted in four fatalities (all of them from one accident, when a passenger ship was struck by a bulk carrier), while the following fatalities were recorded as a result of groundings: 32 persons killed or missing in the Costa Concordia accident and 2 persons missing in the Sea Diamond accident (both were large cruise ships) and 831 persons killed or missing from the sinking of the Princess of the Stars. The latter was a RoPax ship that capsized and sank in South China Sea in 2008 while sailing in the middle of a Typhoon. It was claimed that the ship reported that it faced engine troubles and run aground, while later on it listed and capsized.

Despite the importance of grounding accidents, historically, damaged stability regulations are mostly focusing on the collision damages, while damages from grounding accidents have been comparatively overlooked. Over the years, stability regulations for ships in damaged collision following a collision accident have been the subject of extensive investigation, research and debate. As a result, the new harmonized damaged stability regulation for (dry) cargo and passenger ships, based on the probabilistic framework came into force with SOLAS 2009. According to SOLAS 2009, the basic requirement to ensure safety of ships against grounding accidents is the construction of a double bottom "*extending from the collision bulkhead to the afterpeak bulkhead, as far as this is practicable and compatible with the design and proper working of the ship*" at or above a minimum height from the keel line (SOLAS, Chapter II-1 - Part B-2 - Regulation 9 "Double bottoms in passenger ships and cargo ships other than tankers" [24]). However, available statistics indicate that, the probability of penetrating the double bottom in case of a grounding accident is far from being negligible. Based on the GOALDS statistics [7], the probability of exceedance of the SOLAS 2009 standard double bottom height is equal to 27.3% (95% confidence interval: [16.1%,41.0%]), while the probability of exceedance of the increased double bottom height, in case of passenger ships with large lower holds, is 14.5% (95% confidence interval: [6.5%,26.7%]). In addition, in a series of grounding accidents with severe impact on human life and on the ship itself, the hull breach did not occur at the bottom area, where the double bottom could offer some protection, but at the side of the ship. This was the case of *Express Samina* in 2000 with 81 fatalities, *Sea Diamond* in 2007 with two persons missing and *Costa Concordia* in 2012 with 32 persons killed. Despite of the higher impact of this type of accidents, there is no provision in SOLAS 2009 for the effective protection of ships, not even for large RoPax or Cruise ships, carrying thousands of passengers. In contrast to SOLAS 2009, in the High Speed Craft Code [22] the importance of this type of accidents is realized, and stability requirements in case of side racking damages were included.

From the very beginning of the elaboration of Task 3 it was decided that it is imperative to include two distinct types of damage into consideration, i.e. bottom damage and side damage, which are treated separately. A proposal for a regulatory framework assessing survivability of passenger ships in damaged condition due to a grounding or contact accident has been formulated, based on the probabilistic approach. A methodology is developed for the evaluation of the probability of a particular damage case (the so-called "p-factors") which is not based on the zonal approach used in SOLAS 2009 regulations for the collision damages. Since side damages were not considered in previous studies of grounding accidents, a thorough review of past accidents has been performed to develop/update relevant accident databases. The collected data has been used for the elaboration of a probabilistic model for side damage characteristics. Based on the developed formulation, a dedicated software tool has been developed within the NAPA package, facilitating the evaluation of survivability of passenger ships considering both types of damage (i.e. bottom and side damages).

8.2 Regulatory Framework

With particular reference to buoyancy and stability in damaged condition, safety related regulations aim at ensuring a minimum level of safety for all vessels complying with them. Regulators try to achieve this goal by imposing appropriate technical requirements through regulations, and such technical requirements can have a significant impact on the design of the vessel. The constraints imposed by regulations become even stronger when the space for alternative design solutions is not provided, or it is limited (for instance due to lack of guidelines or experience). It is therefore evident that the rule-development process has a fundamental impact on the characteristics of future designs, and due attention is to be paid when developing new, or amending existing, regulations. In some cases, technically sound but not sufficiently flexible regulations can lead to a sort of standardization of some design features, thus limiting the design flexibility and potentially impairing competitiveness of possibly innovative and effective design solutions.

Regulations intended to be applied to a large population of vessels (as it is the case of SOLAS-related regulations) are always designed having in mind the need for them to be "simple enough". At the same time, however, the interpretation of the adjective "simple" changes as the cultural and technical background evolves. As a result, regulations recently developed and assumed to be sufficiently "simple" for a wide application, would have been referred in the past as "impractical" or just "too complex" for being acceptable.

A typical choice which is to be made when developing stability regulations is whether to implement deterministic or probabilistic approaches. Both options have pros and cons, and the selection of one option instead of the other is a matter of case-by-case judgement. Deterministic approaches are often easier to be developed as regulations, and then to be applied in the design. At the same time, it is today known that deterministic approaches tend to reduce design flexibility and tend to provide a reduced (sort of summarised) view of the addressed problem. On the other side, probabilistic approaches tend to be more complex, thus requiring more efforts in the initial rule-development process and in the subsequent technical implementation. At the same time, probabilistic approaches are known to allow a wider, more comprehensive and more realistic view of the addressed problem, and they tend to increase design flexibility, with the positive result of rewarding clever original design solutions. From a technical and scientific perspective, the modern tendency is to try being fully probabilistic, or at least to embed a sound underlying probabilistic background, supporting a simplified deterministic framework.

One of the objectives of Task 3 is the development of proposals for a sound and practically applicable regulatory framework, able to address grounding damages, possibly resulting in long and shallow damages (raking damages), considering the possibility that such damages extends partially or totally above the double bottom. In the framework of such a development, it is obviously necessary to account for the aforementioned general concepts, and to take into account presently available regulations. To this end, in the following some relevant examples are considered of presently available IMO instruments dealing with undesirable effects coming from grounding accidents. Examples are reported in order to show which characteristics of damages are typically considered in such instruments (direction, length, penetration, etc.) and to show the type of used approach.

In line with the present evolution of knowledge and practice regarding rule-development taking into account risk-assessment, and with particular reference to stability-related-rules, it is herein considered that the more rational way to address the problem of survivability following a grounding accident is by trying to develop a regulatory framework based on probabilistic concepts. In case such an approach were found to be not sufficiently practical, the collected information and the developed tools could then still be used to define a transparent deterministic approach, based on clear probabilistic basis.

8.2.1 SOLAS

In case of presently applicable SOLAS regulations for passenger and cargo vessels, safety against consequences coming from a grounding damage is provided by Chapter II-1 - Part B-2 - Regulation 9 "Double bottoms in passenger ships and cargo ships other than tankers" [24]. In this context, the basic level of safety is provided by specifying a reference minimum height of double bottom, which the Administration may require to be increased in case of large lower holds for passenger ships. Such requirements are summarised in Table 1 (see also [7]).

Table 1: Minimum height of double bottom – SOLAS Ch.II-1, Part B-2, Regulation 9.

Required standard minimum double bottom height (*h*)
$h = \frac{B}{20}$ (where *B* is the ship breadth) In no case is the value of *h* to be less than 760 mm, and need not be taken as more than 2 000 mm
In case of large lower holds in passenger ships, the Administration may require an increased double bottom height

of not more than B/10 or 3 m, whichever is less, measured from the keel line. Alternatively, bottom damages may be calculated for these areas, in accordance with paragraph 8 [of Reg.9, i.e. *damage characteristics to be taken into account for alternative calculations in case of unusual bottom arrangements in a passenger ship or a cargo ship*], but assuming an increased vertical extent.

However, according to II-1/B-2/Reg. 9, it is possible to have "unusual bottom arrangements" not fulfilling the specifications in Table 1. In such case it shall be demonstrated that the ship is capable of withstanding bottom damages having specific deterministic dimensions and positioned in the part of the bottom of the vessel affected by the unusual arrangement. Such deterministic dimensions are reported in Table 2. Compliance, in terms of survivability, is to be proved by demonstrating that the s-factor is not less than 1 for all service conditions.

Table 2: Bottom damage characteristics according to SOLAS Ch.II-1, Part B-2, Regulation 9.

L: ship length B: ship breadth		For $0.3L$ from the forward perpendicular of the ship	Any other part of the ship
Longitudinal extent	$[m]$	$\min\left\{\frac{1}{3}L^{2/3}, 14.5m\right\}$	
Transverse extent	$[m]$	$\min\left\{\frac{B}{6}, 10m\right\}$	$\min\left\{\frac{B}{6}, 5m\right\}$
Vertical extent, measured from the keel line	$[m]$	$\min\left\{\frac{B}{20}, 2m\right\}$	
In case of large lower holds in passenger ships the Administration may require an increased vertical extent. If any damage of a lesser extent than the maximum damage specified above would result in a more severe condition, such damage should be considered.			

Some comments can be done regarding the framework set up in Reg.9:

- The framework itself is deterministic, in terms of damage characteristics. However, the origin of selected damage characteristics is to be sought in a statistical analysis of historical data [21][7]. On the other hand, the selection of the B/20 ratio for the minimum double bottom height seems to be the result of a combination between statistical analysis of historical data for damage penetration and data regarding double bottom height for "as-built" passenger and cargo vessels [21].
- It is implicitly assumed that the specified height of double bottom is sufficient to provide acceptable safety in case of bottom grounding;

- Damages are assumed to have a vertical penetration. As a result, side damages associated with grounding are not considered;
- In case of unusual bottom arrangements, residual stability in damaged condition is to be checked, according to the standard SOLAS 2009 s-factor formulation.
- The case of shallow damages (raking damages) is not explicitly accounted for, because the requirements are based on the specification of maximum damage extent. However, shallow damages are implicitly accounted for by the regulation when requiring that damages of a lesser extent than those specified, are to be taken into account in case they would result in a more severe condition.

8.2.2 2000 HSC Code

In the framework of the "2000 HSC Code" [22] (simply "HSC Code" in later referencing herein), sufficient buoyancy and stability following damage is to be proved by complying with Part A - §2.6 and Part B - §2.13 (in case of passenger craft). The HSC Code considers different types of damage, namely:

- Side damage;
- Bow and stern damage;
- Bottom damage in areas vulnerable to raking;
- Bottom damage in areas not vulnerable to raking.

In dealing with survivability after damage, the HSC Code uses a deterministic framework, where specified damage dimensions are to be used for stability assessment. Damages of lesser extent than those specified, are to be considered whenever they lead to more severe conditions, in line with a classical "worst case scenario" approach. Valuable information regarding the development process of, and some of the underlying assumptions in the HSC Code requirements can be found in [1].

The HSC Code does not explicitly specify the source of the damage to be considered, i.e. whether the specified damage is assumed to be due to collision, contact or grounding, and only the damage position and dimensions are specified. It seems however logical to assume grounding as the underlying source of damage. Among the damages considered by the HSC Code, bottom damages in areas vulnerable and not vulnerable to raking are those assumed herein to be more relevant to grounding accidents. As a result, the assumed characteristics for such type of damage are described in more details in the following.

In the HSC Code, bottom damages are damages extending below the waterline. Two types of underwater hull areas are identified (see Figure 1), namely:

- Area vulnerable to raking;
- Area not vulnerable to raking.

Generally speaking, the lower part of the hull is assumed to be vulnerable to raking, while the higher part of the hull is not assumed to be vulnerable to raking. The part of the hull that is vulnerable to raking is larger in the forward part of the vessel, and smaller in the aft part. Also, for the area to be vulnerable to raking, it must be in contact with water at 90% of maximum speed.

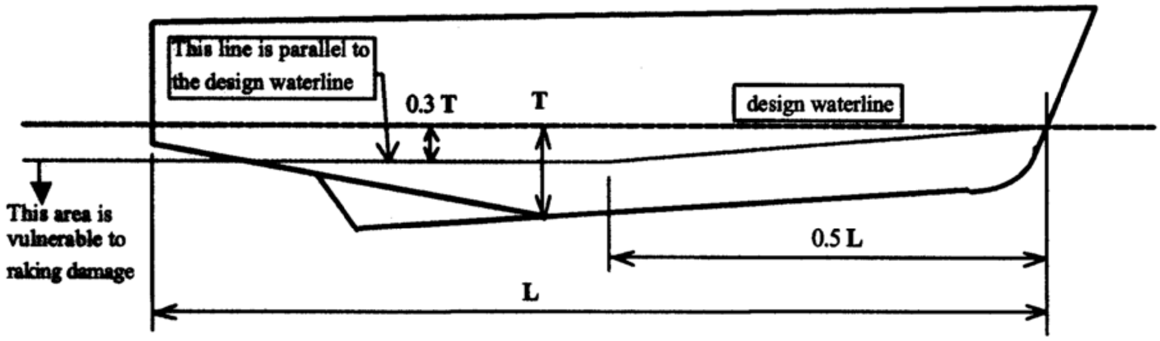


Figure 1: Areas vulnerable / not vulnerable to bottom raking damage (from [22]).

The characteristics of the damage depend on the area where the damage is to be applied (and, partially, on whether the craft is a "category B craft" or not). A summary of bottom damage characteristics is reported in Table 3 in case of damages on the area vulnerable to raking, and in Table 4 in case of damages on the area not vulnerable to raking.

It can be noticed that the specified damage dimensions scale with the cube root of the hull volume. Such type of scaling, which is typical for high-speed craft, is not typically used for conventional cargo and passenger vessel. However, according to [1], the formulae have been derived by considering an approximate equivalence between ship length and $7.5 \cdot \nabla^{1/3}$, and between ship breadth and $1.0 \cdot \nabla^{1/3}$. The longitudinal extent of damage to be taken into account is larger in areas vulnerable to raking compared with areas which are assumed to be not vulnerable to raking. Considering the characteristics of presently built high speed craft, also the penetration is larger in the region vulnerable to raking compared to those assumed to be not vulnerable to raking. The girth length, however, is larger in case of regions not vulnerable to raking damage. In general, the extent of penetration taken into account in case of bottom damages, can be regarded as relatively small in absolute terms (e.g. max 0.5m in case of areas assumed to be vulnerable to raking). It must be said, however, that the reference penetration due to side damages in the HSC Code is specified as $0.2 \cdot \nabla^{1/3}$, i.e. ten times of that specified for bottom damages in areas not vulnerable to bottom raking damages, while keeping a damage length equal to $\min\left\{0.75 \cdot \nabla^{1/3}, \left(3m + 0.225 \cdot \nabla^{1/3}\right), 11m\right\}$ and specifying an unlimited vertical extent.

Table 3: Bottom damage characteristics in areas vulnerable to raking damage, according to 2000 HSC Code [22].

<table>
<tr><th>Damage characteristic</th><th>Specification</th><th>Notes</th></tr>
<tr><td>Longitudinal extent</td><td>Two different longitudinal extents shall be considered separately:

1) 55% of the length L, measured from the most forward point of the underwater buoyant volume of each hull;

2) A percentage of the length L, applied anywhere in the length of the craft, equal to 35% for craft where $L = 50m$ and over and equal to $(L/2+10)\%$ for craft where L is less than $50m$.

In addition, for category B craft, specific stability criteria are provided when assuming a longitudinal extent of raking damage equal to 100% of length L.</td><td></td></tr>
<tr><td>Penetration normal to the shell</td><td>$\min\{0.04 \cdot \nabla^{1/3}, 0.5m\}$</td><td rowspan="2">$\nabla$ is the volume of displacement corresponding to the design waterline (m^3).

Penetration or girth shall under no circumstances extend above the vertical extent of the specified area vulnerable to raking.</td></tr>
<tr><td>Girth along the shell</td><td>$0.1 \cdot \nabla^{1/3}$</td></tr>
<tr><td colspan="3">Raking damage shall be assumed to occur along any fore-and-aft line on the surface of the hull(s) between the keel and the upper limit of the area vulnerable to raking.

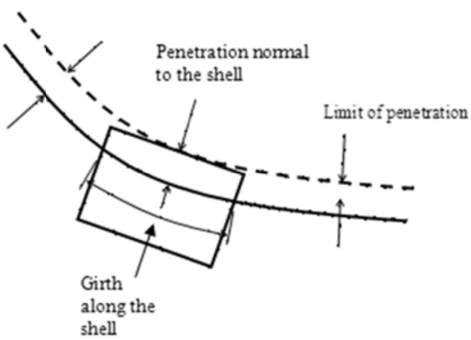
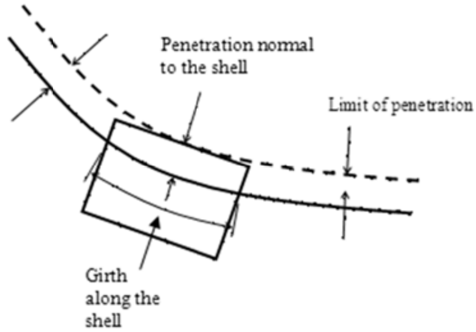
The shape of damage shall be assumed to be rectangular in the transverse plane as illustrated in the figure on the right. Damage is to be assumed at a series of sections within the defined longitudinal extent in accordance with the figure on the right, the mid-point of the damaged girth being maintained at a constant distance from the centreline throughout that longitudinal extent.

</td></tr>
</table>

Table 4: Bottom damage characteristics in areas not vulnerable to raking damage, according to 2000 HSC Code [22].

Damage characteristic	Specification	Notes
Length of damage in the fore-and-aft direction	$\min\left\{0.75\cdot\nabla^{1/3},\left(3m+0.225\cdot\nabla^{1/3}\right),11m\right\}$	∇ is the volume of displacement corresponding to the design waterline (m^3).
Depth of penetration normal to the shell	$0.02\cdot\nabla^{1/3}$	
Athwartships girth	$0.2\cdot\nabla^{1/3}$	
This applies to all parts of the hull(s) below the design waterline which are not defined as vulnerable to raking damage. The shape of damage shall be assumed to be rectangular in the plane of the shell of the craft, and rectangular in the transverse plane as illustrated in the figure on the right.		

8.2.3 MARPOL 73/78

Within the framework of MARPOL [23], and in particular within Annex I "Prevention of pollution by oil", the effect of a hull breach is directly or indirectly addressed in different regulations, aiming at providing sufficient safety against the occurrence of two main types of undesirable consequence of a damage, i.e.: loss of buoyancy and stability, and oil spill. However, due to the historical evolution of various regulations, and considering the inherent higher focus of MARPOL framework to pollution-related issues, consistency between regulations addressing consequences of hull breaches has not been totally maintained. As a result, different damage characteristics and calculation methodologies are considered by MARPOL when dealing with oil spill compared with those used when dealing with subdivision and damage stability requirements. Moreover, efforts towards the implementation of more advanced approaches (from a theoretical and technical point of view) have been mostly spent within the framework specifically dealing with the risk coming from oil spill. In addition to regulations and calculation methods explicitly addressing consequences of hull breaches in terms of oil spill or loss of buoyancy and stability, additional requirements related to minimum width of double hull and minimum height of double bottom are also present in the MARPOL framework, with applicability to either all ships or oil tankers, depending on the regulation.

Due to the dispersion of requirements related to consequences of hull breaches in different regulations of Annex I (particularly Reg.12A, Reg.19, Reg.23, Reg.24, Reg.25 and Reg.28) and associated additional IMO documents [13][14][16], it is therefore difficult to provide a comprehensive overview without entering in the details of each regulation and document. As a result, herein a summary is provided with the intention of reporting how MARPOL is, in particular, addressing the issue of damages due to grounding. For detailed information reference is to be made to the original sources [23][13][14][16].

8.2.3.1 Height of double bottom and width of double hull

Double bottom clearly prevents undesired consequences coming from bottom grounding damages. On the other hand, the presence of a double hull is beneficial both in case of side damages due to contact and grounding and also in case of those collision events resulting in relatively shallow penetrations. By interpreting the text of MARPOL, it seems that such requirements have been set with the primary intention of preventing oil spill, and not by having in mind, as a primary goal, buoyancy and stability in damaged condition. MARPOL requirements for double hull/double bottom are set in Annex I by Reg.12A "Oil fuel tank protection" (for all ships – addressing protection of fuel tanks) and in Reg.19 "Double hull and double bottom requirements for oil tankers delivered on or after 6 July 1996" (for oil tankers – addressing protection of cargo tanks). Such requirements provide minimum distances of fuel tanks (Reg.12A) or cargo tanks (Reg.19) from the shell of the vessel. A brief summary of the requirements is reported in Table 5. It can be noticed that, while the minimum height of double bottom scales according to the ship breadth, the minimum distance of fuel/cargo tanks from the shell side (i.e. the width of the double hull) scales according to the capacity of the oil fuel tanks or according to the deadweight of the vessel. It is worth noticing that the minimum height of double bottom in lieu of fuel tanks from Reg.12A, corresponds to the minimum height of double bottom in SOLAS Reg. 9 ([24] and see Table 1), while such distance is increased by Reg.19 in the region of cargo tanks.

Table 5: Minimum distances of fuel / cargo tanks from the shell according to MARPOL Annex I - Reg.12A and Reg.19 [23].

	Reg.12A (oil fuel tanks) ([1])	Reg.19 (cargo tanks)
Minimum distance of the tank from the bottom of the vessel (double bottom height)	$h = \frac{B}{20}$ $[m]$ but not more than 2.0m and not less than 0.76m. ([2])	$h = \frac{B}{15}$ $[m]$ but not more than 2.0m and not less than 1.0m. ([5])([6])
Minimum distance of the tank from the shell side of the vessel (double hull width)	$w = 0.4 + 2.4 \cdot \frac{C}{20000}$ $[m]$ but not less than 1.0m (or 0.76m for individual tanks with an oil fuel capacity of less than 500 m^3). ([3]) $w = 0.5 + \frac{C}{20000}$ $[m]$ but not more than 2.0m and not less than 1.0m. ([4]) Where "*C*" is the ship's total volume of oil fuel, including that of the small oil fuel tanks, in m^3, at 98% tank filling.	$w = 0.4 + 2.4 \cdot \frac{DW}{20000}$ $[m]$ but not less than 0.76m. ([7]) $w = 0.5 + \frac{DW}{20000}$ $[m]$ but not more than 2.0m and not less than 1.0m. ([8]) Where "*DW*" is the ship deadweight in tonnes. Wing tanks or spaces shall extend either for the full depth of the ship's side or from the top of the double bottom to the uppermost deck.

([1]) Alternative probabilistic methodology is available in Reg.12A based on accidental oil fuel outflow performance standard.

([2]) For ships, other than self-elevating drilling units, having an aggregate oil fuel capacity of 600m^3 and above.

([3]) For ships having an aggregate oil fuel capacity of 600 m^3 or more but less than 5000 m^3.

([4]) For ships having an aggregate oil fuel capacity of 5000 m^3 and over.

([5]) For oil tankers of 5000 tonnes deadweight and above. The requirement can be dispensed provided that the design of the tanker is such that the cargo and vapour pressure exerted on the bottom shell plating forming a single boundary between the cargo and the sea does not exceed the external hydrostatic water pressure.

([5]) For oil tankers of less than 5000 tonnes deadweight the minimum value can be reduced from 1.0m to 0.76m.

([7]) Allowed for tankers of less than 5000 tonnes deadweight. Alternatively the capacity of each cargo tank shall not exceed 700 m^3.

([8]) For oil tankers of 5000 tonnes deadweight and above.

8.2.3.2 Deterministic damage assumptions

Deterministic damages are specified by MARPOL Annex I, when considering oil spill (Reg.24, Reg.25 and Reg.26) and also when considering subdivision and damage stability requirements (Reg.28). Damage characteristics are specified separately for side damage and bottom damage. Furthermore oil tankers of 20000 tonnes deadweight and above delivered on or after

6 July 1996 have to comply with subdivision and damage stability requirements considering an additional type of damage, i.e. a bottom raking damage type, with specified characteristics.

Deterministic damage characteristics to be taken into account in the calculation of hypothetical oil outflow (Reg.24) partially differ from damage characteristics to be taken into account for subdivision and damage stability assessment (Reg.28) in respect to bottom damages, while deterministic side damage characteristics are the same in Reg.24 and Reg.28. Deterministic side damage characteristics are reported in Table 6, while a comparison of characteristic for deterministic bottom damage between Reg.24 and Reg.28 is reported in Table 7. It is to be noted that, in Reg.28, damages of lesser extent than that specified are to be considered when they lead to a more severe condition. Finally, Table 8 reports characteristics of the deterministic bottom raking damage, to be used in accordance with Reg.28, for calculations related to subdivision and damage stability for oil tankers of 20000 tonnes deadweight and above, delivered on or after 6 July 1996. It can be noticed that the assumed bottom raking damage is implicitly characterised by a shallow penetration, since it is assumed to breach only the outer hull of the vessel.

Table 6: Deterministic side damage characteristics according to MARPOL Annex I - Reg.24 and Reg.28 [23].

Longitudinal extent (length)	$\min\left\{\frac{1}{3}L^{2/3}, 14.5m\right\}$
Transverse extent (penetration)	$\min\left\{\frac{B}{5}, 11.5m\right\}$
Vertical extent (height)	From bottom, upwards without limit.
L [m]: ship length ; *B* [m]: ship breadth	

Table 7: Deterministic bottom damage characteristics according to MARPOL Annex I - Reg.24 and Reg.28 [23].

	Reg. 24 (related to calculation of hypothetical oil outflow from oil tankers)		Reg. 28 (related to subdivision and damage stability requirements for oil tankers)	
	For $0.3 \cdot L$ from the forward perpendicular of the ship	Any other part of the ship	For $0.3 \cdot L$ from the forward perpendicular of the ship	Any other part of the ship
Longitudinal extent (length)	$\frac{L}{10}$	$\min\left\{\frac{L}{10}, 5m\right\}$	$\min\left\{\frac{1}{3}L^{2/3}, 14.5m\right\}$	$\min\left\{\frac{1}{3}L^{2/3}, 5m\right\}$
Transverse extent (width)	$\min\left\{\frac{B}{6}, 10m\right\}$ but not less than 5m	$5m$	$\min\left\{\frac{B}{6}, 10m\right\}$	$\min\left\{\frac{B}{6}, 5m\right\}$
Vertical extent (penetration) (*)	$\min\left\{\frac{B}{15}, 6m\right\}$	$\min\left\{\frac{B}{15}, 6m\right\}$	$\min\left\{\frac{B}{15}, 6m\right\}$	$\min\left\{\frac{B}{15}, 6m\right\}$
L [m]: ship length ; *B* [m]: ship breadth (*) Measured from ship bottom, at centreline				

Table 8: Deterministic bottom raking damage characteristics according to MARPOL Annex I - Reg.28 [23].

	For ships of 75000 tonnes deadweight and above	For ships of less than 75000 tonnes deadweight
Longitudinal extent (length)	$0.6 \cdot L$ measured from the forward perpendicular	$0.4 \cdot L$ measured from the forward perpendicular
Transverse extent (width)	$\frac{B}{3}$ anywhere in the bottom	
Vertical extent (penetration)	Breach of the outer hull	
L [m]: ship length ; *B* [m]: ship breadth		

8.2.3.3 Probabilistic damage characterisation

Some of the requirements in MARPOL Annex I make reference to a probabilistic characterisation of side and bottom damage characteristics. Requirements based on the probabilistic approach, as the unique approach or as an alternative to the deterministic approach, are only dealing with oil spill. On the other hand, subdivision and damage stability requirements are based solely on the deterministic approach.

A probabilistic approach in accordance with MEPC.110(49) [13] can be used as an alternative to the double bottom and double hull specification of Reg.19 (see Table 5). On the other hand, a simplified probabilistic approach [14] is to be used in Reg. 23 "Accidental oil outflow performance", for oil tankers of 5000 tonnes of deadweight and above delivered on or after 1 January 2010. As an alternative to the simplified probabilistic approach embedded in Reg.23, the more sophisticated approach according to MEPC.110(49) [13] can be used as an equivalent alternative.

Also in the probabilistic approach, damages are split in two categories: side damages and bottom damages. According to MEPC.110(49) [13], side damages are assumed to be due to collision, while bottom damages are assumed to be due to grounding. Probability distributions for damage characteristics are explicitly reported in MEPC.110(49) [13]. Probability distributions are explicitly reported for the following damage characteristics:

- Side damage due to collision:
  - *Longitudinal location* – In terms of x = dimensionless distance from A.P. relative to the ship's length between perpendiculars;
  - *Longitudinal extent* – In terms of y = dimensionless longitudinal extent of damage relative to the ship's length between perpendiculars;
  - *Transverse penetration* – In terms of z_t = dimensionless transverse penetration relative to the ship's breadth;
  - *Vertical extent* – In terms of z_v = dimensionless vertical extent relative to the ship's depth;
  - *Vertical location* – In terms of z_l = dimensionless vertical distance between the baseline and the centre of the vertical extent z_v relative to the distance between baseline and deck level (normally the ship's depth)

- Bottom damage due to stranding:
  - *Longitudinal location* – In terms of x = dimensionless distance from A.P. relative to the ship's length between perpendiculars;
  - *Longitudinal extent* – In terms of y = dimensionless longitudinal extent of damage relative to the ship's length between perpendiculars;
  - *Vertical penetration* – In terms of z_v = dimensionless vertical penetration relative to the ship's depth;
  - *Transverse extent* – In terms of b = dimensionless transverse extent to bottom damage relative to the ship's breadth;
  - *Transverse location* – In terms of b_l = dimensionless transverse location of bottom damage relative to the ship's breadth;

The analytical expressions for the distribution of damage characteristics can be found in MEPC.110(49) [13]. Herein, graphs are reported using figures taken from MEPC.122(52) [14] for side damage characteristics (Figure 2) and for bottom damage characteristics (Figure 3).

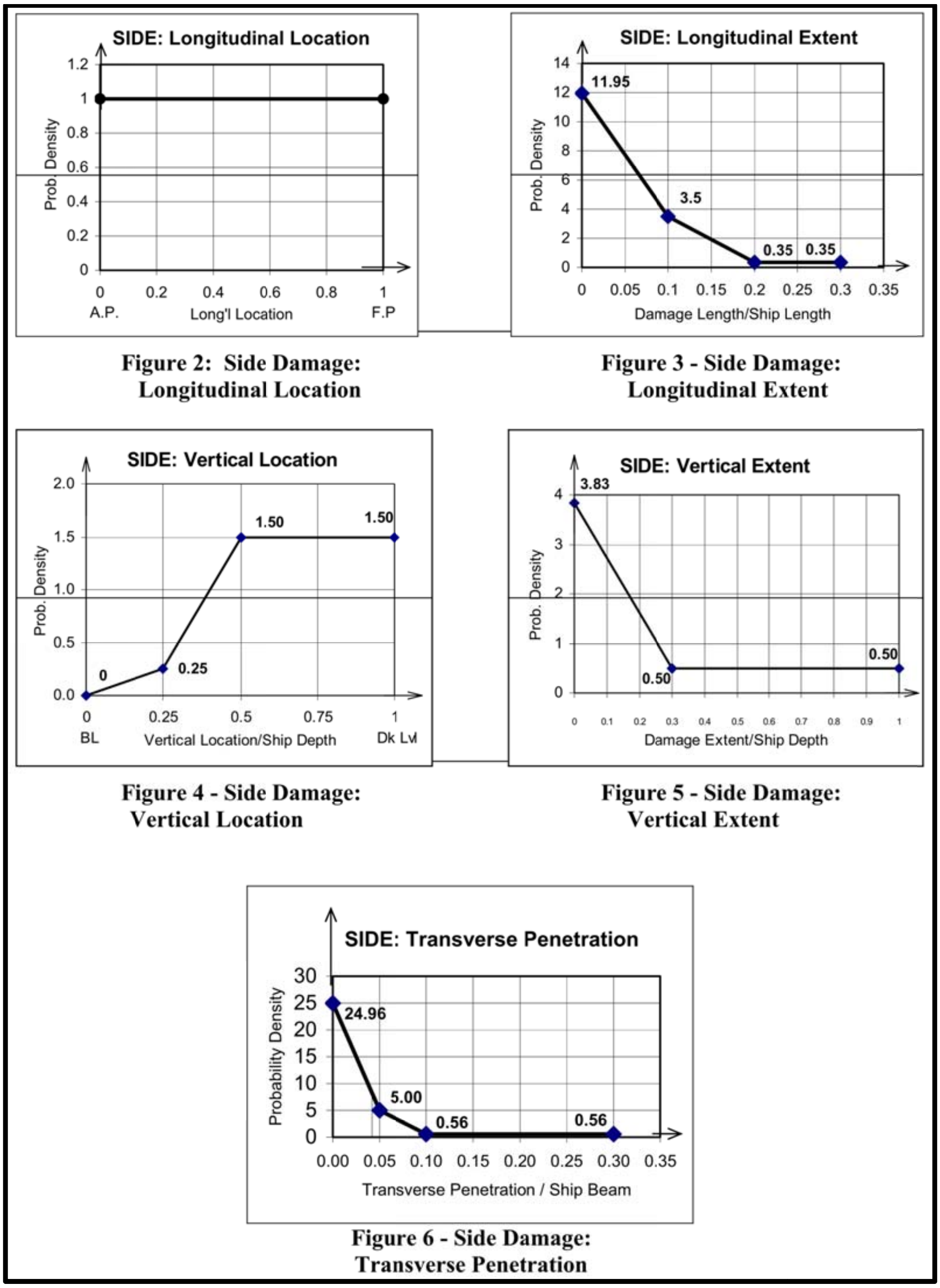


Figure 2: MARPOL – Probability density functions of characteristic of side damage due to collision for analyses related to oil spill according to MEPC.110(49) [13]. Figures taken from MEPC.122(52) [14].

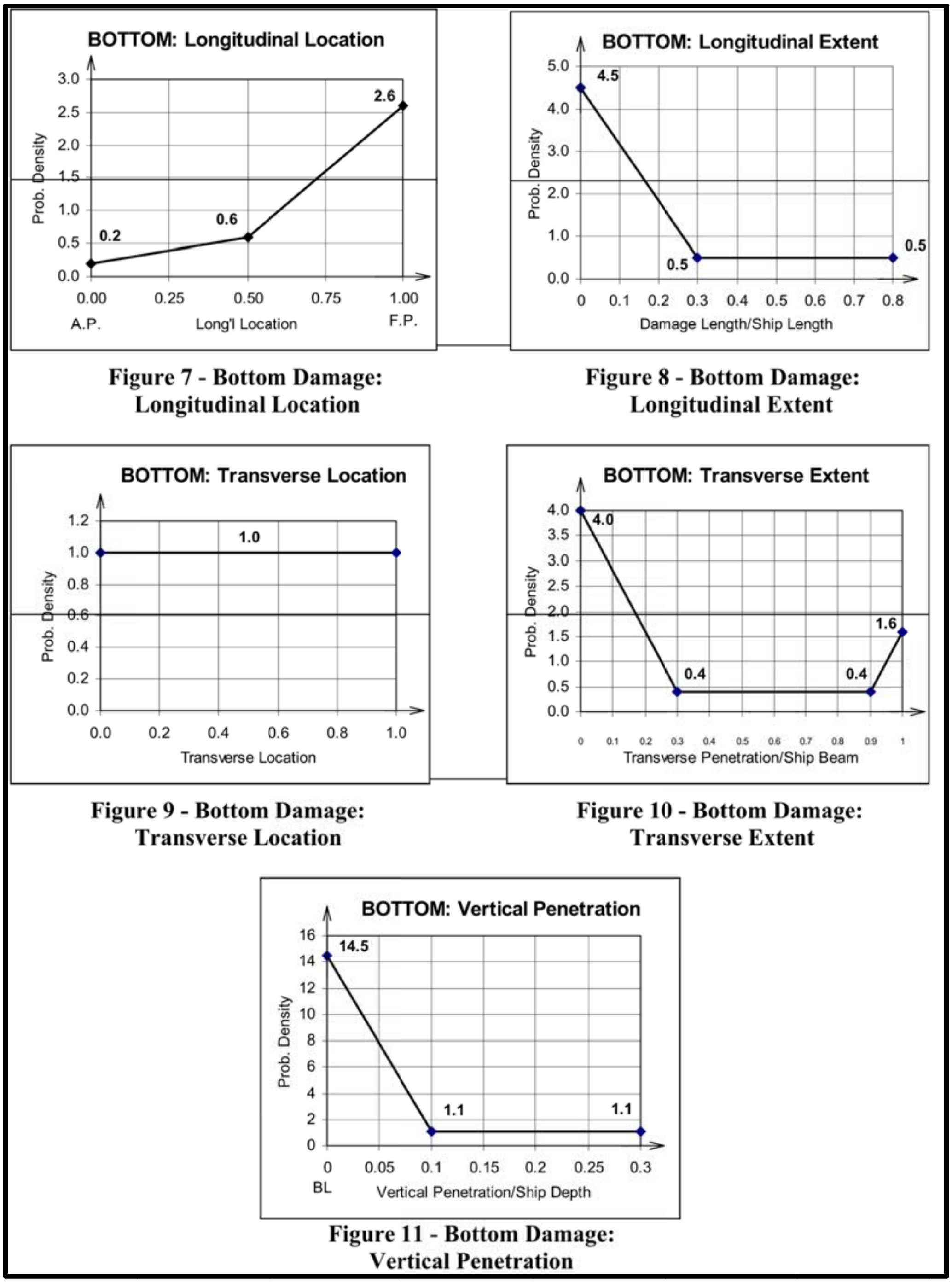


Figure 3: MARPOL – Probability density functions of characteristic of bottom damage due to stranding for analyses related to oil spill according to MEPC.110(49) [13]. Figures taken from MEPC.122(52) [14].

8.3 Geometrical modelling of damages

Damages due to grounding have, in general, complex shapes. However, it is very difficult to develop practically applicable models, suitable for design and regulatory purposes, handling complex generic damage shapes. For this reason it is necessary to introduce some simplifications, with the aim of developing practically applicable tools. Herein two classes of damages are considered, depending on the assumed principal direction of the penetration (vertical / horizontal), namely:

- Bottom damages, with primarily vertical penetration direction (Figure 4);
- Side damages, with primarily horizontal penetration direction (Figure 5).

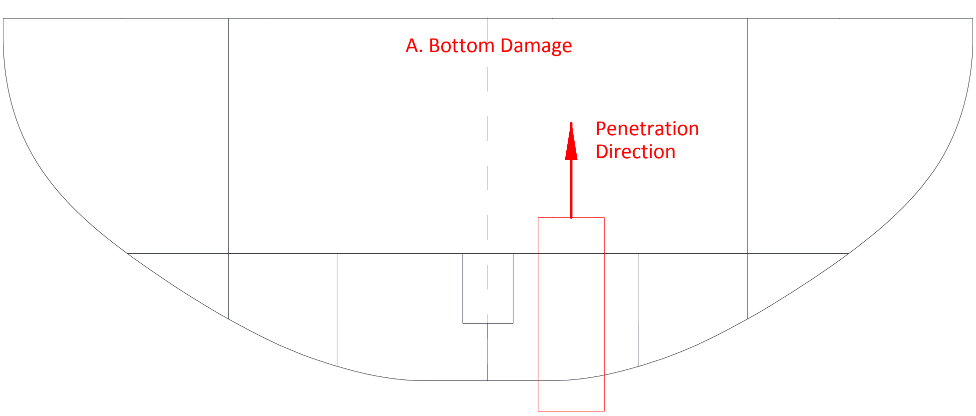


Figure 4: Sketch of bottom damage.

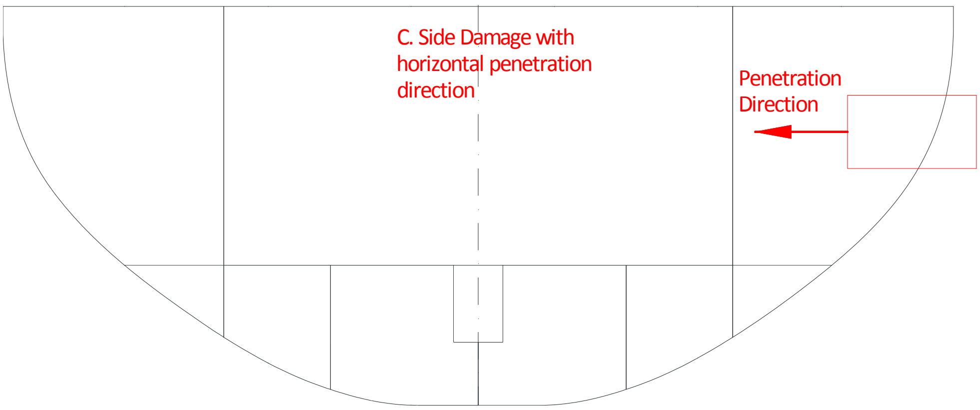


Figure 5: Sketch of side damage.

Starting from this basic qualitative classification, it is then necessary to clearly and unambiguously specify the geometrical model for each type of specified damage. Indeed, in order for the damages to be applied within a proper deterministic or probabilistic framework, it is necessary to provide a clear definition allowing the generation of damages with reference to the geometrical model of the vessel and of the subdivision/arrangement. In the following, details of the geometrical models for bottom (type B00) and side (type S00) damages are reported.

8.3.1 Bottom damages (Type B00)

A damage of type "B00" [3] is intended to be a bottom damage, with vertical penetration. The damage is assumed to be box shaped, and the geometrical definition of the damage follows the background from the GOALDS project [6]. The damage is intended to be a "potential damage", this means that the damage can partially extend outside the vessel. The damage is defined in terms of dimensional and dimensionless quantities, as appropriate. The defining quantities for a damage of type B00 are:

- Longitudinal position of forward end of damage: X_F $[\mathrm{m}]$;
- Transversal dimensionless position of centre of measured damage: $\eta_{dam} = Y_{dam} / b\left(X_F, z^*\right)$ $[\text{-}]$;
- Longitudinal extent of potential damage, i.e. potential damage length: $L_{x,p}$ $[\mathrm{m}]$;
- Transversal extent of potential damage, i.e. potential damage width: $L_{y,p}$ $[\mathrm{m}]$;
- Vertical extent of potential damage, i.e. potential damage penetration: $L_{z,p}$ $[\mathrm{m}]$;
- Vertical position for the transversal positioning of damage: z^* $[\mathrm{m}]$;

In the definition of η_{dam}, the quantity Y_{dam} [m] is the dimensional transversal position of the centre of the measured damage. The quantity $b\left(X_F, z^*\right)$ [m] is the breadth of the vessel at a longitudinal position corresponding to the forward end of damage, $x = X_F$, and vertical position $z = z^*$. Note that Y_{dam} is not to be confused with the transversal position of the centre of potential damage $Y_{dam,p}$, which is to be calculated starting from the starboard and port side limits of $b\left(X_F, z^*\right)$, Y_{dam} and $L_{y,p}$ as described in the next section.

It is assumed that the software is able to determine the starboard and port side limits of $b\left(X_F, z^*\right)$ given X_F and z^*, starting from the geometrical definition of the hull.

In addition to the above, a generic damage can also be associated with a given probability p. This probability can be used for later post processing. It will be assumed that the quantity p can also represent an absolute frequency, a relative frequency, or it can be empty, depending on the user.

As a result, the damage is assumed to be fully characterised by the generic table line shown in Table 9.

Table 9: Definition table for damage of type B00.

Damage ID	*Damage type*	*Probability/frequency*	*V1*	*V2*	*V3*	*V4*	*V5*	*V6*
Integer representing the damage ID	B00	p	X_F	η_{dam}	$L_{x,p}$	$L_{y,p}$	$L_{z,p}$	z^*
Notes: acceptable values for η_{dam} are in the range $-0.5 \le \eta_{dam} \le 0.5$								

8.3.1.1 Detailed description for the generation of potential damage box

Herein, a detailed description is provided regarding the way of generating the potential damage box, given the variables describing the damage, as specified in the previous section (see Table 9).

The ship is assumed to have a right handed reference system as follows:

- X-axis: pointing from aft to forward;
- Y-axis: pointing from starboard to port side, with $y = 0$ at the ship centreline;
- Z-axis: pointing upwards, with $z = 0$ at the bottom of the vessel.

The damage is assumed to conventionally extend, in the vertical direction, from $z = -\infty$ up to $z = L_{z,p}$ (i.e. the damage extends downwards without limitation). A generic positioning of the damage is shown in Figure 6, Figure 7 and Figure 8, with reference quantities identified. A thorough description of the involved quantities is reported in the following description of the steps which are necessary to generate the potential damage box.

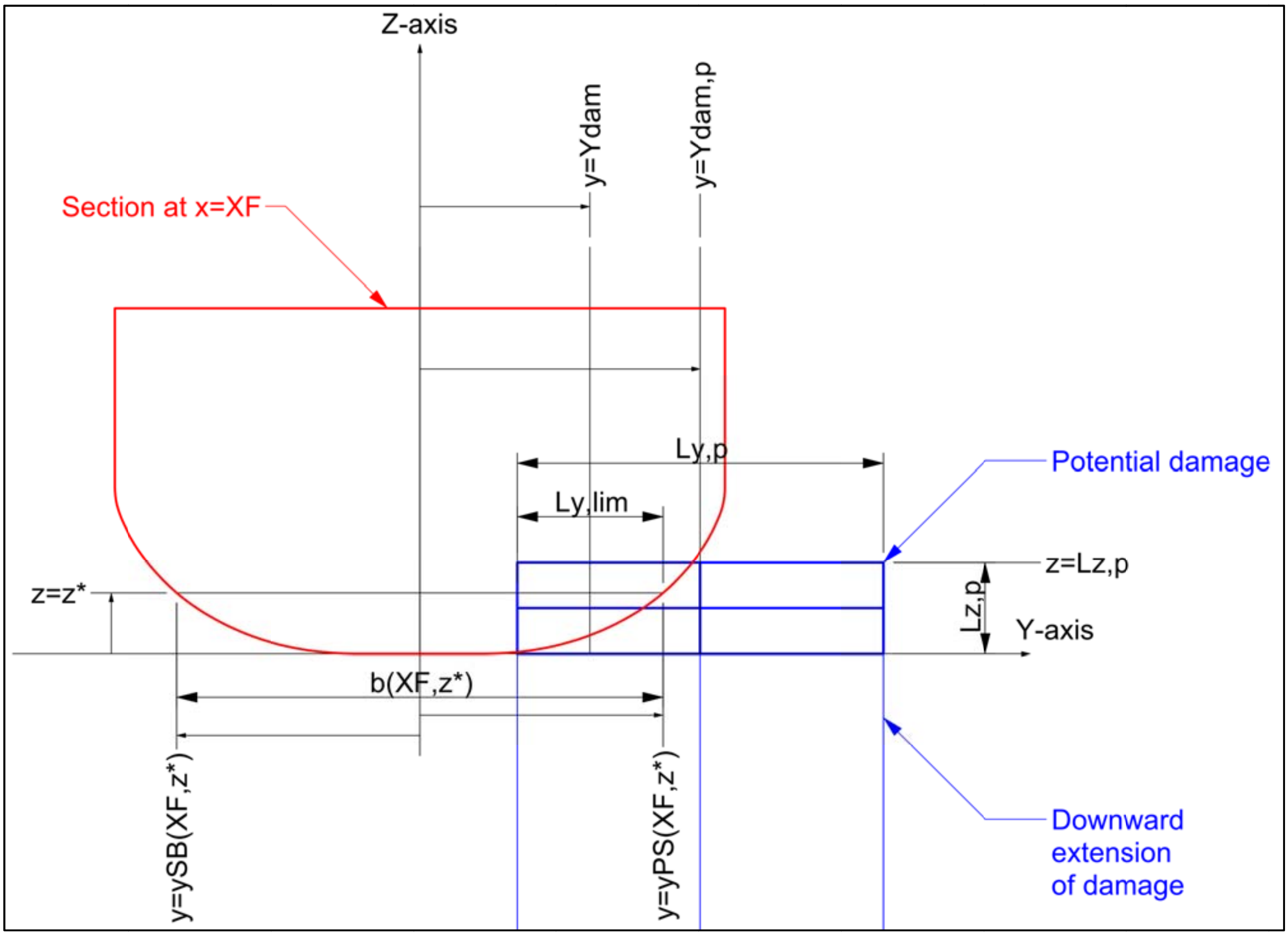


Figure 6: Generic positioning of damage – Transversal YZ view.

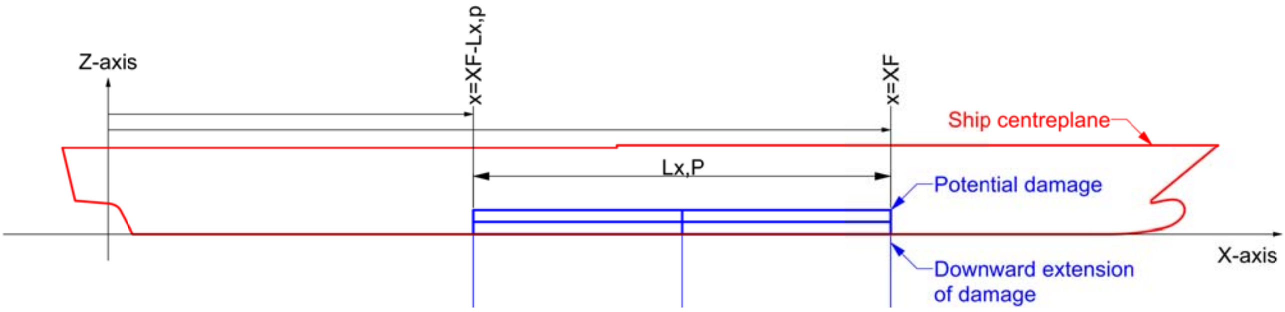


Figure 7: Generic positioning of damage – Longitudinal XZ view.

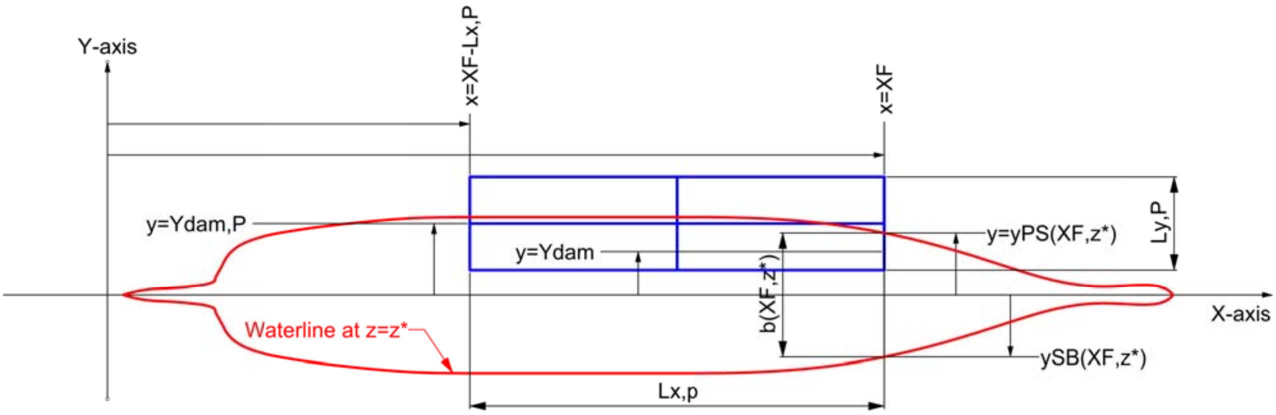


Figure 8: Generic positioning of damage – Planar XY view.

The steps for the generation of the potential damage box are as follows:

1) Set the forward limit of damage at $x = X_F$;
2) From the hull geometry, determine the starboard and port side limits of the local breadth at a height $z = z^*$ for the ship section at $x = X_F$. The transversal coordinates of such limits are defined as $y_{PS}\left(X_F, z^*\right)$ (portside limit) and $y_{SB}\left(X_F, z^*\right)$ (starboard limit). From these limits[1], the local breadth $b\left(X_F, z^*\right)$ and its centre $y_c\left(X_F, z^*\right)$ are determined as[2]:

$$\begin{cases} y_c\left(X_F, z^*\right) = \dfrac{y_{PS}\left(X_F, z^*\right) + y_{SB}\left(X_F, z^*\right)}{2} \\ b\left(X_F, z^*\right) = y_{PS}\left(X_F, z^*\right) - y_{SB}\left(X_F, z^*\right) \end{cases} \tag{1}$$

[1] If an intersection is not found, as could happen, for instance, for X_F in the very forward or very aft part of the vessel, and for small values of z^*, set $y_{PS}\left(X_F, z^*\right) = y_{SB}\left(X_F, z^*\right) = 0$. In case multiple intersections are found then $y_{PS}\left(X_F, z^*\right)$ is set as the maximum y-coordinate among the intersections, and $y_{SB}\left(X_F, z^*\right)$ is set as the minimum y-coordinate among the intersections, in such a way that $b\left(X_F, z^*\right)$ represents the maximum breadth at $x = X_F$ and $z = z^*$.

[2] For port/starboard symmetric vessels it is $y_{PS}\left(X_F, z^*\right) = -y_{PS}\left(X_F, z^*\right)$ and hence $y_c\left(X_F, z^*\right) = 0$

3) Given the dimensionless transversal position η_{dam} of the centre of measured damage at $x = X_F$, the dimensional transversal position Y_{dam} of the centre of measured damage at $x = X_F$ is determined as follows:

$$Y_{dam} = y_c\left(X_F, z^*\right) + \eta_{dam} \cdot b\left(X_F, z^*\right) \tag{2}$$

4) The dimensional transversal position $Y_{dam,p}$ of the centre of potential damage is determined, starting from Y_{dam}, η_{dam} and the transversal extent $L_{y,p}$ of potential damage, as follows:

$$\begin{cases} Y_{dam,P} = Y_{dam} + \dfrac{sign(\delta)}{2} \cdot \max\left\{\left(L_{y,p} - L_{y,lim}\right) \ ; \ 0\right\} \\ \text{where} \\ \delta = Y_{dam} - y_c\left(X_F, z^*\right) \\ L_{y,lim} = \min\left\{2 \cdot \left(y_{PS}\left(X_F, z^*\right) - Y_{dam}\right) \ ; \ 2 \cdot \left(Y_{dam} - y_{SB}\left(X_F, z^*\right)\right)\right\} \\ \\ \text{Note: } sign(\delta < 0) = -1 \ ; \ sign(\delta = 0) = 0 \ ; \ sign(\delta > 0) = 1 \end{cases} \tag{3}$$

5) The potential damage box is therefore positioned in such a way to cover the following region:

$$\begin{cases} \text{Longitudinal extent: } X_F - L_{x,p} \le x \le X_F \\ \\ \text{Transversal extent: } Y_{dam,P} - \dfrac{L_{y,p}}{2} \le y \le Y_{dam,P} + \dfrac{L_{y,p}}{2} \\ \\ \text{Vertical extent: } -\infty < z \le L_{z,p} \end{cases} \tag{4}$$

8.3.1.2 Examples

This section reports worked examples, in order to clarify the application. Two example damages are considered for a notional sample vessel. The two damages, a "wide damage" and a "non-wide" damage, share the same characteristics, with the exception of the transversal extent of the damage. The characteristics of the two damages are reported in Table 10, while a graphical representation of the two damages is shown in Figure 9, Figure 10 and Figure 11.

Quantities reported in Table 10 are identified depending on their source. Variables identified as "input" are the input variables characterising the damage. Variables which are to be determined by geometrical operations involving the ship hull and the position of the forward end of damage are identified as "from hull geometry and damage position". Variables identified as "Calculated (eq. (#))" are derived variable by means of equations reported herein.

In the example 3D views in Figure 9, Figure 10 and Figure 11, for representation purposes, an orange box is shown below $z = 0$ (ship bottom) with the intention of representing the unlimited downward extension of the damage.

Table 10: Characteristics of example damages and derived quantities.

Source	Quantity		Wide damage	Non-wide damage
Input	X_F	[m]	150.000	150.000
Input	η_{dam}	[-]	0.350	0.350
Input	$L_{x,p}$	[m]	80.000	80.000
Input	$L_{y,p}$	[m]	18.000	4.000
Input	$L_{z,p}$	[m]	4.500	4.500
Input	z^*	[m]	3.000	3.000
From hull geometry and damage position	$y_{PS}\left(X_F, z^*\right)$	[m]	11.950	11.950
From hull geometry and damage position	$y_{SB}\left(X_F, z^*\right)$	[m]	-11.950	-11.950
Calculated (eq. (1))	$y_c\left(X_F, z^*\right)$	[m]	0.000	0.000
Calculated (eq. (1))	$b\left(X_F, z^*\right)$	[m]	23.900	23.900
Calculated (eq. (2))	Y_{dam}	[m]	8.365	8.365
Calculated (eq. (3))	$L_{y,lim}$	[m]	7.170	7.170
Calculated (eq. (3))	$Y_{dam,p}$	[m]	13.780	8.365
Calculated (eq. (4))	Longitudinal extent	[m]	$70.000 \le x \le 150.000$	$70.000 \le x \le 150.000$
Calculated (eq. (4))	Transversal extent	[m]	$4.780 \le y \le 22.780$	$6.365 \le y \le 10.365$
Calculated (eq. (4))	Longitudinal extent	[m]	$-\infty \le z \le 4.500$	$-\infty \le z \le 4.500$

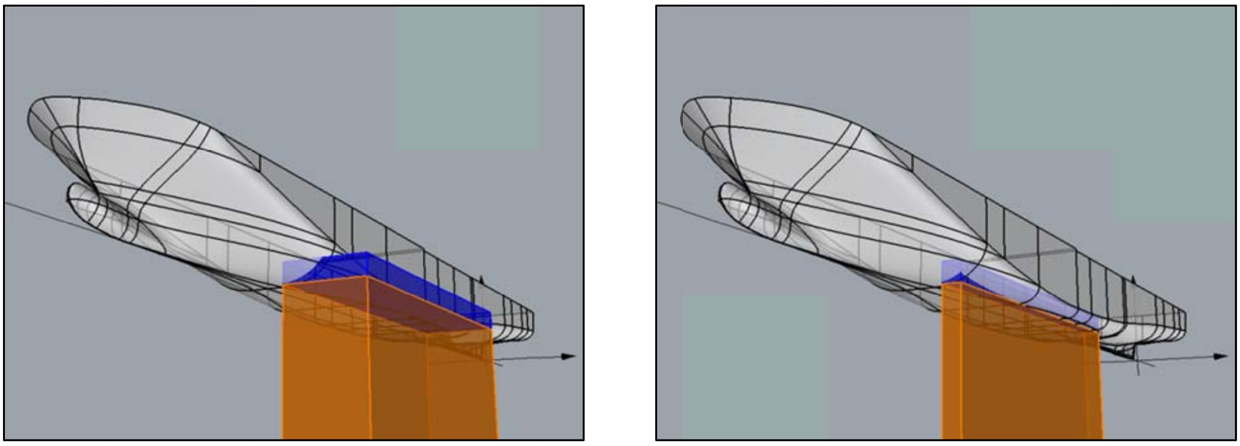


Figure 9: Wide (left) and non-wide (right) damage examples. Example view 01. The orange box below $z = 0$ is meant to represent the downward extension of damage towards $z = -\infty$.

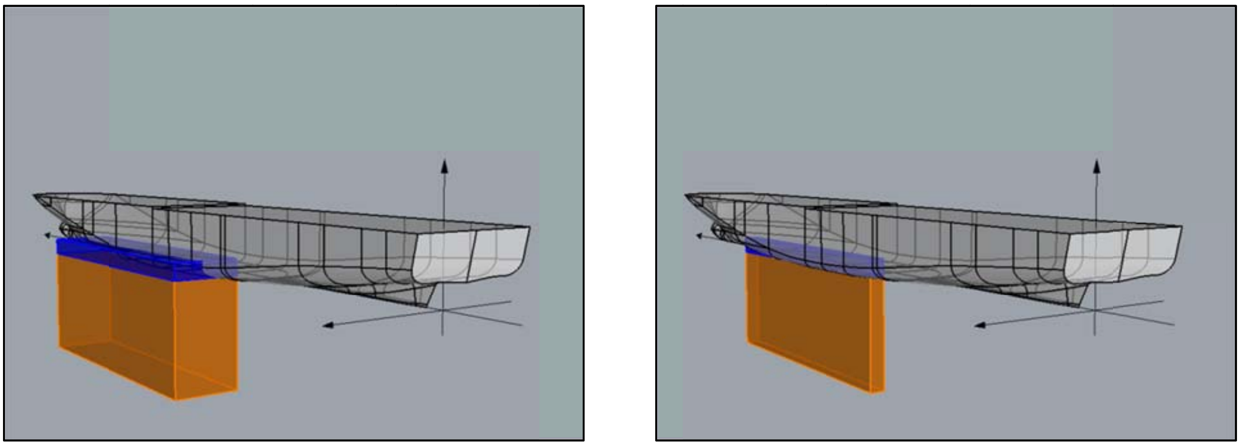


Figure 10: Wide (left) and non-wide (right) damage examples. Example view 02. The orange box below $z = 0$ is meant to represent the downward extension of damage towards $z = -\infty$.

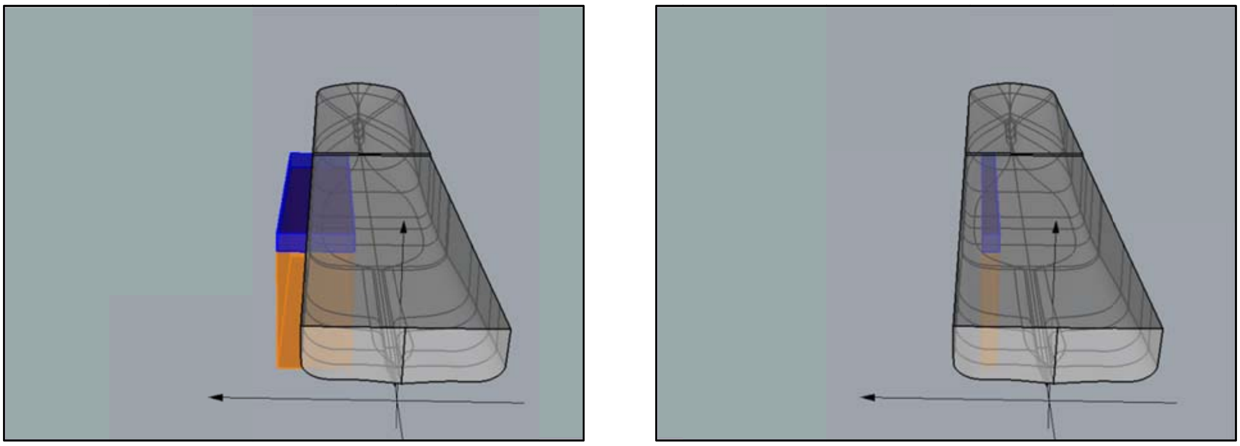


Figure 11: Wide (left) and non-wide (right) damage examples. Example view 03. The orange box below $z = 0$ is meant to represent the downward extension of damage towards $z = -\infty$.

8.3.2 Side damages (Type S00)

A damage of type “S00” [9] is intended to be a side damage, with horizontal penetration. The penetration is defined to be orthogonal to the centreplane of the vessel. The penetration is measured inboard along a waterline which is specified by the defining quantities of the damage. The damage is intended to be a “potential damage”, this meaning that the damage can partially extend outside the vessel.

The description of this type of damage follows a logic which is similar to the one used for damages of bottom type.

The main scope of damage of type “S00” is to provide a practical geometrical modelling for damages occurring in case of side grounding accidents.

In general terms, the defining quantities for a damage of type S00 are:

- Indicator for the side of damage: ind_{side} [-] ($+1$: port side ; -1: starboard side)
- Longitudinal position of forward end of damage: X_F [m] ;
- Longitudinal extent of potential damage, i.e. potential damage length: $L_{x,p}$ [m] ;
- Transversal extent of potential damage, i.e. potential damage penetration: $L_{y,p}$ [m] ;
- Vertical position of lower limit of potential damage: $z_{LL,p}$ [m] ;
- Height of potential damage above its lower limit: H_p [m] ;
- Vertical position of waterline for the determination of the damage penetration surface: z^* [m] ;

Considering a ship-fixed right-handed reference system $Oxyz$, where x is the ship longitudinal axis (pointing forward), y is the ship transversal axis (pointing to port side), z is the vertical axis (pointing upwards), a damage of type S00:

- Extends longitudinally in the range $X_F - L_{x,p} \leq x \leq X_F$;
- Extends vertically in the range $z_{LL,p} \leq z \leq z_{LL,p} + H_p$;
- Extends inboard on the side specified by ind_{side}, up to a limit which is identified by the geometry of the waterline at $z = z^*$ and by the penetration $L_{y,p}$ to be taken orthogonal to the ship centreplane.

It is assumed, hence necessary in practice, that the software used for the generation of the damage shape is able to determine the ship waterline at $z = z^*$, from the geometrical definition of the hull shell. From the geometry of the reference waterline at $z = z^*$, the penetration $L_{y,p}$ and the damage side ind_{side}, it is therefore possible to determine the inboard limitation for the damage penetration. Such limitation is assumed to be the same for the whole damage height, this meaning that the inboard limit penetration surface is evaluated, by definition, by using the waterline at $z = z^*$ and the internal limitation of damage penetration is then defined as being independent of z.

In addition to the above geometrical considerations, a generic damage can also be associated with a given probability p. This probability can be used for later post processing. It will be assumed that the quantity p can also represent an absolute frequency, a relative frequency, or it can be empty, depending on the user’s choice.

As a result, the damage is assumed to be fully characterised by the generic table line shown in Table 11.

Table 11: Definition table for damage of type S00.

Damage ID	*Damage type*	*Probability/frequency*	*V1*	*V2*	*V3*	*V4*	*V5*	*V6*	*V7*
Integer representing the damage ID	S00	p	ind_{side}	X_F	$L_{x,p}$	$L_{y,p}$	$z_{LL,p}$	H_p	z^*
Notes: acceptable values for ind_{side} are "+1" (for port side damage) and "-1" (for starboard side damage)									

8.3.2.1 Detailed description for the generation of potential damage solid

Herein, a detailed description is provided regarding the procedure for generating the solid object representing the potential damage, given the variables describing the damage, as specified in the previous section (see Table 9).

In the following discussion, the ship is assumed to have a right handed reference system as follows:

- X-axis: pointing from aft to forward;
- Y-axis: pointing from starboard to port side, with $y = 0$ at the ship centreplane;
- Z-axis: pointing upwards, with $z = 0$ at the bottom of the vessel.

The damage is assumed to:

- Extend longitudinally in the range $X_F - L_{x,p} \le x \le X_F$;
- Extend vertically in the range $z_{LL,p} \le z \le z_{LL,p} + H_p$;
- Extend transversally from outside up to an inboard limit positioned at $y = y_{int,lim}(x)$, which is described later in equation (5) and associated text.

A generic positioning of the damage is shown in Figure 12, Figure 13 and Figure 14, with reference quantities identified. A thorough description of the steps which are necessary to generate the potential damage solid is reported in the following.

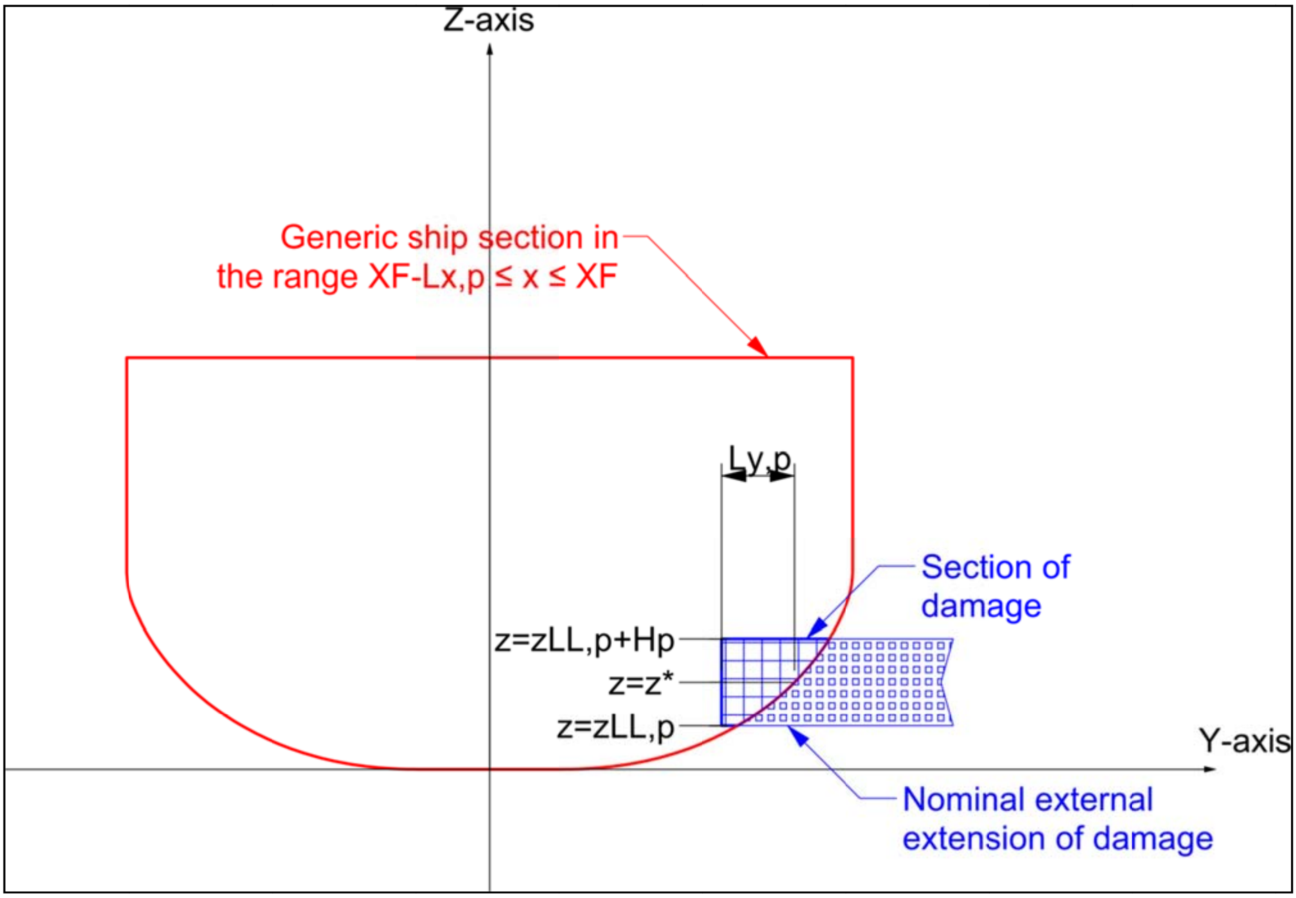


Figure 12: Generic positioning of damage – Transversal YZ view.

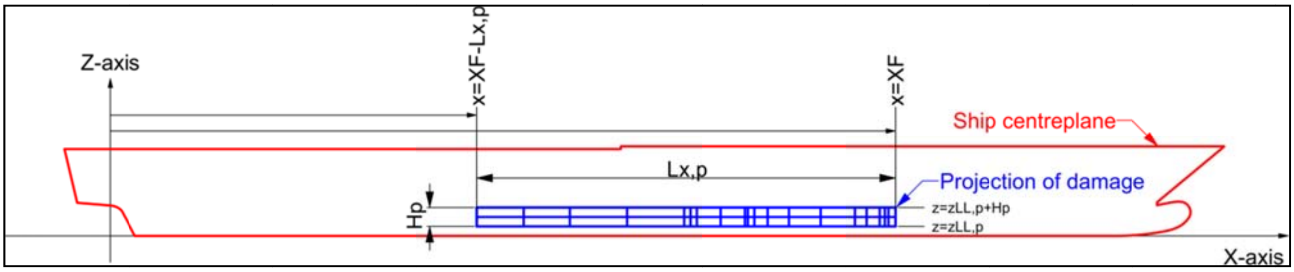


Figure 13: Generic positioning of damage – Longitudinal XZ view.

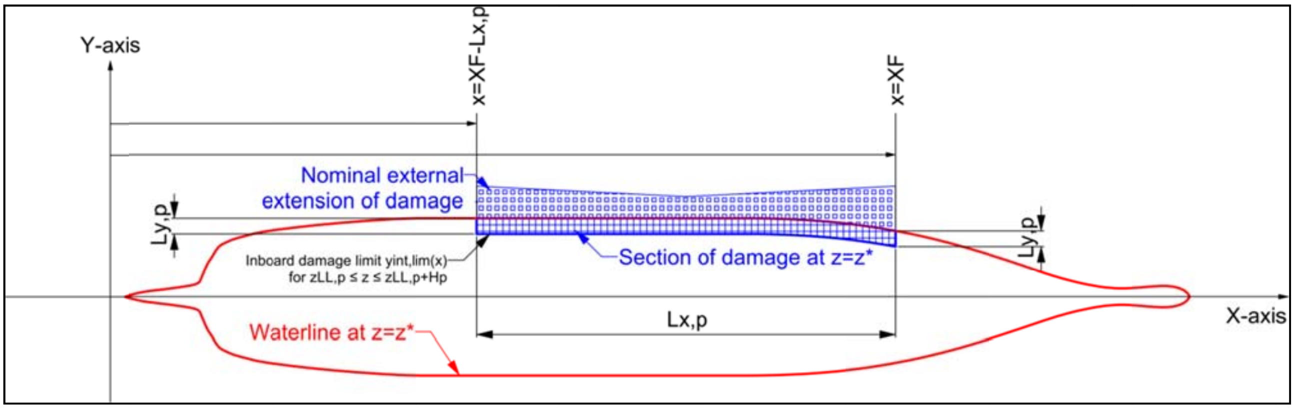


Figure 14: Generic positioning of damage – Planar XY view.

The steps for the generation of the potential damage solid are described as follows:

1) Identify the damage side (port or starboard side) using the characterising variable ind_{side} in Table 11;
2) Starting from the hull geometry, for each longitudinal position x in the range of damage $X_F - L_{x,p} \le x \le X_F$, determine the outermost transversal coordinate of the shell at a waterline $z = z^*$ on the appropriate side of the vessel (see point 1)), and define such coordinate as $y_{ext}(x)$ [3,4];
3) At each longitudinal position x in the range of damage $X_F - L_{x,p} \le x \le X_F$, define the inboard limit of the damage $y_{int,lim}(x)$ as follows:

$$y_{int,lim}(x) = \begin{cases} y_{ext}(x) - L_{y,p} & \text{for port side damage } (ind_{side} = +1) \\ y_{ext}(x) + L_{y,p} & \text{for starboard side damage } (ind_{side} = -1) \end{cases} \quad (5)$$
$$\text{for } X_F - L_{x,p} \le x \le X_F$$

4) The potential side damage is therefore generated in such a way to cover the following region of the space:

$$\begin{cases} \text{Longitudinal extent: } X_F - L_{x,p} \le x \le X_F \\ \text{Transversal extent: } \begin{cases} y_{int,lim}(x) \le y(x) < +\infty & \text{for port side damage } (ind_{side} = +1) \\ -\infty < y(x) \le y_{int,lim}(x) & \text{for starboard side damage } (ind_{side} = -1) \end{cases} \\ \text{Vertical extent: } z_{LL,p} \le z \le z_{LL,p} + H_p \end{cases} \quad (6)$$

8.3.2.2 Examples

The objective of this section is to provide some visual examples of side damages generated in accordance with the description given above.

Figure 15 shows a standard damage situation. The damage is assumed to occur on the port side of the vessel. The external limit $y_{ext}(x)$ is firstly generated, for sections in the range $X_F - L_{x,p} \le x \le X_F$ using the hull waterline at $z = z^*$. From $y_{ext}(x)$, given the damage penetration

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[3] If the ship shell does not exist at a generic section x and waterline z^*, as could happen, for instance, for x in the very forward or very aft part of the vessel, and for small values of z^*, set, conventionally, $y_{ext}(x) = 0$. In case multiple transversal coordinates of the shell are found at a generic section x and waterline z^*, then:

- For port side damages: $y_{ext}(x)$ is set as the maximum (hence outermost) y-coordinate of the shell at section x and waterline z^*;
- For starboard damages: $y_{ext}(x)$ is set as the minimum (hence outermost) y-coordinate of the shell at section x and waterline z^*.

[4] Note that, for port side damages, typically (though not strictly necessarily) it is $y_{ext}(x) \ge 0$, whereas for starboard damages, typically (though not strictly necessarily) it is $y_{ext}(x) \le 0$.

$L_{y,p}$, the inboard limit coordinate $y_{int,lim}(x)$ can be obtained as specified in (5). Knowing the lower limit $z_{LL,p}$ and the height of the damage H_p , it is therefore possible to identify the damage region in the space, as specified in (4). The resulting damage is then assumed to be virtually extended sideward without limit up to $y=+\infty$. This damage can be considered as a "standard" condition, since there are no specific issues associated with its generation.

The situation is slightly different for the example shown in Figure 16, where a damage is shown which is assumed to occur in the very aft part of the vessel. Due to the fact that the length of the damage is assumed to be, for the sake of explanation, quite long, the potential damage extends also backwards outside the vessel. In this specific case, the damage is at the starboard side. In the very forward part of the damage, the waterline at $z=z^*$ crosses the skeg of the vessel, and therefore, for the initial forward part of the damage, it is possible to easily identify $y_{ext}(x)$ from the hull geometry. However, when moving backwards, aft of the extreme aft limit of the skeg at $z=z^*$, the absence of hull requires special attention and, as explained in the previous section, to conventionally set $y_{ext}(x)$ at the centreplane of the vessel, i.e. at $y_{ext}(x)=0$. The discontinuity due to the end of the skeg at $z=z^*$ can be understood by looking at the projection shown in the right view of Figure 16. Nevertheless, by the application of the procedure described in the previous sections, the damage can then be generated without further issues, exactly as done in the previous example case. Since the damage is at the starboard side, the damage region is assumed to extend sideward up to $y=-\infty$.

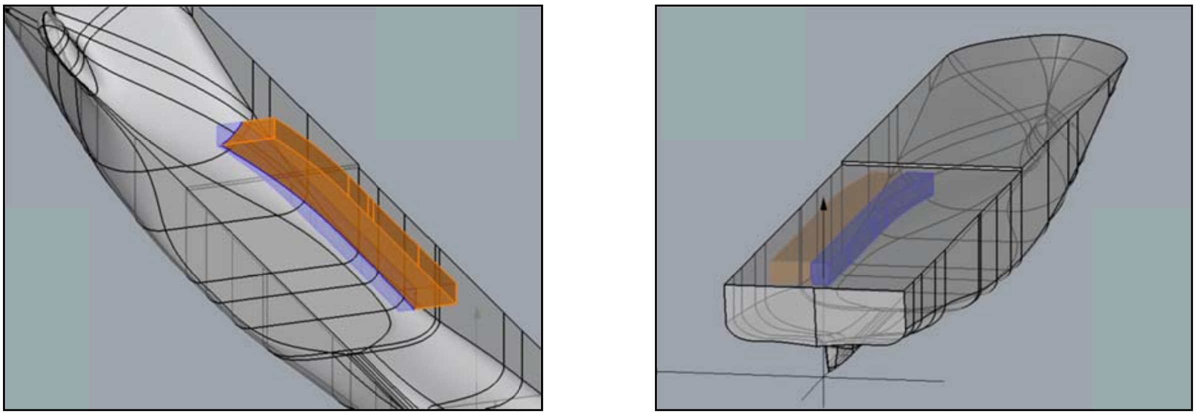

Figure 15: Example damage #01 on port side. The orange solid is meant to represent the outward extension of damage towards $y=+\infty$.

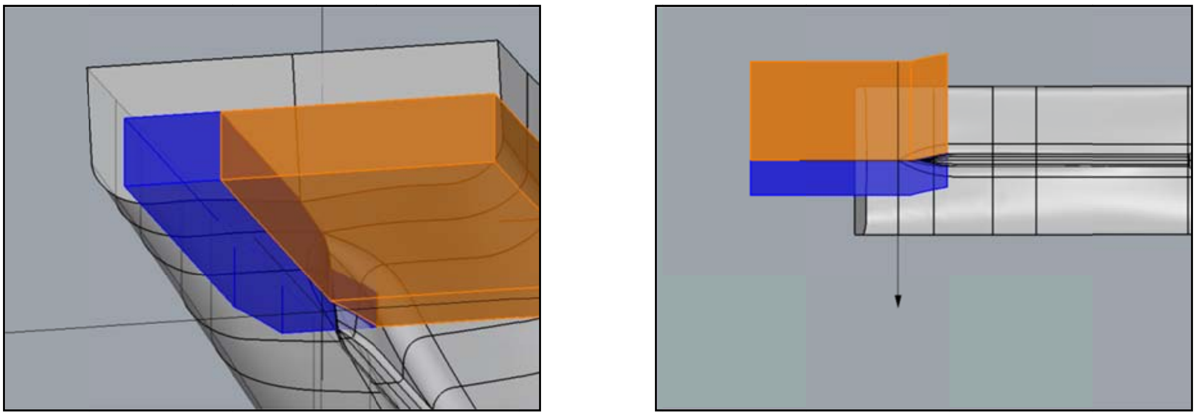

Figure 16: Example damage #02 on starboard side. The orange solid is meant to represent the outward extension of damage towards $y = -\infty$.

8.4 Development of accidents databases

One of the objectives of the EMSA III study is the identification of historical raking damages, and the modelling of damages due to grounding. According to the description of work, Subtask 3.a will make reference to data and information available from previous research, particularly the GOALDS project, and additional data as of today [12].

Depending on the assumed principal direction of the penetration (vertical / horizontal), two main types of damages due to grounding have been considered during the elaboration of Task 3 of the EMSA III study:

- damages to the ship's bottom, with a principally vertical direction of penetration (Type 'B00') and
- damages to the ship's side, with a principally horizontal direction of penetration (Type 'S00').

Data relevant to accidents of Type 'B00' (Bottom Damages) have been extensively analysed in the GOALDS project [27] and the corresponding distribution functions are readily available from [7]. However, data relevant to accidents of Type 'S00' (Side Damages), particularly for passenger ships have never been published before (to the knowledge of the Task 3 participants). It has been decided therefore to develop a database with relevant accidents and to perform a statistical analysis of the collected data. The present chapter provides a description of the developed data base and of the collected data. The results of the statistical analysis of the collected data are presented in a following chapter.

Since the data from grounding accidents to passenger ships resulting to side damages were expected to be relatively few, it was decided to collect also data from accidents with containerships. This is a procedure that was adopted also in the GOALDS project [27], where the various ship types were divided in two main categories, i.e. "full ships" and "non-full ships". The analysis of data from grounding accidents carried out within GOALDS, with emphasis to bottom damages [7], verified the initial assumptions with respect to the statistical distribution of damage characteristics of the two ship types considered, and indicated a common behaviour of the statistical properties of the grounding damage characteristics of passenger ships and containerships (non-full ships) on one hand, and tankers and bulk carriers (full ships) on the other hand. Based on the experience gained from GOALDS, it was decided to adopt the same procedure also in the present study. It was decided however to initially develop two different databases, one for passenger ships and one for containerships instead of combining all accidents in one database from the very beginning.

The accident types considered included collision (CN), grounding (GR) and contact (CT). Collision accidents were included because one of the objectives of Task 1 was to revise and update the risk model for collision developed in GOALDS, considering additional information from recent accidents. Contact accidents were included because they are associated with hull breaches at the side of the ship, which are of particular interest for the present study. The definitions for the accident types used in this study are those given in MSC/Circ.953 [28]:

- *Collision: striking or being struck by another ship (regardless of whether under way, anchored or moored).*
- *Stranding or grounding: being aground, or hitting/touching shore or sea bottom or underwater objects (wrecks, etc.).*
- *Contact: striking any fixed or floating object other than those included in Nos. 1 or 2.*

8.4.1 Structure of the Data Bases

In the framework of the present study two different databases have been developed, one for passenger ships (i.e. RoPax, RoPax-Rail, cruise ships and pure passenger ships) and one for containerships. Both data bases contain data from accidents of the following types:

- collision (CN),
- grounding (GR) and
- contact (CT).

Both databases were developed in MS Access and they share a practically similar structure. For each accident, the following type of information may be recorded:

- Accident's ID number
- Ship's Data
  - IMO Number
  - Name
  - Type (Passenger, RoPax, RoPax-Rail or Cruise)
  - Due or Delivered Year
  - Current Status (Delivered, Lost or Scrapped)
  - Scrap or Loss Year (if applicable)
  - Main Particulars (L_{OA}, L_{BP}, B, T, D_{bhd}, D_{upd})
  - Service Speed (V_S)
  - Froude Number
  - Capacity (DWT, GRT)
  - Number of Passengers (in case of Passenger Ship)
  - Number of Cars, Lorries/Trailers (in case of a RoPax or RoPax-Rail)
  - Crew Number
  - Ship's Class (current and at the time of the accident)
  - IACS classed ship (Yes/No/Unknown)
- Incident's Data
  - Casualty Type (collision, grounding or contact)
  - Incident Severity (Serious / Not serious)
  - Total Loss (Yes / No)
  - IACS classed ship at the time of incident (Yes/No/Unknown)
  - Casualties (Number of Persons Killed, Number of Missing)
  - Area of Incident (Open Sea / Limited Waters / Terminal areas / Shipyard/Dry-dock / Unknown)
  - Location of Incident (Marsden Grid, Start Latitude, Start Longitude, SIS Zone).
  - Weather At Time Of Incident (Calm / Rough / Unknown)
  - Ship's Operating Condition (Under repair / At Berth / In Port / Discharging / Sailing/En-route / At Anchor / Ballasting / Bunkering / Loading / Manoeuvring / Towed / Mooring / Under Construction / Unknown)
  - Other information

- Struck/Striking/Unknown
- Water Ingress (Yes/No/Unknown)
- Sinking (Yes/No/Unknown)
- Fire after Collision (Yes/No/Unknown)
- Navigation (Powered/ Drift/Unknown)
- Sea bottom type (Hard/Soft/Unknown)
- Ship Staying Aground (Yes/No/Unknown)

o Incident's Severity with respect to the vessel (No damage sustained / Minor damage / Major damage / Break up / Total loss / Unknown)

o For Collision Accidents
- Struck / Striking / Unknown
- Fire After Collision (Yes / No)
- Other ship type (Bulk Carrier / Oil Tanker / Chemical/Oil Tanker / Containership / Fishing Vessel / Passenger Ship / OBO Tanker / Tug / Motor Vessel / Submarine / Crew Boat / Command Ship / Sailboat-Yacht / Trawler / Supply Vessel / LPG / LNG / Sloop / FPSO / Ro-Ro Ship / Refrigerated Cargo Ship / Barge / General Cargo Ship / Dredger / Workboat / Jack-Up Rig / Drilling Vessel / Passenger/Ro-Ro Ship / Cruise Ship / Floating Crane / Bridgedecker / Pollution Control Vessel / Sludge Carrier / Pallets Carrier)
- Other Ship's Size (Larger / Smaller / Similar)
- Other Ship's Operating Condition (Under repair / At Berth / In Port / Discharging / Sailing/En-route / At Anchor / Ballasting / Bunkering / Loading / Manoeuvring / Towed / Mooring / Under Construction / Unknown)

o For Contact Accidents:
- Contact with (Floating object / Fixed installation / Unknown)
- Contact type (Powered / Drift / Unknown)

o For Grounding Accidents
- Grounding type (Powered / Drift / Unknown)
- Sea Bed Info (Hard / Soft / Unknown)
- Extend of flooding (Above Double Bottom / Bellow Double Bottom / In Fore Peak / In Engine Room / Unknown)
- Staying Aground (Yes / No / Unknown)
- Refloating Info[5] (With tug assistance / By own means / Unknown)

• Damage Info
  - o Hull Touches at (Bottom / Side / Appendage / Bow / Stern / Unclear)
  - o Hull Breach at (Bottom / Side / Appendage / Bow / Stern / Unclear / None)
  - o Number of Breaches
  - o Damage Zones Affected
  - o Inner Hull Penetration[6] (Yes / No / Unknown)
  - o Inner Bottom Penetration (Yes / No / Unknown)
  - o Car deck Breached[7] (Yes / No / Unknown)
  - o Damage Length (In case of multiple penetrations from foremost to aftmost point)
  - o Sum of Actual Damage Length (in case of multiple penetrations)

[5] Only if Staying Aground='Yes'
[6] In case of containerships
[7] In case of a RoPax or RoPax-Rail

- Damage Penetration (measured upwards from bottom in case of bottom damage or inwards horizontally in case of side damage)
- Damage Width (measured horizontally across the bottom in case of bottom damage or vertically across the side in case of side damage)
- Sum of Actual Damage Width (in case of multiple penetrations)
- Damage Area (Sum of areas of all breaches)
- Longitudinal Position (Distance of foremost point of breach from AP)
- Lower Starting Point (Distance of lowest point of breach from bottom in case of side damage)
- Transverse Position (Transverse distance from Centre line in case of bottom damage)
- Water Ingress (Yes / No / Unknown)
- Damage extend above water line (Yes / No / Unknown)
- Damage extend above bulkhead deck (Yes / No / Unknown)

8.4.2 Collected Data

Two already existing ship accidents databases developed by NTUA-SDL in the framework of the EU project GOALDS (passenger ships, [11]) and of the bilateral research project CONTIOPT (containerships, [10]) carried out by Germanischer Lloyd SE and NTUA have been used as the starting points of the present work. Within Task 3, these databases where extended to include as many additional accidents as possible, while at the same time the already included accidents were thoroughly revisited in order to verify existing data and to supplement it with missing information using various possible sources. Relevant information was searched in the online databases Sea-web and GISIS (Global Integrated Shipping Information System), from the project partners, Flag administrations and also from the internet. Accidents investigation reports were located in the web pages of the following organizations:

- Accident Investigation Board, Finland
- Accident Investigation Board, Norway
- Australian Transport Safety Bureau
- Danish Maritime Authority
- Federal Bureau of Maritime Casualty Investigation, Germany
- Hellenic Bureau for Marine Casualties Investigation
- Isle of Man Ship Registry
- Marine Accident Investigation Branch, UK
- Marine Accident Investigation Office, France
- Marine Accident Investigation Section, China
- Marine Casualties Investigative Body, Italy
- Marine Safety Investigation Unit, Malta
- Maritime Safety Tribunal, Korea
- Ministry of Shipping, Mauritius
- National Transportation Safety Board, U.S.A.
- Panama Maritime Authority
- Swedish Accident Investigation Board
- The Bahamas Maritime Authority
- Transport Accident Investigation Commission, New Zealand

- Transportation Safety Board of Canada
- Transport Safety Board of Japan
- United States Coast Guard, USA

In total, 31 investigation reports pertaining to accidents with passenger ships (RoPax, RoPax-Rail, Cruise ships, Pure Passenger ships) issued by the above organizations were collected; of which 10 were found in GISIS and the remaining 21 from the internet. Of these 31 reports, 12 were related to collision accidents, 10 were related to groundings and 9 to contacts. In addition, 101 investigation reports pertaining to accidents with containerships issued by the above organizations were collected; of which 20 were found in GISIS and the remaining 81 from the internet (69 reports were related to collision accidents, 29 to groundings and 3 to contacts).

The following parameters were used to filter the casualty data:

Sampling plan of Passenger ships

- Ship types: Cruise, Pure Passenger ships, Ro-Pax and RoPax-Rail;
- Casualty time period: 1990-2013
- GT ≥ 1,000
- ≥ 80 m length
- Built ≥ 1982
- Froude No. ≤ 0.5 – to eliminate HSC from the study;

Sampling plan of Containerships

- Ship types: Fully Cellular Containerships;
- Casualty time period: 1990-2012 (October)
- GT ≥ 1,000
- Built ≥ 1982

The full set of available data, including accidents to both passenger ships and containerships was used in the development of the probabilistic model for the breach characteristics for the side damages (type S00), i.e. for the derivation of the probability density functions and cumulative distribution functions for the location and extend. The dependent probabilities in the Risk Model were calculated using only data from serious accidents to passenger ships (data from accidents to containerships and data from non-serious accidents to passenger ships were excluded). Finally, the frequencies of grounding and contact accidents were calculated using only accidents for IACS classed passenger ships in the period from the year 2000 to year 2013.

8.4.2.1 Passenger Ships

In total, 430 accidents to passenger ships have been identified and included in the data base. Their distribution with respect to the types of accident considered and the origin of information is presented in Table 12. Their distribution with respect to the types of accident considered and the ship types is presented in Table 13. The distribution of collected accidents with respect to the types of accident considered and the area of operation at the time of the accident is presented in Table 14.

Table 12: Passenger ships database: type of accident and origin of information

	Collisions	Groundings	Contacts	Total
GOALDS	73	94	0	167
EMSA III	63	32	168	263
TOTAL	136	126	168	430

Table 13: Passenger ships database: type of accident and type of ship

	Collisions	Groundings	Contacts	Total
RoPax	102	81	123	306
RoPax-Rail	4	1	11	16
Cruise	27	38	34	99
Passenger	3	6	0	9
TOTAL	136	126	168	430

Table 14: Passenger ships database: type of accident and area of operation

	Collisions	Groundings	Contacts	Total
Open Sea	13	3	4	20
Limited waters	50	95	31	176
Terminal areas	73	27	133	233
Unknown	0	1	0	1
TOTAL	136	126	168	430

The impact of the accident for the three accident types considered for the case of RoPax and RoPax-Rail ships is presented in Table 15. Corresponding results for the cruise and pure passenger ships are presented in Table 16. The impact of the collected accidents on human life (number of persons killed plus number of persons missing) is presented in Table 17.

Table 15: Impact of the accident for the case of RoPax and RoPax-Rail ships

	Collisions	Groundings	Contacts	Total
No damage sustained	12	13	6	31
Minor damage	65	17	74	156
Major damage	17	35	31	83
Total Loss	0	2	0	2
Break up	0	1	0	1
Unknown	12	14	23	49
TOTAL	106	82	134	322

Table 16: Impact of the accident for the case of Cruise and Pure Passenger ships

	Collisions	Groundings	Contacts	Total
No damage sustained	2	9	1	12
Minor damage	16	8	20	44
Major damage	6	21	9	36
Total Loss	0	2	0	2
Break up	0	0	0	0
Unknown	6	4	4	14
TOTAL	30	44	34	108

Table 17: Impact on human life

	Collisions	Groundings	Contacts	Total
RoPax	1	831[8]	2	834
RoPax-Rail	0	0	0	0
Cruise	0	34[9]	3	37
Passenger	4	0	0	4
TOTAL	5	865	5	875

The annual distribution of serious and non-serious accidents to passenger ships is presented in Figure 17 to Figure 22.

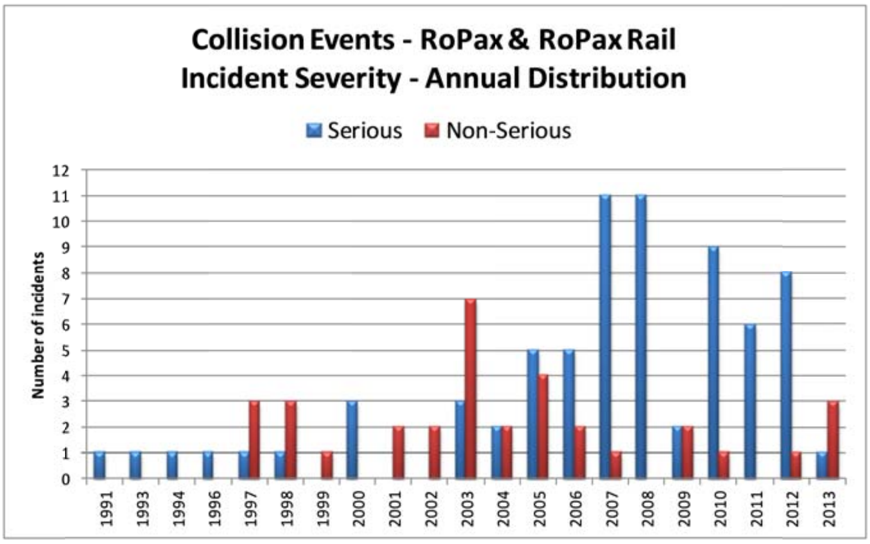

Figure 17: Annual distribution of RoPax and RoPax-Rail collision accidents

8 RoPax, PRINCESS OF THE STARS, Grounding in 2008 /SOUTH CHINA SEA: fatalities=831 (523 killed, 308 missing). While sailing, the ship was caught by a Typhoon. It was claimed that the ship reported that it faced engine troubles and run aground, while later on the ship listed and capsized. The circumstances of this accident are unclear and may not be suitable for drawing conclusions on the impact of grounding accidents on human life.

9 Costa Concordia (32 persons killed or missing) and Sea Diamond (2 persons missing)

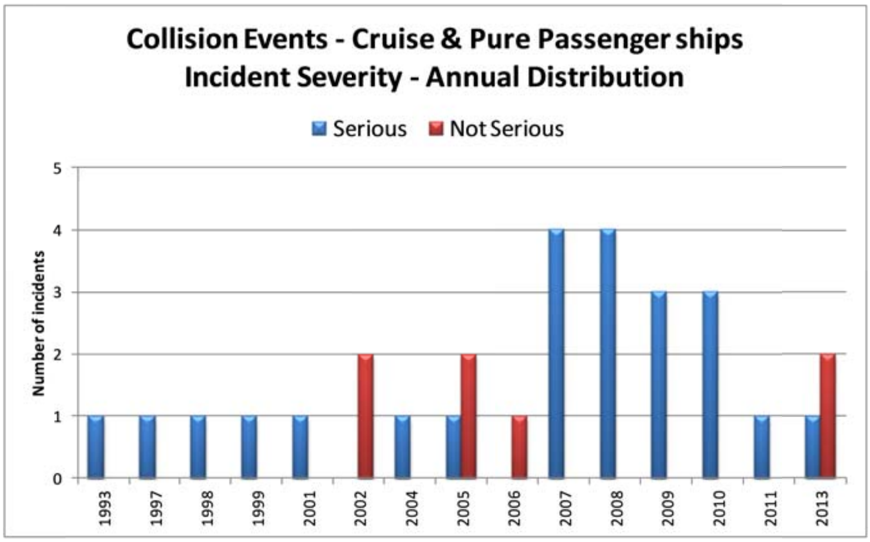

Figure 18: Annual distribution of Cruise ships and Pure Passenger ships collision accidents

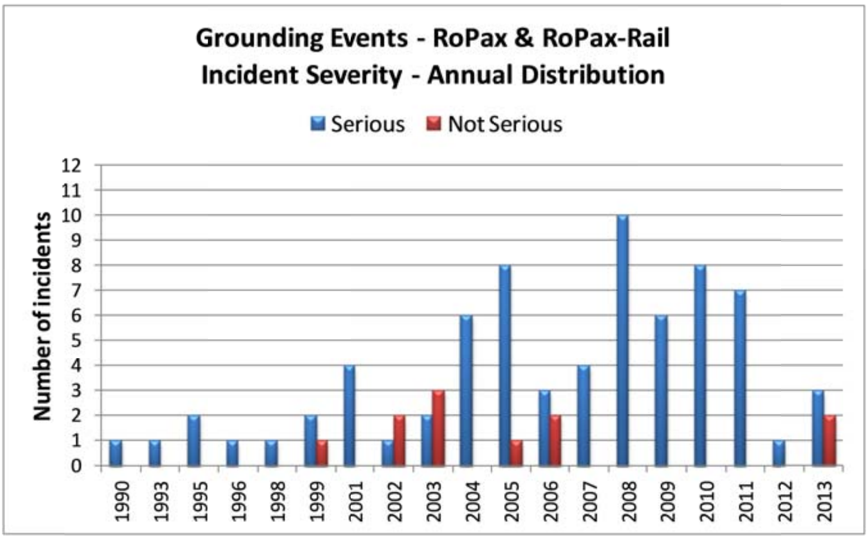

Figure 19: Annual distribution of RoPax and RoPax-Rail grounding accidents

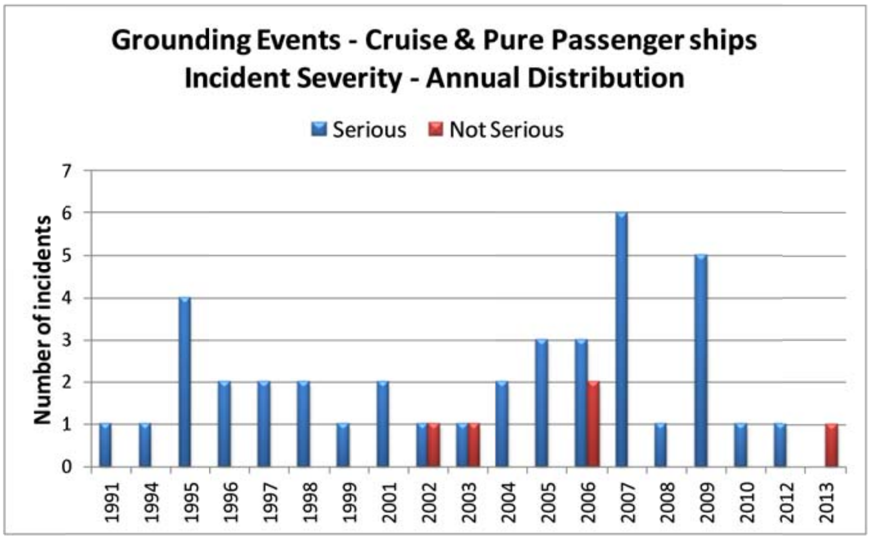

Figure 20: Annual distribution of Cruise ships and Pure Passenger ships grounding accidents

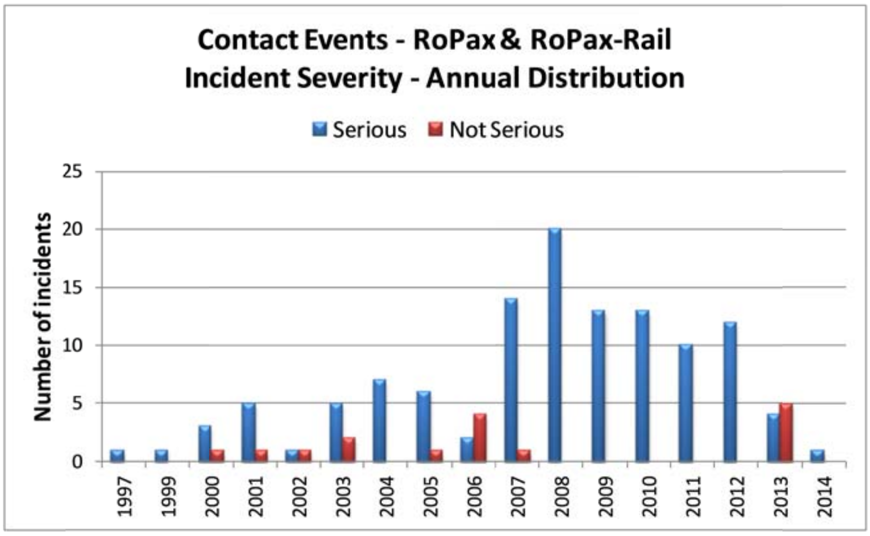

Figure 21: Annual distribution of RoPax and RoPax-Rail contact accidents

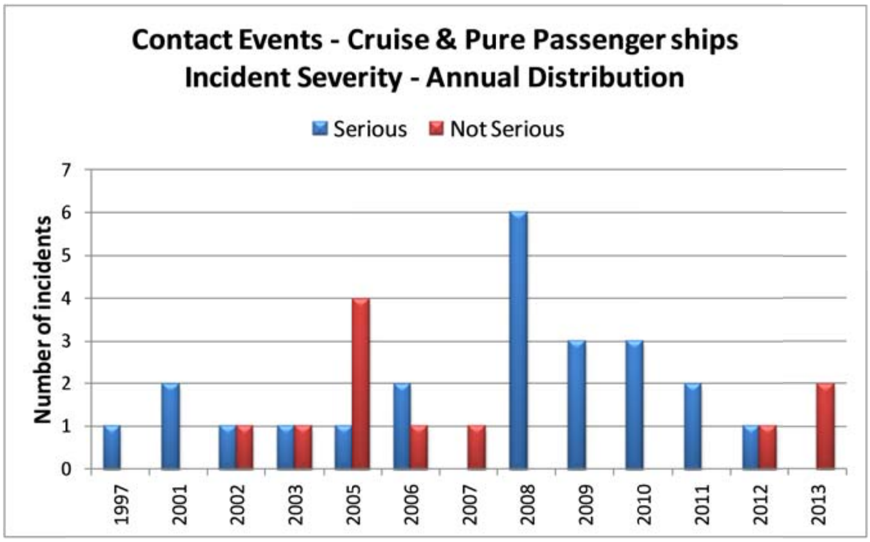

Figure 22: Annual distribution of Cruise ships and Pure Passenger ships contact accidents

A considerable increase in the number of accidents per year is observed roughly after 2005 in the above figures. The same tendency has been observed also in other studies, looking to other accident types and/or other ship types. Most probably, this tendency has to do with a change in the reporting practice. It should be also noted that, since we are looking at accidents to ships being built on or after 1982, in 1990 we are considering only a part of the fleet at risk, with an age not greater than 8 years, while in the following years we are considering an increasing percentage of the fleet (e.g. in 2008 ships with an age up to 26 years). This fact partly explains the small number of accidents around the year 1990, and its subsequent gradual increase, up to year 2008. Apart from a possible congestion of sea routes due to the increased number of ships during the last decades, there is no obvious reason to believe that there is any real increase in the accidents frequency over the last 10 years, and it is concluded that the recent figures are closer to reality than older data. Therefore, in the calculation of the initial accidents frequency, only data from year 2000 up to year 2013 were used.

The location of the breach(es) along the hull of the ship in case of collision accidents to passenger ships is summarised in Table 18 to Table 20.

Table 18: Passenger ships database: location of breach(es) per type of ship for collision accidents (struck & striking)

Hull Breach Location	RoPax & RoPax Rail	Cruise & Pure Passenger Ships	Total
Side	38	11	49
Bottom	0	0	0
Bow	7	2	9
Stern	2	1	3
Outfitting	1	0	1
Unclear	15	2	17
None	43	14	57
Total	106	30	136

Table 19: Passenger ships database: location of breach(es) for collision accidents to RoPax & RoPax-Rail ships (struck / striking)

Hull Breach Location	Struck	Striking	Unclear	Total
Side	14	8	16	38
Bottom	0	0	0	0
Bow	1	6	0	7
Stern	1	0	1	2
Outfitting	0	0	1	1
Unclear	3	5	7	15
None	12	15	16	43
Total	31	34	41	106

Table 20: Passenger ships database: location of breach(es) for collision accidents to cruise & pure passenger ships (struck / striking)

Hull Breach Location	Struck	Striking	Unclear	Total
Side	5	3	3	11
Bottom	0	0	0	0
Bow	0	2	0	2
Stern	1	0	0	1
Outfitting	0	0	0	0
Unclear	0	2	0	2
None	3	4	7	14
Total	9	11	10	30

The location of the breach(es) along the hull of the ship in case of grounding and contact accidents to passenger ships is summarised in Table 21 and Table 22.

Table 21: Passenger ships database: location of breach(es) per type of ship for grounding accidents

Hull Breach Location	RoPax & RoPax Rail	Cruise & pure passenger ships	Total
Side	9	4	13
Bottom	15	12	27
Bow	2	0	2
Stern	0	0	0
Outfitting	7	5	12
Unclear	21	7	28
None	28	16	44
Total	82	44	126

Table 22: Passenger ships database: location of breach(es) per type of ship for contact accidents

Hull Breach Location	RoPax & RoPax Rail	Cruise & pure passenger ships	Total
Side	66	8	74
Bottom	0	0	0
Bow	0	0	0
Stern	0	0	0
Outfitting	3	5	8
Unclear	22	3	25
None	43	18	61
Total	134	34	168

8.4.2.2 Containerships

In total, 866 accidents to containerships have been identified and included in the data base. Their distribution with respect to the accident types considered and the origin of information is presented in Table 23.

Table 23: Containerships database: distribution of data with respect to the type of accident and origin of information

	Collisions	Groundings	Contacts	Total
CONTIOPT	466	265	135	866
EMSA III	0	0	0	0
TOTAL	466	265	135	866

The distribution of collected accidents with respect to the types of accident considered and the area of operation at the time of the accident is presented in Table 24.

Table 24: Containerships database: distribution of data with respect to the type of accident and area of operation

	Collisions	Groundings	Contacts	Total
Open Sea	93	16	7	116
Limited waters	225	195	29	449
Terminal areas	145	53	99	297
Unknown	3	1	0	4
TOTAL	466	265	135	866

The impact of the accident for the three accident types considered is presented in Table 25. The impact of the collected accidents on human life (number of persons killed plus number of persons missing) is presented in Table 26.

Table 25: Impact of the accident for the case of containerships

	Collisions	Groundings	Contacts	Total
No damage sustained	3	7	2	12
Minor damage	202	57	47	306
Major damage	206	108	71	385
Total Loss	0	6	0	6
Break up	0	5	0	5
Unknown	55	82	15	152
TOTAL	466	265	135	866

Table 26: Impact on human life

	Collisions	Groundings	Contacts	Total
Containerships	8	1	0	9

The annual distribution of serious and non-serious accidents to containerships is presented in the following figures.

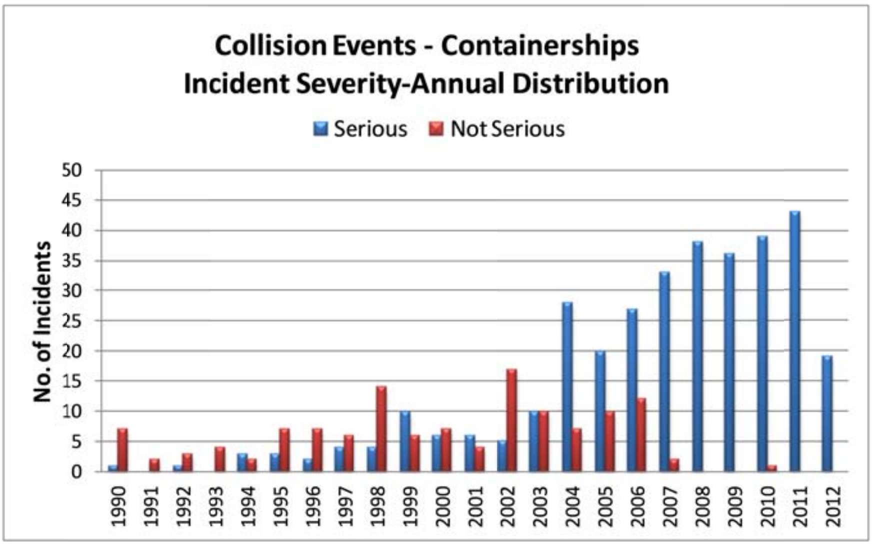

Figure 23: Annual distribution of containerships collision accidents

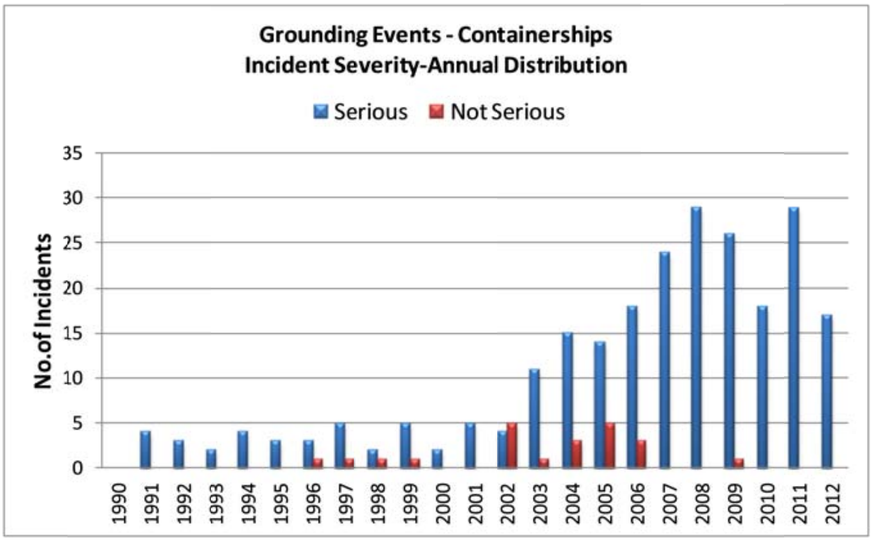

Figure 24: Annual distribution of containerships grounding accidents

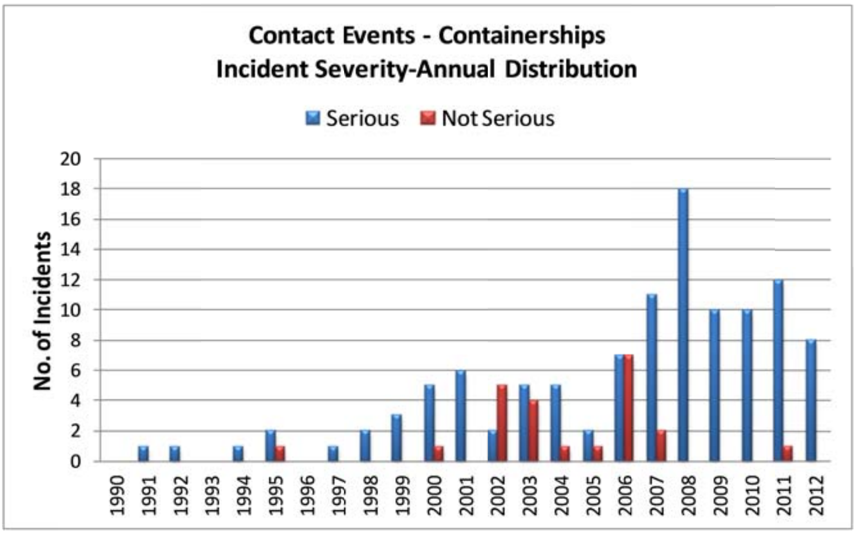

Figure 25: Annual distribution of containerships contact accidents

The location of the breach(es) along the hull of the ship in case of collision accidents to containerships is summarised in Table 27.

Table 27: Containerships data base: location of breach(es) for collision accidents

Hull Breach Location	Struck	Striking	Unclear	Total
Side	60	38	3	101
Bottom	0	0	0	0
Bow	0	32	0	32
Stern	2	0	0	2
Outfitting	2	0	1	3
Unclear	46	56	49	151
None	48	75	54	177
Total	158	201	107	466

The location of the breach(es) along the hull of the ship in case of grounding and contact accidents of containerships is reported in Table 28.

Table 28: Containerships data base: location of breach(es) for grounding and contact accidents

Hull Breach Location	Grounding Accidents	Contact Accidents	Total
Side	20	32	52
Bottom	47	3	50
Bow	6	13	19
Stern	0	1	1
Outfitting	14	10	24
Unclear	53	42	95
None	125	34	159
Total	265	135	400

8.4.2.3 Side hull breaches due to grounding and contact accident

One of the main objectives of the development of the accident databases was to obtain sufficient quantitative data to support the development of a probabilistic model for the location and extent of a hull breach as a result of a grounding or a contact accident. The initial scope of the present study was somehow limited to the case of (racking) damages due to groundings. During the elaboration of the work however, it was recognized that contacts should be included at least in the database and probably also in the development of the probabilistic model.

Two sets of geometric characteristics were selected in Task 3 in order to uniquely define the location and extent of a hull breach due to a bottom or side damage [8], [3], [4] and [9]. These characteristics are discussed in §8.3.1 and §8.3.2 and are summarised again, for ease of reference, in Table 29. It should be noted that in case of multiple breaches, an artificial damage envelope is used, corresponding to the bounding region (box) enclosing all the breaches. This is the same procedure as the one followed in GOALDS for the case of bottom damages.

Table 29: Geometrical Modelling of Bottom / Side Breach

Bottom Damage	Side Damage
Longitudinal position of forward end of damage	Longitudinal position of forward end of damage
Longitudinal extent of potential damage, i.e. potential damage length	Longitudinal extent of potential damage, i.e. potential damage length
Transversal dimensionless position of centre of measured damage	Transversal extent of potential damage, i.e. potential damage penetration
Transversal extent of potential damage, i.e. potential damage width	Vertical position of lower limit of potential damage
Vertical extent of potential damage, i.e. potential damage penetration	Height of potential damage above its lower limit
	Indicator for the side of damage (Port or Starboard)

Although the number of accidents in the two databases is quite large, only in a limited number of cases it was possible to retrieve quantitative information regarding the location and extent of the resulting hull breaches. As a matter of fact, this type of information was omitted even from the investigation reports in several cases. It should be reminded that in this study we were particularly interested in accidents resulting to hull breaches to the side of the ship, since the case of the bottom damage was investigated by the GOALDS project. The number of accidents for which it was possible to find the required quantitative information regarding various the breach characteristics is presented in Table 30 (side breaches only).

Table 30: Collected quantitative data for the location and extent of side hull breaches

	Passenger ships		Containerships		Total
	Groundings	Contacts	Groundings	Contacts	
Longitudinal position of forward end of damage	4	10	0	6	20
Longitudinal extent of potential damage	5	29	3	13	50
Transversal extent (penetration) of potential damage	1	1	0	3	5
Vertical position of lower limit of potential damage	4	13	2	4	23
Height of potential damage above its lower limit	4	13	1	7	25

As it may be observed in Table 30, quantitative information regarding the actual location and extent of the resulting hull breaches is rather scarce. However, for some of the cases included in Table 30, quantitative information in the investigations report was missing, but it was possible to derive reasonable estimations based on other evidence (such as drawings or photographs of the breaches). The damage characteristic for which it was most difficult to find quantitative information was the transverse extent (penetration). From the five accidents included in Table 30, only in the case of one passenger ship grounding and one containership contact it was possible to find explicit measurements of the resulting penetration. For the remaining three cases the penetration was estimated based on other evidence. However, for 25 additional accidents (18 passenger vessels, 7 container vessels) it is known that the penetration was "small". In these cases, the breach was qualitatively described as a "gash", "tear", "crack" or "minor". This fact was explored during the development of the probabilistic model for the side damage characteristics in order to support the development of reasonable non-dimensional distributions for the potential damage penetration.

A possible explanation for the lack of quantitative information on the damage depth would be that it is not possible to measure the penetration unless an inner bulkhead has been involved. Passenger ships are mainly transversely subdivided; therefore the actual size of a (small) penetration has no impact on the survivability of the ship. In addition, in the absence of a longitudinal boundary in a small distance from the hull, it may seem meaningless to define and measure the actual penetration (the longitudinal bulkheads limiting the lower hold in the case of large RoPax ships are located at a transverse distance from the outer hull which is very far compared with the penetration from a typical gash). In the case of the containerships, it seems that the inner hull was not affected from the accidents, which is also supporting the hypothesis of relatively shallow penetrations.

8.5 Probabilistic model for bottom damage characteristics

During the GOALDS project, a probabilistic model for bottom damage characteristics was developed [8], starting from the GOALDS database of grounding accident data and associated bottom damage characteristics [7]. The GOALDS database represents an updated and cleaned version of the database for grounding damages originally collected in the framework of the HARDER project.

During GOALDS, separate probabilistic models were developed for "full ships" (tankers and bulk carriers) and "non-full ships" (other type of vessels). Furthermore, a modelling was developed also considering data from all types of vessels, as a single dataset ("all ships" model). Passenger vessels were considered to be sufficiently well represented by damage characteristics in the category of "non-full ships".

According to this background, herein, the GOALDS model for "non-full ships" [8] has been considered, in order to provide appropriate probability distributions for damage characteristics of grounding damages of type "B00" [3] and [4], with the aim of applying such model to the specific case of passenger vessels. Also, in the implementation of the GOALDS probabilistic model, suggestions given in [6] have been taken into account.

The distributions given in [8] for all damage characteristics have been used, with the exception of the distribution for the transversal position of the damage which has been modified in accordance with the indications in [6]. The difference between [8] and [6] regarding the distribution of transversal position of the centre of measured damage is that, in [8], such distribution is conventionally assumed to be uniform on a support equal to the reference ship breadth (B), while in [6] it is suggested to use a distribution which is uniform on a support equal to the local ship breadth, at a specified waterline at a height of z^* from the base plane and at a section corresponding to the forward end of the damage ($b\left(X_F, z^*\right)$). Such modification is assumed to be acceptable in view of the fact that the distribution of the transversal position of the centre of measured damage in GOALDS was not directly derived from the data, due to the absence of such information in the database, and it was therefore assumed to be uniform. Regarding damage penetration, the ship-size-dependent model developed in GOALDS has been used (see Appendix 3 in [8]).

Summarising, the considered probabilistic model, based on GOALDS results, provide distributions for the following damage characteristics relevant to type "B00" damages, i.e. bottom grounding damages:

- Longitudinal position of forward end of damage: X_F [m] (see Table 31);
- Transversal dimensionless position of centre of measured damage: $\eta_{dam} = Y_{dam} / b\left(X_F, z^*\right)$ [-] (see Table 32) ;
- Longitudinal extent of potential damage, i.e. potential damage length: $L_{x,p}$ [m] (see Table 33);
- Transversal extent of potential damage, i.e. potential damage width: $L_{y,p}$ [m] (see Table 34);
- Vertical extent of potential damage, i.e. potential damage penetration: $L_{z,p}$ [m] (see Table 35).

The vertical position of the waterline used for the transversal positioning of damage, z^* [m], is herein fixed to correspond to the upper limit of the damage.

Table 31: Distribution of dimensionless longitudinal position of forward end of damage.

Dimensionless longitudinal position of forward end of damage $\xi_{F,dam} = X_F / L_{ship}$, $\xi_{F,dam} \in [0,1]$	
$CDF(x)$	$\alpha_1 \cdot x + (1-\alpha_1) \cdot x^{\alpha_2}$
$PDF(x)$	$\alpha_1 + \alpha_2 \cdot (1-\alpha_1) \cdot x^{(\alpha_2 - 1)}$
α_1	0.325
α_2	3.104
Note: here X_F is intended to be measured starting with $X_F = 0$ at X_{MIN} and $L_{ship} = X_{MAX} - X_{MIN}$.	

Table 32: Distribution of dimensionless transversal position of centre of measured damage.

Dimensionless transversal position of centre of measured damage $\eta_{dam} = Y_{dam} / b\left(X_F, z^*\right)$, $\eta_{dam} \in [-0.5, 0.5]$	
$CDF(x)$	$x + 0.5$
$PDF(x)$	1
Note: ship centreplane is assumed to be at $y = 0$	

Table 33: Distribution of dimensionless longitudinal extent of potential damage (potential damage length).

Dimensionless potential damage length $\lambda_{x,p} = L_{x,p} / L_{ship}$, $\lambda_{x,p} \in [0,1]$	
$CDF(x)$	$\dfrac{\alpha_1 \cdot x^2 + \alpha_2 \cdot x}{x + (\alpha_1 + \alpha_2 - 1)}$
$PDF(x)$	$\dfrac{\alpha_1 \cdot x^2 + (\alpha_1 + \alpha_2 - 1) \cdot (2 \cdot \alpha_1 \cdot x + \alpha_2)}{[x + (\alpha_1 + \alpha_2 - 1)]^2}$
α_1	0.231
α_2	0.845

Table 34: Distribution of dimensionless transversal extent of potential damage (potential damage width).

Dimensionless potential damage width $\lambda_{y,p} = L_{y,p} / B$, $\lambda_{y,p} \in [0,1]$	
$CDF(x)$	$\dfrac{\alpha_1 \cdot x^2 + \alpha_2 \cdot x}{x + (\alpha_1 + \alpha_2 - 1)}$
$PDF(x)$	$\dfrac{\alpha_1 \cdot x^2 + (\alpha_1 + \alpha_2 - 1) \cdot (2 \cdot \alpha_1 \cdot x + \alpha_2)}{[x + (\alpha_1 + \alpha_2 - 1)]^2}$
α_1	0.110
α_2	0.926

Table 35: Distribution of dimensional vertical extent of potential damage (potential damage penetration), measured from baseline. Ship-size-dependent model.

Dimensional potential damage penetration $L_{z,p}$ [m] , $L_{z,p} \in [0, L_{z,p,\max}]$	
$CDF(x)$	$\dfrac{\alpha_1 \cdot x}{x + L_{z,p,\max} \cdot (\alpha_1 - 1)}$
$PDF(x)$	$\dfrac{L_{z,p,\max} \cdot \alpha_1 \cdot (\alpha_1 - 1)}{[x + L_{z,p,\max} \cdot (\alpha_1 - 1)]^2}$
Parameters	$\alpha_1 = 1.170$ $\alpha_B = 0.636$ $k_{MB} = 0.503$ $L_{z,p,\max}(B) = \min\{k_{MB} \cdot B^{\alpha_B}, T\}$ with B in $[m]$
Note: this is the distribution of the damage penetration measured from the bottom, fixing the vertical position of the bottom, conventionally, at $z_{bottom} = 0$	

8.6 Probabilistic model for side damage characteristics

This section provides results from the probabilistic modelling of side damage characteristics. The probabilistic model has been developed starting from the available database.

8.6.1 Available data

The dataset which has been used for the statistical analysis represents a database of damage characteristics for passenger and container vessels, following grounding/contact accidents.

The aim of the analysis reported herein is to develop a probabilistic model for side damage characteristics intended to be used in case of passenger vessels. However, in order to try increasing the available data set, also data coming from some accidents occurred to containerships have been considered. The rationale behind the addition of this data comes, mainly, from the outcomes of the GOALDS project. Indeed, in the course of the GOALDS statistical analysis of bottom grounding damage characteristics, and associated subsequent probabilistic modelling, it was noted that vessel types which could be categorised as "non-full" were characterised by similar distributions of grounding damage characteristics [27][7][8]. On the basis of this observation, a single modelling developed for the wider category of non-full was considered to be sufficiently representative also for passenger vessels. According to this background, it has been considered appropriate, herein, to consider passenger vessels and also containerships together, with the aim of developing a model suitable for non-full vessels and, hence, for passenger vessels. Nevertheless, in the course of the following statistical analysis, passenger vessels and container vessels will be separately highlighted, in order to provide the reader with a clear evidence of possible differences in the behaviour of the data between the two categories of vessels. When necessary, the observed differences between passenger and container vessels will be discussed during the exploratory data analysis.

A summarising table regarding database characteristics is reported in Table 36, where data are reported for the entire database and, separately, also for passenger vessels (referred to as "Pass.") and containerships (referred to as "Cont.").

Table 36: Main information regarding data in the database.

Total number of samples:	63 (Pass.: 36; Cont.: 27)
Contacts:	53 (Pass.: 31 ; Cont.: 22)
Groundings:	10 (Pass.: 5 ; Cont.: 5)
Range of length between perpendiculars:	Maximum: 281.29m (Pass.: 269.14m ; Cont.: 281.29m) Minimum: 64.90m (Pass: 64.90m ; Cont.: 96.00m)
Range of breadth:	Maximum: 40.00m (Pass.: 35.50m ; Cont.: 40.00m) Minimum: 14.00m (Pass: 14.00m ; Cont.: 17.20m)
Range of draught:	Maximum: 14.02m (Pass.: 8.30m ; Cont.: 14.02m) Minimum: 2.50m (Pass: 2.50m ; Cont.: 6.51m)

Data available from the database, and relevant to the present analysis, are the following:

- Measured longitudinal position of forward end of damage: X_F [m];
- Measured longitudinal extent of damage, i.e. measured damage length: L_x [m];
- Measured transversal extent of damage, i.e. measured damage penetration: L_y [m];
- Measured vertical position of lower limit of damage: z_{LL} [m];
- Measured height of damage above its lower limit: H [m];

It is important to note that, similarly to what was done also in the framework of the GOALDS project [27][7][8][26], in case of damages characterised by multiple holes, the variables described above represent the overall extent of the part of the vessel affected by the damage, and not the extent of the single hole. This means that, basically, a multiple-hole damage is substituted by an "equivalent" damage representing the envelope of the damaged region of the vessel, in an approximate way. Bearing in mind the overall complexity of the problem, such approach is considered to be an acceptable "equivalent" simplification for the determination of the probability of flooding of different compartments. At the same time, the approach is considered to be an acceptable "equivalent" simplification when static ship stability is considered. Of course, the approach cannot be considered suitable for the characterisation of damages to be used for dynamic flooding simulations, where the actual dimension of each breach on the vessel is fundamental in determining the flooding rate and, thus, the dynamic/transient behaviour of the vessel. However, this approach of substituting multiple damages by the described "equivalent" damage is regarded to be appropriate, since the probabilistic model coming from the analysis reported herein is intended to be applied to the case of static damage stability evaluation.

As a further introductory note, it is anticipated that data regarding damage penetration are very scarce in the dataset, and mostly of qualitative type. This aspect will be further discussed in the relevant section of this report.

8.6.2 Scope of the analysis and notes on the methodology

The scope of the analysis is to derive appropriate probabilistic models, defining the distributions of the random variables, characterising a damage occurring on the side of the vessel. As already anticipated, the random variables describing the potential damage are the following:

- Indicator for the side of damage: ind_{side} [-] (+1: port side ; −1: starboard side)
- Longitudinal position of forward end of damage: X_F [m];
- Longitudinal extent of potential damage, i.e. potential damage length: $L_{x,p}$ [m];
- Transversal extent of potential damage, i.e. potential damage penetration: $L_{y,p}$ [m];
- Vertical position of lower limit of potential damage: $z_{LL,p}$ [m];
- Height of potential damage above its lower limit: H_p [m];

Moreover, an additional modelling variable z^* [m] needs to be defined, representing the vertical position of waterline for the determination of the damage penetration surface. This variable will be defined with the aim of maintaining simplicity and robustness of the model.

From the description of available data in the previous section, it is clear that the number of samples is not large. Moreover, not all recorded accidents contain all the information. This results in the fact that, for each specific random variable to be modelled, the number of available data is even less than the total number of samples. The reduction in the available data is particularly relevant when considering more than one random variable at time, as it will later be the case for the probabilistic modelling of $z_{LL,p}$ and H_p.

Due to the large level of uncertainty coming from the limited sample size, a procedure will be followed in the modelling development using explanatory data analysis to drive the selection of the mathematical models for the probability distributions of the various random variables. Such models will be defined in a way which is consistent with the data, trying to keep the models as simple as possible, and trying to keep, when possible and justifiable, the same modelling already proposed in case of bottom damage [8][4]. That is to say that the modelling will not be based exclusively on data fitting, but qualitative considerations will also play an important role.

Moreover, the modelling will be developed keeping explicit evidence of the associated characterising parameters. Such explicit parameterisation of the probabilistic models is aimed at providing analytical tools which can be easily updated/tuned/modified, if deemed necessary.

The main assumptions which will be used in the probabilistic modelling are the following:

- The variables ind_{side}, X_F, $L_{x,p}$, $L_{y,p}$ and $z_{LL,p}$, as well as the variables ind_{side}, X_F, $L_{x,p}$, $L_{y,p}$ and H_p, are statistically independent each other;
- The variables $z_{LL,p}$ and H_p are statistically independent with respect to ind_{side}, X_F, $L_{x,p}$, $L_{y,p}$, but it are statistically dependent each other. This means, in particular, that H_p, i.e. the vertical extent of the potential damage, is considered to be statistically dependent with respect to $z_{LL,p}$, i.e. the vertical position of the lower limit of potential damage.

It is to be noted that actual (measured) length of the damage L_x, i.e. the part of the potential length $L_{x,p}$ actually within the limits of the vessel (which is the variable measured in the database), cannot be independent of X_F (see [8]). However, $L_{x,p}$ is meant to be a random variable which, after the truncation at the aft end of the vessel, is giving a good representation of the distribution of damage length available in the database.

As a final comment it is noted that, in the following analysis, the length between perpendiculars will be considered as the "reference length of the ship", L_{ship}. The reference ship breadth, B_{ship}, and the reference ship draught, T_{ship}, correspond to those reported in the available database.

8.6.3 Damage side

In the probabilistic model it is assumed that the damage has an equal probability of occurring on each side of the vessel. This meaning that:

$$\begin{cases} \Pr\{ind_{side} = +1\} = \Pr\{\text{port side damage}\} = \alpha_1 \\ \Pr\{ind_{side} = -1\} = \Pr\{\text{starboard side damage}\} = 1 - \alpha_1 \\ \alpha_1 = 0.5 \end{cases} \quad (7)$$

Changing the value of the parameter α_1 in (7) allows to model a different probability of damage occurrence for the port side and the starboard side of the vessel.

8.6.4 Forward end of damage

The nondimensional longitudinal position of the forward end of damage is defined as:

$$\xi_{F,dam} = \frac{X_F}{L_{ship}} \quad (8)$$

which is in line with [27][7][8]. Figure 26 shows a scatter plot of $\xi_{F,dam}$ versus the ship length using the available data. The total number of available samples for the analysis of this variable is 20 (Pass.: 14 ; Cont.: 6). Of these 20 samples, 16 are contacts (Pass.: 10 ; Cont.: 6) and 4 are groundings (Pass.: 4 ; Cont.: 0). It can be noticed that the number of data is quite limited, and this unavoidably leads to a large uncertainty in the outcomes from any statistical analysis performed on the dataset.

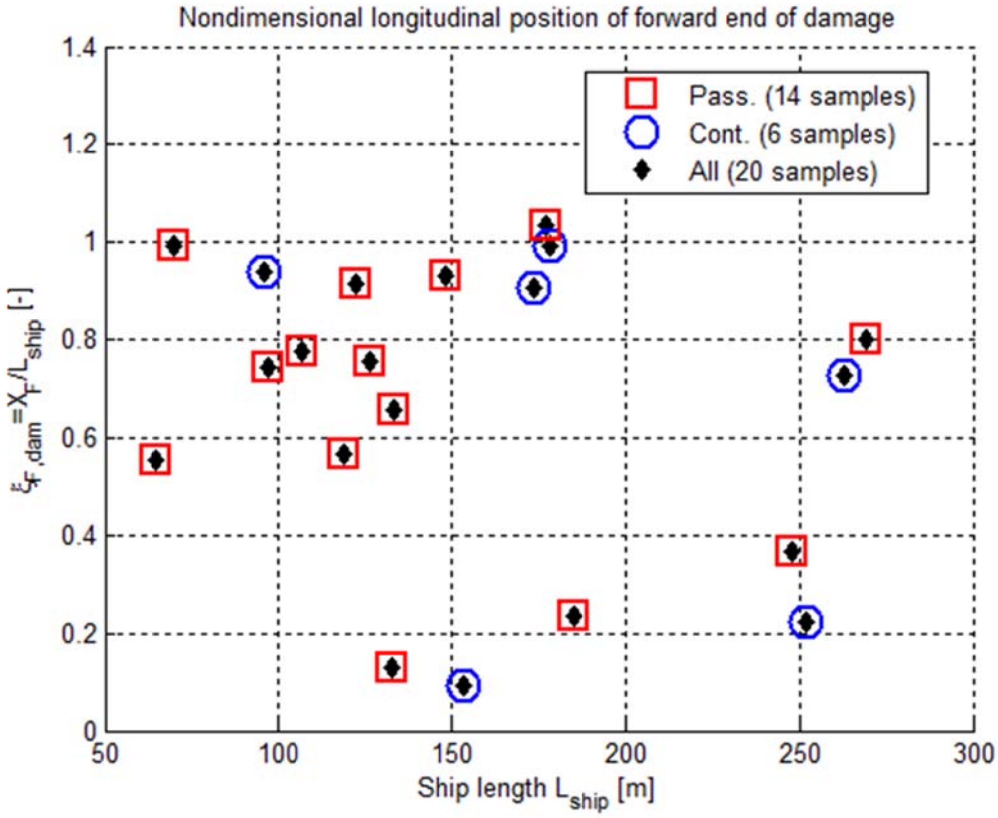

Figure 26: Scatter plot of nondimensional longitudinal position of forward end of damage versus the ship length.

The analysis of the available data [2] indicates that it can be assumed acceptable to apply a nondimensional ship-size-independent probabilistic model for $\xi_{F,dam}$, when the size of the vessel is measured by means of the ship length. The first aim of the analysis is to check whether a nondimensional approach, independent of the ship size, can be used for describing the distribution of the forward end of damage. It might be useful to remind here, that the underlying theoretical background in present SOLAS 2009 assumes a nondimensional, ship-size-independent modelling for the longitudinal position of the damage due to collision. Moreover, a nondimensional ship-size-independent model for the longitudinal position of the forward end of damage was also considered appropriate within the GOALDS project for the probabilistic modelling of bottom damage characteristics [27][7][8].

According to the obtained result, the cumulative distribution (CDF) of $\xi_{F,dam}$, together with associated 95% confidence intervals, has been estimated from the available data, separately for the groups of all vessels, only for passenger vessels and only for container vessels. Results are shown in Figure 27. The same figure also reports the GOALDS model (cumulative distribution – CDF – and probability density – PDF – functions) originally derived for bottom grounding damages, which takes the following form [8]:

$$cdf_{\xi_{F,dam}}(\xi_{F,dam}=x)=\alpha_1\cdot x+(1-\alpha_1)\cdot x^{\alpha_2}$$
$$pdf_{\xi_{F,dam}}(\xi_{F,dam}=x)=\alpha_1+\alpha_2\cdot(1-\alpha_1)\cdot x^{(\alpha_2-1)}$$
$$\alpha_1=0.325\ \ ;\ \ \alpha_2=3.104$$
$$\xi_{F,dam}\in[0,1] \tag{9}$$

The corresponding dimensional version of (9) is:

$$cdf_{X_F}(X_F=x)=\alpha_1\cdot\frac{x}{X_{F,\max}}+(1-\alpha_1)\cdot\left(\frac{x}{X_{F,\max}}\right)^{\alpha_2}$$
$$pdf_{X_F}(X_F=x)=\frac{1}{X_{F,\max}}\left[\alpha_1+\alpha_2\cdot(1-\alpha_1)\cdot\left(\frac{x}{X_{F,\max}}\right)^{(\alpha_2-1)}\right]$$
$$\alpha_1=0.325\ \ ;\ \ \alpha_2=3.104\ \ ;\ \ X_{F,\max}=L_{ship}$$
$$X_F\in\left[0,X_{F,\max}\right] \tag{10}$$

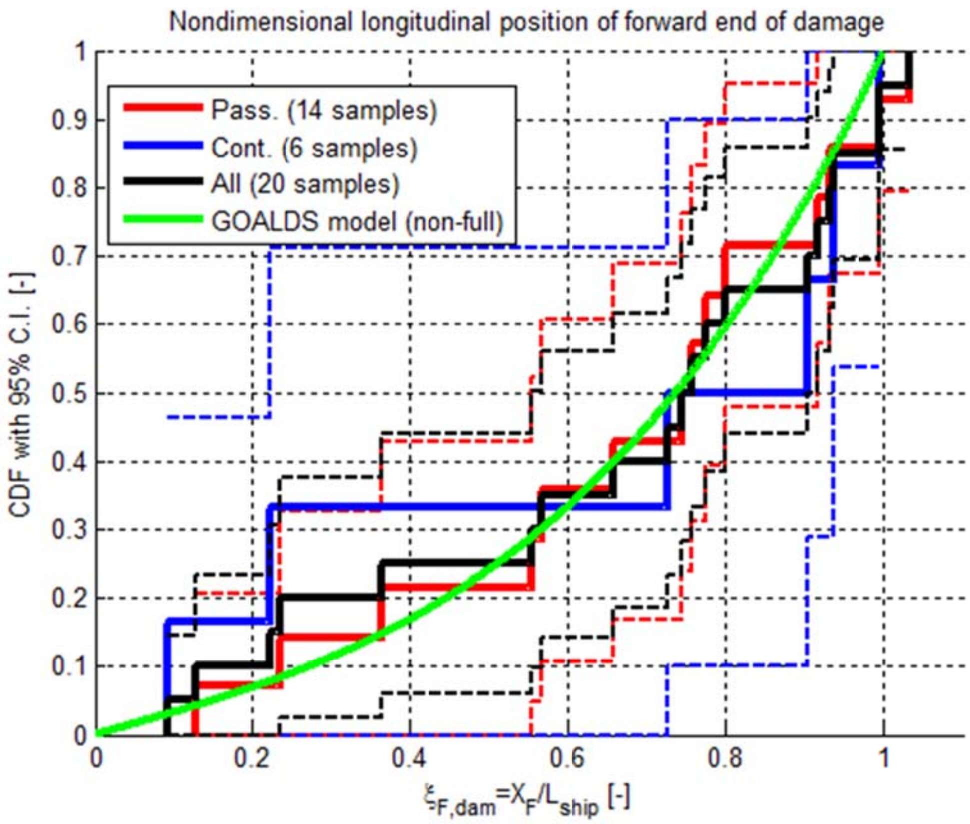

Figure 27: Cumulative distribution (CDF) of nondimensional longitudinal position of forward end of damage, and comparison with GOALDS modelling for bottom grounding damages for non-full vessels.

Looking at the results in Figure 27 it can be seen that the uncertainty in the estimation of the cumulative distribution for $\xi_{F,dam}$ is large, due to the limited sample size. Nevertheless, qualitatively, container vessels and passenger vessels seem to show a quite similar behaviour, which seems to justify the idea of merging these two categories of vessels as it done in GOALDS. In general, there is a larger probability for the damage to have a starting point in the forward part of the vessel and the observed distribution is very well approximated by the GOALDS model, which was developed on the basis of a significantly larger sample of data. As a result of the analysis, it can be considered appropriate to use the GOALDS modelling, originally developed for bottom grounding damages also for the modelling of the cumulative distribution of $\xi_{F,dam}$ in case of side damages.

8.6.5 Damage length

The nondimensional measured damage length is defined as:

$$\lambda_x = \frac{L_x}{L_{ship}} \tag{11}$$

where L_x [m] is the measured longitudinal damage extent as reported in the database. The definition (11) is in line with [27][7][8].

Figure 28 shows a scatter plot of λ_x versus the ship length using the available data. The total number of available samples for the analysis of this variable is 53 (Pass.: 34 ; Cont.: 19). Of these 53 samples, 45 are contacts (Pass.: 29 ; Cont.: 16) and 8 are groundings (Pass.: 5 ; Cont.: 3). Although the sample size is larger than in case of the analysis of X_F, still the number of data is not very large, and this unavoidably leads to a relatively large uncertainty in the outcomes from any statistical analysis performed on the dataset.

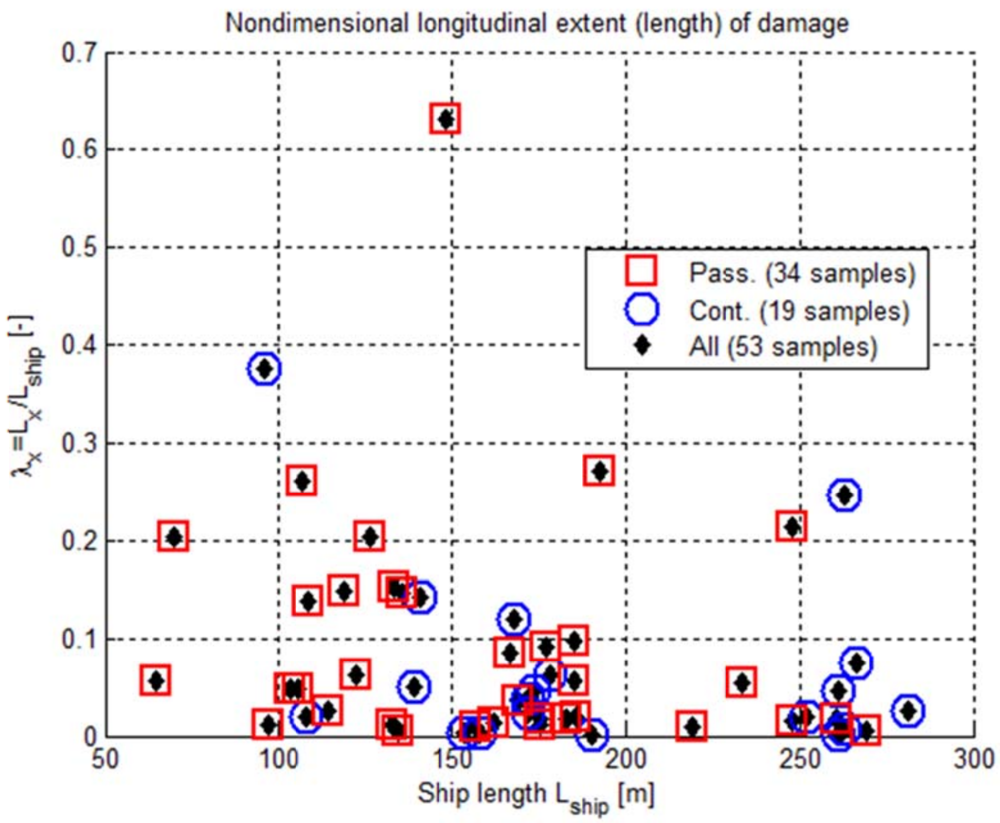

Figure 28: Scatter plot of nondimensional longitudinal extent (length) of damage versus the ship length.

The analysis of available data [2] indicates that it is acceptable to apply a nondimensional ship-size-independent probabilistic model for λ_x, when the size of the vessel is measured in terms of ship length.

The next step in the analysis is the determination of a model for the distribution of the so-called potential damage length [8]. Indeed, following [29] and as explained in [8], it is not possible to consider the measured nondimensional damage length λ_x and the nondimensional longitudinal position of the forward end of the damage $\xi_{F,dam}$, as independent random variables. This is because, for geometrical reason, the maximum measurable nondimensional longitudinal extent of the damage, say $\lambda_{x,\max}$, depends on the longitudinal position of the forward end of the damage, $\xi_{F,dam}$. In order to model the longitudinal positioning of the damage and the longitudinal damage extent as independent random variables, which is the aim herein and which is the approach used in [8], it is necessary to introduce a virtual random variable, namely the so-called potential damage length $\lambda_{x,p}$, in such a way that the distribution of λ_x coming from the probabilistic modelling of $\xi_{F,dam}$ and $\lambda_{x,p}$ is in line with the actual distribution observed from the available data. Following [8], and assuming that the maximum nondimensional potential damage length is smaller or equal to 1 (i.e. maximum potential damage length smaller or equal to the ship length), the relation between the cumulative distributions of the involved random variables is (eq. (A2.4) in [8]):

$$cdf_{\lambda_{x,p}}\left(\lambda_{x,p}=q\right)=\frac{cdf_{\lambda_x}\left(\lambda_x=q\right)-cdf_{\xi_{F,dam}}\left(\xi_{F,dam}=q\right)}{1-cdf_{\xi_{F,dam}}\left(\xi_{F,dam}=q\right)}=$$

$$=1-\frac{1-cdf_{\lambda_x}\left(\lambda_x=q\right)}{1-cdf_{\xi_{F,dam}}\left(\xi_{F,dam}=q\right)} \tag{12}$$

$$\text{with } q\in[0,1]$$

The distributions cdf_{λ_x} and $cdf_{\xi_{F,dam}}$ are assumed to be given, or estimated, and the distribution $cdf_{\lambda_{x,p}}$ turns out to be a consequence of the data and/or assumptions. Herein, both $cdf_{\xi_{F,dam}}$ and cdf_{λ_x} are obtained from the available data. The distribution of λ_x as estimated from the available data is shown in Figure 29.

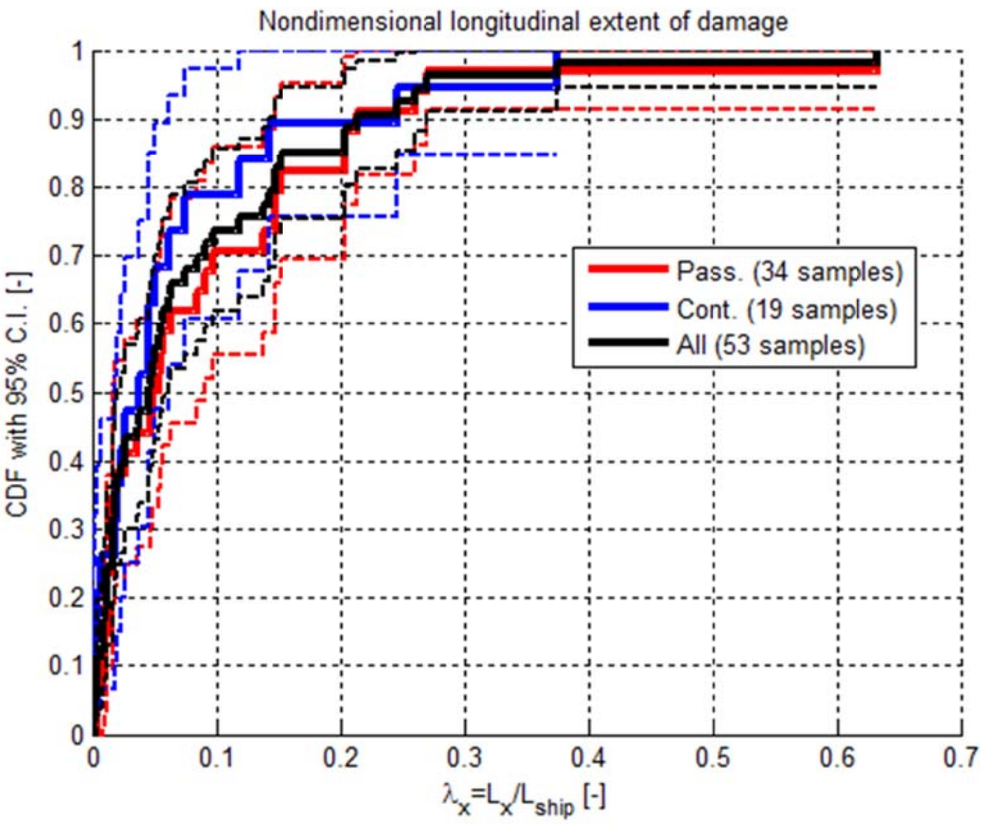

Figure 29: Cumulative distribution (CDF) of nondimensional measured longitudinal extent of damage.

In order to be in line with the GOALDS modelling for bottom grounding damages, the following analytical model is assumed for the cumulative distribution of the dimensionless potential damage length:

$$cdf_{\lambda_{x,p}}\left(\lambda_{x,p}=x\right)=\frac{\alpha_1\cdot\left(\frac{x}{\lambda_{x,p,\max}}\right)^2+\alpha_2\cdot\left(\frac{x}{\lambda_{x,p,\max}}\right)}{\left(\frac{x}{\lambda_{x,p,\max}}\right)+\left(\alpha_1+\alpha_2-1\right)}$$

$$pdf_{\lambda_{x,p}}\left(\lambda_{x,p}=x\right)=\frac{d}{dx}cdf_{\lambda_{x,p}}\bigg|_{\lambda_{x,p}=x}=\frac{\alpha_1\cdot\left(\frac{x}{\lambda_{x,p,\max}}\right)^2+\left(\alpha_1+\alpha_2-1\right)\cdot\left(2\cdot\alpha_1\cdot\left(\frac{x}{\lambda_{x,p,\max}}\right)+\alpha_2\right)}{\lambda_{x,p,\max}\cdot\left[\left(\frac{x}{\lambda_{x,p,\max}}\right)+\left(\alpha_1+\alpha_2-1\right)\right]^2} \tag{13}$$

$$\lambda_{x,p}\in\left[0,\lambda_{x,p,\max}\right]$$

where $\lambda_{x,p,\max}$ is the maximum dimensionless damage length assumed in the modelling. The corresponding dimensional version of (13) is:

$$cdf_{L_{x,p}}\left(L_{x,p}=x\right)=\frac{\alpha_1\cdot\left(\frac{x}{L_{x,p,\max}}\right)^2+\alpha_2\cdot\left(\frac{x}{L_{x,p,\max}}\right)}{\left(\frac{x}{L_{x,p,\max}}\right)+\left(\alpha_1+\alpha_2-1\right)}$$

$$pdf_{L_{x,p}}\left(L_{x,p}=x\right)=\frac{d}{dx}cdf_{L_{x,p}}\bigg|_{L_{x,p}=x}=\frac{\alpha_1\cdot\left(\frac{x}{L_{x,p,\max}}\right)^2+\left(\alpha_1+\alpha_2-1\right)\cdot\left(2\cdot\alpha_1\cdot\left(\frac{x}{L_{x,p,\max}}\right)+\alpha_2\right)}{L_{x,p,\max}\cdot\left[\left(\frac{x}{L_{x,p,\max}}\right)+\left(\alpha_1+\alpha_2-1\right)\right]^2} \tag{14}$$

$$L_{x,p}\in\left[0,L_{x,p,\max}\right]$$

From the available data $\lambda_{x,p,\max}$ is fixed a-priori to the maximum observed dimensionless damage length, namely:

$$\lambda_{x,p,\max}=0.632\quad\text{(fixed from available data)} \tag{15}$$

which corresponds to a maximum dimensional damage length equal to:

$$L_{x,p,\max}=0.632\cdot L_{ship}\quad\text{(fixed from available data)} \tag{16}$$

The determination of parameters α_1 and α_2 in (13) is, instead, carried out by means of a nonlinear least-square fitting of the model (13), using (15), on the inferred distribution $cdf_{\lambda_{x,p}}$ (according to (12)). Results from the fitting are shown in Figure 30. With reference to (13), the final model parameters are therefore as follows:

$$\lambda_{x,p,\max} = 0.632 \Leftrightarrow L_{x,p,\max} = 0.632 \cdot L_{ship} \quad \text{(fixed from available data)}$$
$$\alpha_1 = -0.03886 \quad [-0.04499, -0.03272] \qquad (17)$$
$$\alpha_2 = 1.124 \quad [1.116, 1.132]$$

Intervals reported for coefficients α_1 and α_2 correspond to 95% confidence interval from the nonlinear fit. As a result, they only reflect the fitting uncertainty, which is a small part of the overall uncertainty. In reality, the modelling of $cdf_{\lambda_{x,p}}$ has an overall uncertainty which can be considered to be comparable with, but, due to the additional uncertainty in $cdf_{\xi_{F,dam}}$, likely larger than, the uncertainty in the estimated cdf_{λ_x} (see Figure 29, and see also the discussion on a similar topic in [8]).

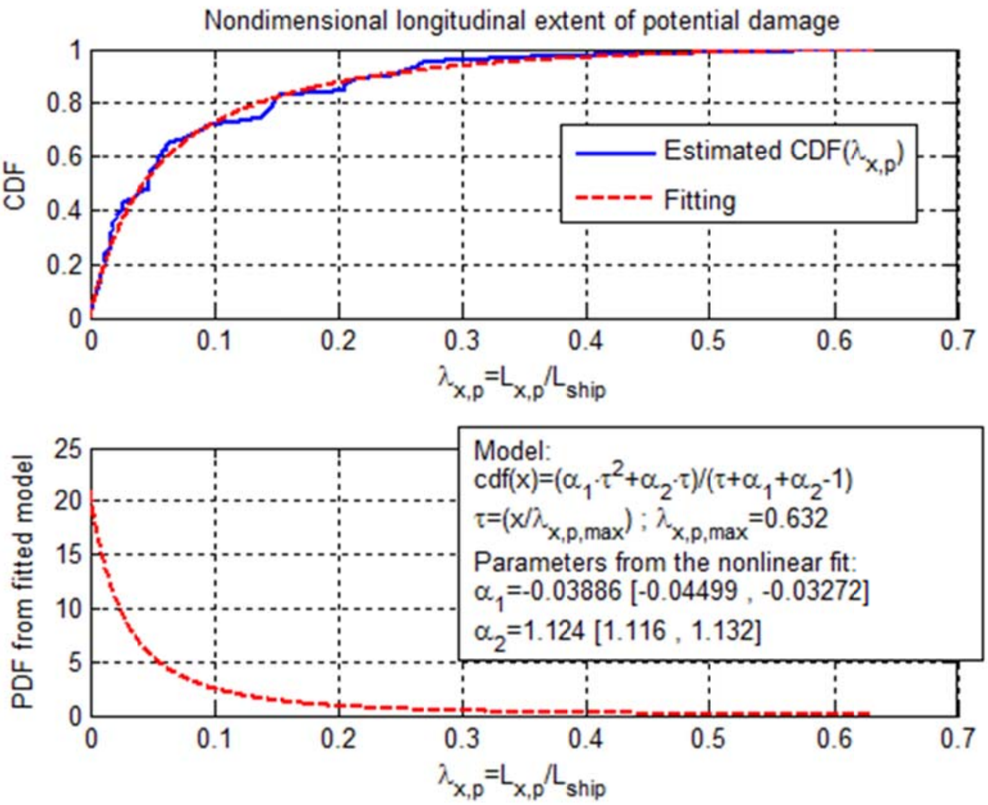

Figure 30: Fitted model for the distribution for nondimensional longitudinal extent of potential damage.

At this stage, however, it is necessary to make some further qualitative consideration regarding the modelling obtained from the available data. Indeed, available data represent accidents leading to hull breaching, which are caused by contact with rocks, with fixed installations and also with floating objects. Cases of contacts with fixed installations are expected to occur at limited speed, and hence they are expected to lead to relatively small damage lengths. In case of contacts with floating objects, it is expected that, with some exceptions (e.g. icebergs, offshore platforms (semi-submersible)) the floating object will be, usually, relatively small compared with the vessel, and it is therefore expectable that the damage length associated with such type of contacts is relatively small as well. Relatively larger damages are, instead, expected to occur when the vessel gets in contact with rocks, which is something possibly occurring at speeds up to the ship service/maximum speed. In the available database, accidents of this type are a minority. It can therefore be expected that the modelling in Figure 30 could have been influenced by accidents associated with relatively small damage lengths, shifting the distribution of the dimensionless longitudinal damage extent towards smaller values.

In the course of the GOALDS project, a modelling for the nondimensional longitudinal damage extent specific for non-full vessels was instead developed taking into account only “grounding accidents”, i.e. accidents where the vessel got in contact with the seabed [27][7][8]. It is therefore worth comparing the modelling developed herein, with the modelling developed in GOALDS, in order to highlight the differences. Such comparison is reported in Figure 31. It can be noticed that the GOALDS model is significantly shifted towards longer potential damages. This difference, which is driven by the differences in the underlying database of damages, could be the result of the fact that, in the GOALDS modelling, contacts with floating objects or fixed installations were not taken into account, while herein such cases basically represent the majority of the database. Moreover, the present modelling only addresses side damages, while the GOALDS modelling concentrated on bottom damages (although it cannot be completely ruled out that some of the accidents in the original GOALDS database were actually side, or almost-side damages).

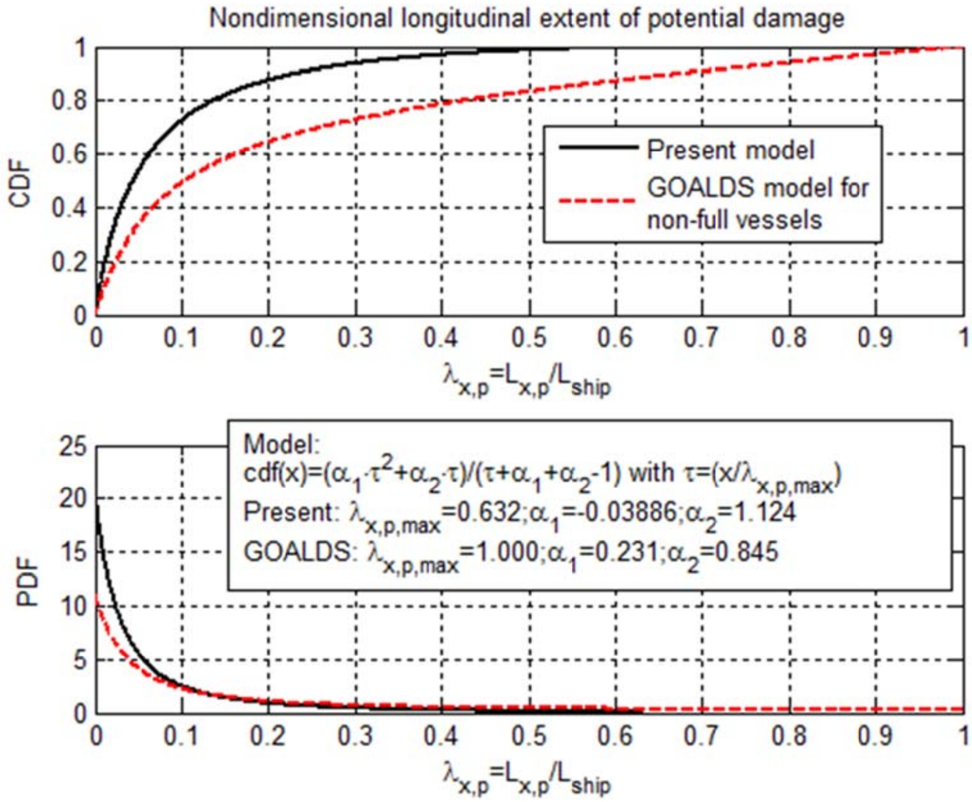

Figure 31: Distribution for nondimensional longitudinal extent of potential damage. Comparison between present modelling and GOALDS bottom grounding modelling for non-full vessels.

With the presently available data it is not possible to develop a model only addressing accident cases where the ship got in contact with rocks, i.e. a "pure grounding" model. As a result, it might be possible that the model developed herein, being characterised by a distribution of potential damage length shifted towards shorter damages, is not conservative. It would therefore not be unreasonable to consider the option of applying the modelling developed in GOALDS also for the case of side damages, or to consider the possibility of an intermediate model between the one developed herein and the one developed in GOALDS.

8.6.6 Lower limit and vertical extent of damage

The vertical position of the lower limit of damage from the ship bottom and the vertical extent of the damage are analysed together in this section because, as it will be described later, part of the analysis will deal with the possible statistical dependence of these random variables.

At first, two nondimensional damage characteristics are defined as follows:

$$\zeta_{LL} = \frac{z_{LL}}{T_{ship}} \qquad \vartheta = \frac{H}{T_{ship}} \tag{18}$$

where z_{LL} [m] is the measured vertical position of the lower edge of the damage (i.e. the lower limit of the damage) as measured from the bottom of the ship, and H [m] is the measured vertical extent of the damage, i.e. the measured vertical distance between the lower edge and the upper edge of the damage at the ship side. These two dimensional variables are made dimensionless by using the reference ship draught T_{ship} [m] reported in the database. It must be underlined that the draught T_{ship} is a reference ship draught, and not the draught at the time of accident. Although there is no complete uniformity among samples regarding the definition of T_{ship}, it can be assumed that T_{ship} is representative of a relative high reference ship draught, such as the design/scantling/summer/maximum subdivision draught.

The main objectives of the analysis of the two damage characteristics addressed in this section are:

- Understanding which type of approach is more appropriate for describing the observed behaviour: a dimensional approach or a nondimensional one;
- Understanding whether it is possible to model the two considered damage characteristics as statistically independent random variables, or whether it is necessary to introduce a statistical dependence between them;
- Understanding whether, in the context of the analysis of these two damage characteristics, it is appropriate or not to combine data coming from accidents occurred to passenger vessels with data coming from accidents occurred to container vessels.

8.6.6.1 Lower limit of damage

The starting point of the analysis is the checking of the available data regarding the lower limit of damage. Figure 32 shows a scatter plot of the available data, where z_{LL} and ζ_{LL} are reported versus the ship length and the ship draught. Data from passenger vessels and from container vessels are separately highlighted. The total number of available samples for the analysis of this variable is 23 (Pass.: 17 ; Cont.: 6). Of these 23 samples, 17 are contacts (Pass.: 13 ; Cont.: 4) and 6 are groundings (Pass.: 4 ; Cont.: 2).

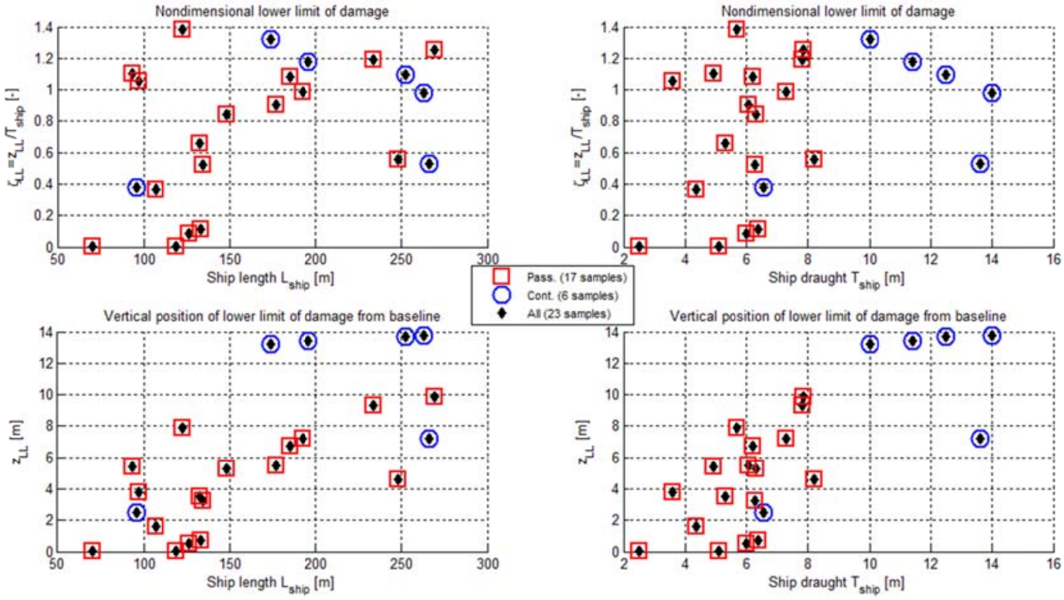

Figure 32: Scatter plot of dimensional and nondimensional vertical position of lower edge of damage from ship bottom versus ship length and ship draught.

From the analysis of available data in Figure 32, ζ_{LL} can be considered to be a more suitable variable for a simplified modelling of the vertical positioning of the damage compared with it dimensional counterpart z_{LL} [2]. The available data also indicate that, as a first step, a uniform distribution for ζ_{LL} could be considered from zero, up to a maximum dimensionless value $\zeta_{LL,p,\max}=1.4$ (the actually observed maximum value for ζ_{LL} is 1.39). However, such modelling would provide a maximum position of the lower limit of potential damage, $z_{LL,p,\max}$, which scales linearly with the ship draught. This means that, according to such a modelling, a very large draught can correspond to a maximum lower limit of the potential damage which is high above the waterline. Such a situation could be considered unlikely to occur in a real grounding accident. It is therefore worth investigating whether it could be reasonable, for practical purposes, to limit the maximum vertical position of the lower limit of damage ($z_{LL,p,\max}$) to a certain maximum value. To this end, Figure 33 reports a scatter plot of the difference $z_{LL}-T_{ship}$, i.e. the position of the lower limit of the damage above the waterline corresponding to the reference ship draught, versus the reference ship draught.

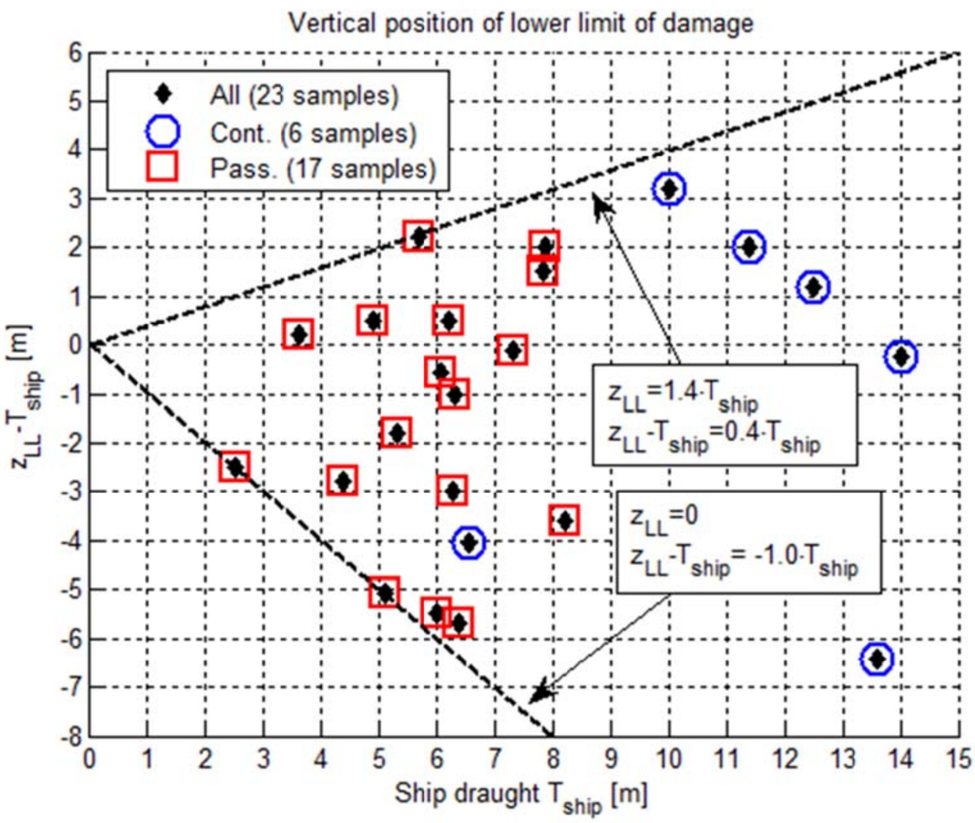

Figure 33: Scatter plot of dimensional vertical position, relative to T_{ship}, of lower edge of damage, versus ship draught.

The scatter plot in Figure 33 shows that the maximum value of $z_{LL} - T_{ship}$ is limited for large ship draughts, and a limit could be identified at a value of 3.2m, corresponding to the maximum value observed from the data. The presence of such an absolute limit could make physical sense. Indeed, it could be reasonably considered as unlikely the fact that a vessel can get in contact with a rock, or an installation, which is geometrically such as to damage only the very high part of the above water hull, without damaging the lower part. Of course there could be exceptions, such as the contact with a crane. However, being herein the interest focussed on developing a model more suitable for grounding damages, a very high damage fully above waterline could be considered a very unlikely event. Actually, the scatter plot also indicates that a lower limitation could be set to $z_{LL} - T_{ship}$. However, considering that a grounding is very much expectable to damage also the very lower part of the vessel, imposing a minimum limitation to $z_{LL} - T_{ship}$ would likely not go in the direction of what the probabilistic modelling is intended to represent.

According to the above considerations, it could be reasonable to consider as a physically justifiable option, a maximum dimensionless vertical position of the lower limit of damage as:

$$\zeta_{LL,p,\max} = \min\left\{\beta_{1,\zeta}, 1+\frac{\beta_{2,\zeta}}{T_{ship}}\right\}$$
$$\beta_{1,\zeta} = 1.4 \;\; ; \;\; \beta_{2,\zeta} = 3.2m \quad (19)$$
$$\text{with } T_{ship} \text{ in [m]}$$

Now it is necessary to verify whether the variable $\zeta_{LL,p}$ can be considered to be uniformly distributed between 0 and $\zeta_{LL,p,\max}$ as defined in (19), and this is done in Figure 34. The statistics for passenger vessels is well represented by the considered model. On the other hand, the few data from container vessels seems to be less in line with the considered model. Nevertheless, the application of a Kolmogorov-Smirnov test does not reject, at 5% significance level, the null hypothesis that data from container vessels can come from a uniform distribution between 0 and $\zeta_{LL,p,\max}$ as defined in (19) (p-value: 0.102). Considering this outcome, and considering the primary interest in developing a model for passenger vessels, it can therefore be considered acceptable to use a uniform distribution between 0 and $\zeta_{LL,p,\max}$ as defined in (19).

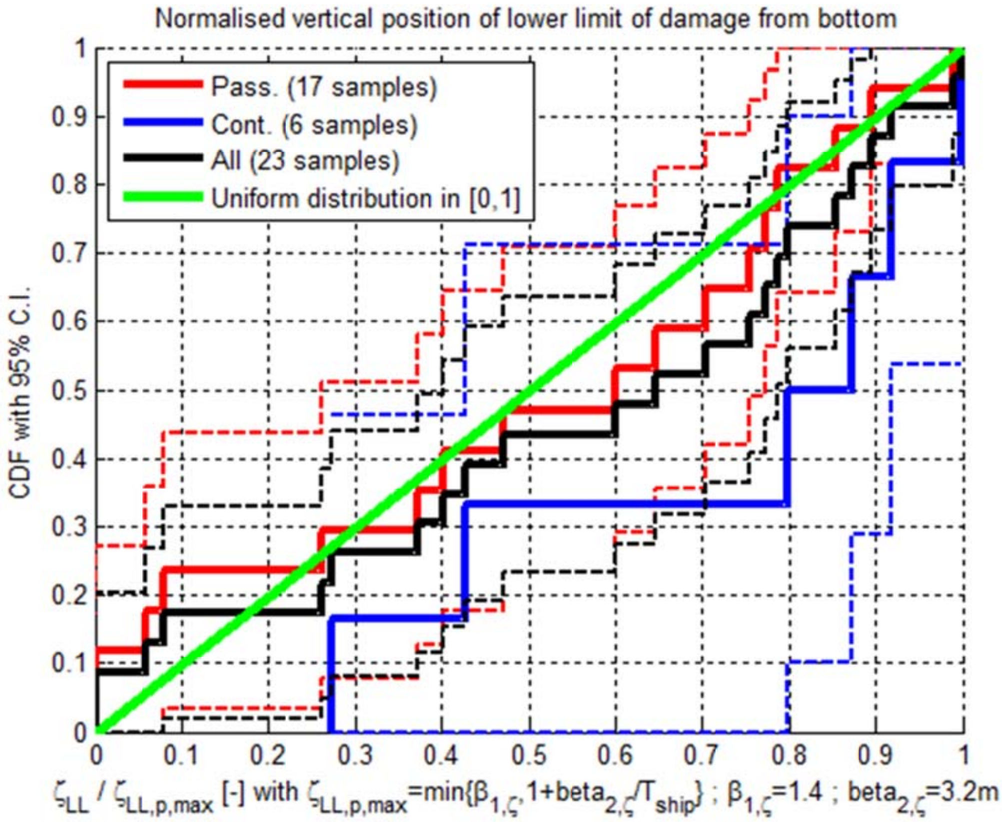

Figure 34: Cumulative distribution (CDF) of normalised vertical position of lower limit of damage from bottom, and comparison with a uniform distribution modelling.

Eventually the distribution of the vertical position of the lower limit of the damage from the ship bottom becomes, in nondimensional and in dimensional form:

Nondimensional form:

$$cdf_{\zeta_{LL,p}}\left(\zeta_{LL,p}=x\right)=\frac{x}{\zeta_{LL,p,\max}} \;\; ; \; pdf_{\zeta_{LL,p}}\left(\zeta_{LL,p}=x\right)=\frac{1}{\zeta_{LL,p,\max}}$$

$$\zeta_{LL,p,\max}=\min\left\{\beta_{1,\zeta}\;,\;1+\frac{\beta_{2,\zeta}}{T_{ship}}\right\} \;\; ; \; \beta_{1,\zeta}=1.4 \;\; ; \; \beta_{2,\zeta}=3.2m \;\; ; \; T_{ship} \text{ in [m]}$$

$$\zeta_{LL,p}\in\left[0,\zeta_{LL,p,\max}\right] \tag{20}$$

Dimensional form:

$$cdf_{z_{LL,p}}\left(z_{LL,p}=x\right)=\frac{x}{z_{LL,p,\max}} \;\; ; \; pdf_{z_{LL,p}}\left(z_{LL,p}=x\right)=\frac{1}{z_{LL,p,\max}}$$

$$z_{LL,p,\max}=\min\left\{\beta_{1,\zeta}\cdot\mathrm{T}_{ship}\;,\;\mathrm{T}_{ship}+\beta_{2,\zeta}\right\} \;\; ; \; \beta_{1,\zeta}=1.4 \;\; ; \; \beta_{2,\zeta}=3.2m \;\; ; \; T_{ship} \text{ in [m]}$$

$$z_{LL,p}\in\left[0,z_{LL,p,\max}\right]$$

8.6.6.2 Vertical extent of damage

Following the analysis and modelling of the lower limit of damage, the next step is the exploratory analysis and modelling of the vertical extent of damage. Figure 35 shows scatter plots of the measured vertical extent of damage and of the measured nondimensional vertical extent of damage versus the reference ship length and the reference ship draught. The total number of available samples for the analysis of this variable is 27 (Pass.: 17 ; Cont.: 10). Of these 27 samples, 22 are contacts (Pass.: 13 ; Cont.: 9) and 5 are groundings (Pass.: 4 ; Cont.: 1). In addition, Figure 36 and Figure 37 show different scatter plots relating the vertical extent of damage and the vertical position of the lower limit of damage.

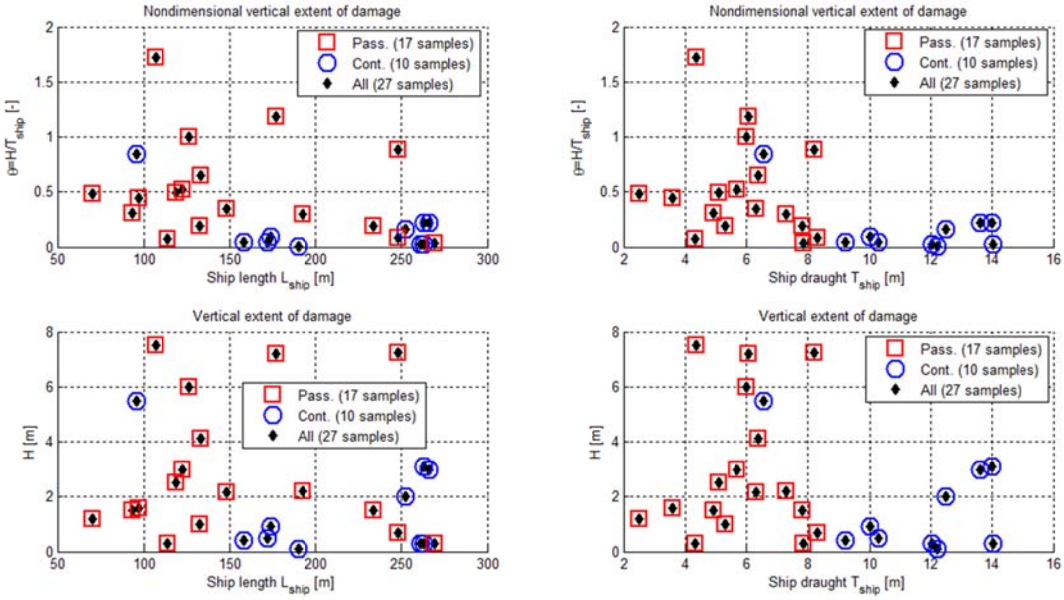

Figure 35: Scatter plot of dimensional and nondimensional vertical extent of damage versus ship length and ship draught.

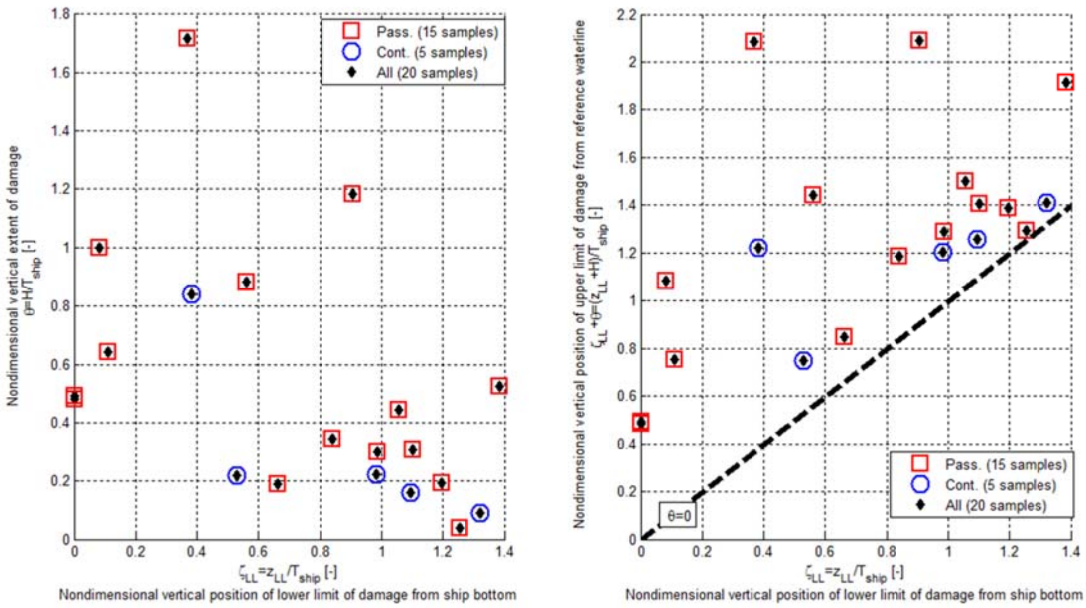

Figure 36: Scatter plot of nondimensional vertical extent of damage and nondimensional position of upper limit of damage, versus nondimensional vertical position of lower limit of damage.

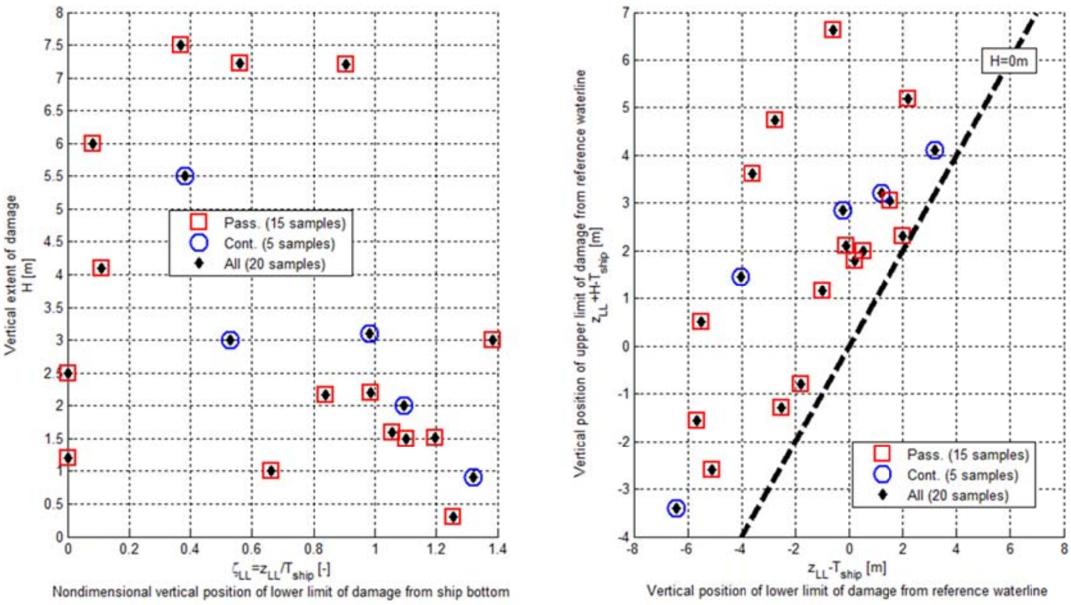

Figure 37: Scatter plot of dimensional vertical extent of damage, versus nondimensional vertical position of lower limit of damage, and dimensional vertical position of upper limit of damage from reference waterline versus dimensional vertical position of lower limit of damage from reference waterline.

The available data indicate [2] that it is justifiable to proceed with a modelling of the distribution of the vertical damage extent, which:

- Is based on a ship-size-independent approach for the distribution of H;
- Is based on the whole sample of data (passenger vessels plus container vessels).

In addition, the available data indicate [2] that there is some dependence between the vertical position of the lower limit of damage and the vertical extent of damage. Unfortunately, the limited availability of samples does not allow drawing any clear definite conclusion on which modelling approach is definitely the most suitable. However, it seems that the most appropriate approach for modelling the vertical extent of damage is a dimensional approach, without dependence on the ship size, but with a dependence of the vertical extent of damage from the vertical position of the lower limit of damage. Such dependence should reflect the reduction of the vertical extent of damage as the lower limit of damage moves upwards towards, and above, the reference waterline. In addition, it seems appropriate to set a maximum absolute vertical position of the upper limit of damage from the reference waterline. Such modelling characteristics can be considered to reasonably reflect the contact with an external object (e.g. a rock) having absolute dimensions which, to a certain extent, are independent of the actual size of the vessel. In addition to the above, it is reasonable to consider that data for the measured vertical extent of damage are sufficiently representative of data for the potential vertical extent of damage.

Therefore, the first step of the probabilistic modelling for the distribution of the vertical extent of potential damage (H_p), is to enforce the above ideas through the definition of a maximum vertical extent of potential damage, $H_{p,\max}$, which depends on the lower limit of the potential damage, i.e.:

$$\begin{aligned} & H_{p,\max} = H_{p,\max}\left(z_{LL,p}\right) \\ & z_{LL,p} \in \left[0, z_{LL,p,\max}\right] \end{aligned} \tag{21}$$

According to the above considerations $H_{p,\max}\left(z_{LL,p}\right)$ must fulfil two conditions:

- It must be lower or equal than a maximum absolute potential damage height, say H_{am};
- The damage must not extent above the reference waterline for more than a specified upper limit, say h_{ul} .

The enforcement of the two conditions mentioned before leads to:

$$H_p\left(z_{LL,p}\right) \le H_{p,\max}\left(z_{LL,p}\right) = \min\left\{H_{am}\ ,\ h_{ul} + T_{ship} - z_{LL,p}\right\} \tag{22}$$

It is very important to note that the modelling for $H_{p,\max}\left(z_{LL,p}\right)$ in (22) must be consistent with the modelling for $z_{LL,p,\max}$ (see (20)). Indeed, the maximum vertical position of the upper limit of the damage from the ship bottom shall always be at or above the maximum value of the vertical position of the lower limit of damage from the ship bottom. For this reason, the value of the term h_{ul} shall always be such that:

$$h_{ul} + T_{ship} - z_{LL,p,\max} \ge 0 \Rightarrow h_{ul} \ge z_{LL,p,\max} - T_{ship} \tag{23}$$

According to (22), it is possible to provide a graphical representation for $H_{p,\max}\left(z_{LL,p}\right)$ as shown in Figure 38, from which it can be seen that the limitation given by h_{ul} becomes effective only when $z_{LL,p}$ is large enough. It is worth noting that the position of the knuckle point, in terms of corresponding $z_{LL,p}$, depends on the reference ship draught T_{ship} .

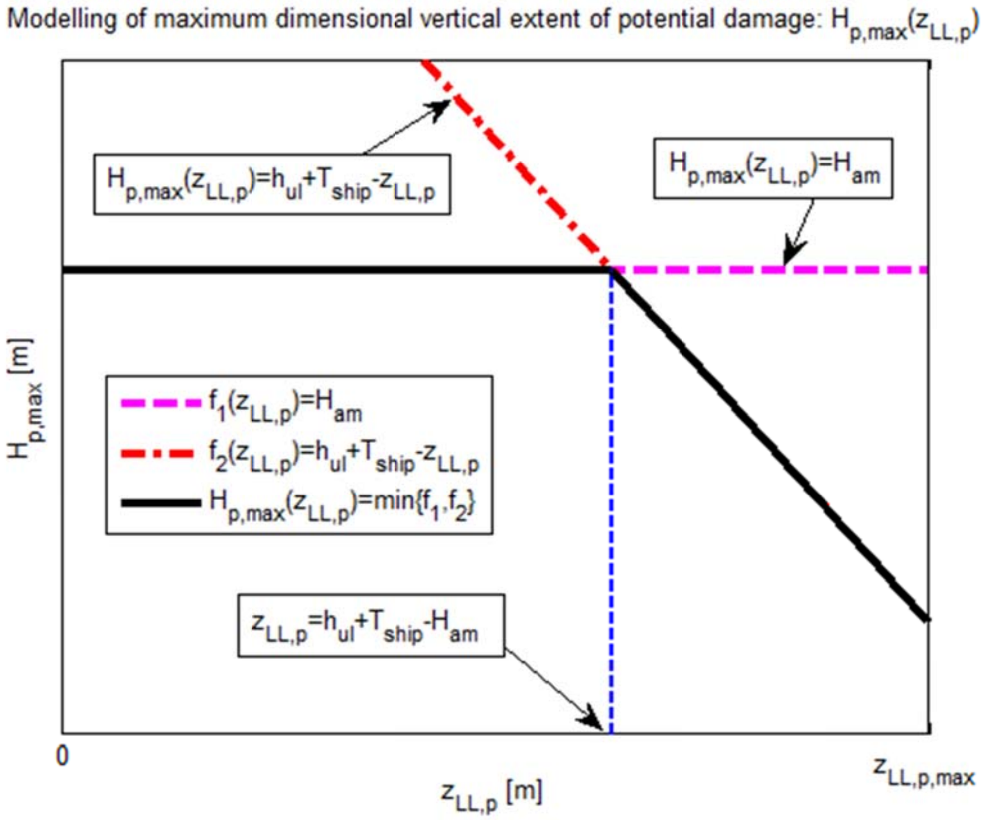

Figure 38: Graphical representation of maximum dimensional vertical potential damage extent as function of the dimensional vertical position of the lower limit of damage from the ship bottom.

Considering the available data, it is possible to set the values of the modelling parameters H_{am} and h_{ul} as follows:

$$\begin{aligned} H_{am} &= 7.5m \\ h_{ul} &= 6.6m \end{aligned} \tag{24}$$

The modelling for the maximum vertical extent of potential damage takes, therefore, the following form:

$$\begin{aligned} &H_{p,\max}\left(z_{LL,p}\right) = \min\left\{H_{am}\ ,\ h_{ul} + T_{ship} - z_{LL,p}\right\} \\ &H_{am} = 7.5m\ ;\ h_{ul} = 6.6m\ ;\ T_{ship}\ \text{and}\ z_{LL,p}\ \text{in [m]} \end{aligned} \tag{25}$$

The next step of the analysis is to provide a modelling for the distribution of H_p. To this end, two dimensionless variables are firstly defined, i.e.

$$\gamma_{z_{LL}} = \frac{z_{LL,p}}{z_{LL,p,\max}\left(T_{ship}\right)}$$
$$\gamma_H = \frac{H_p}{H_{p,\max}\left(z_{LL,p}\right)}$$
$$z_{LL,p} = z_{LL} \;\; ; \;\; H_p = H \qquad (26)$$

$$z_{LL,p,\max}\left(T_{ship}\right) = \min\left\{\beta_{1,\zeta} \cdot \mathrm{T}_{ship} \;\; , \;\; \mathrm{T}_{ship} + \beta_{2,\zeta}\right\} \;\; ;$$
$$H_{p,\max}\left(z_{LL,p}\right) = \min\left\{H_{am} \;\; , \;\; h_{ul} + T_{ship} - z_{LL,p}\right\}$$
$$\beta_{1,\zeta} = 1.4 \;\; ; \;\; \beta_{2,\zeta} = 3.2m \;\; ; \;\; H_{am} = 7.5m \;\; ; \;\; h_{ul} = 6.6m \;\; ;$$
$$T_{ship}, H \text{ and } z_{LL} \text{ in [m]}$$

The variable $\gamma_{z_{LL}}$ represents the normalised vertical position of the lower limit of damage from the ship bottom (see also Figure 34). The variable γ_H represents the normalised vertical extent of the damage. The normalisation is carried out using the maximum values given by the assumed modelling (20) and (25). Figure 39 shows a scatter plot of γ_H versus $\gamma_{z_{LL}}$.

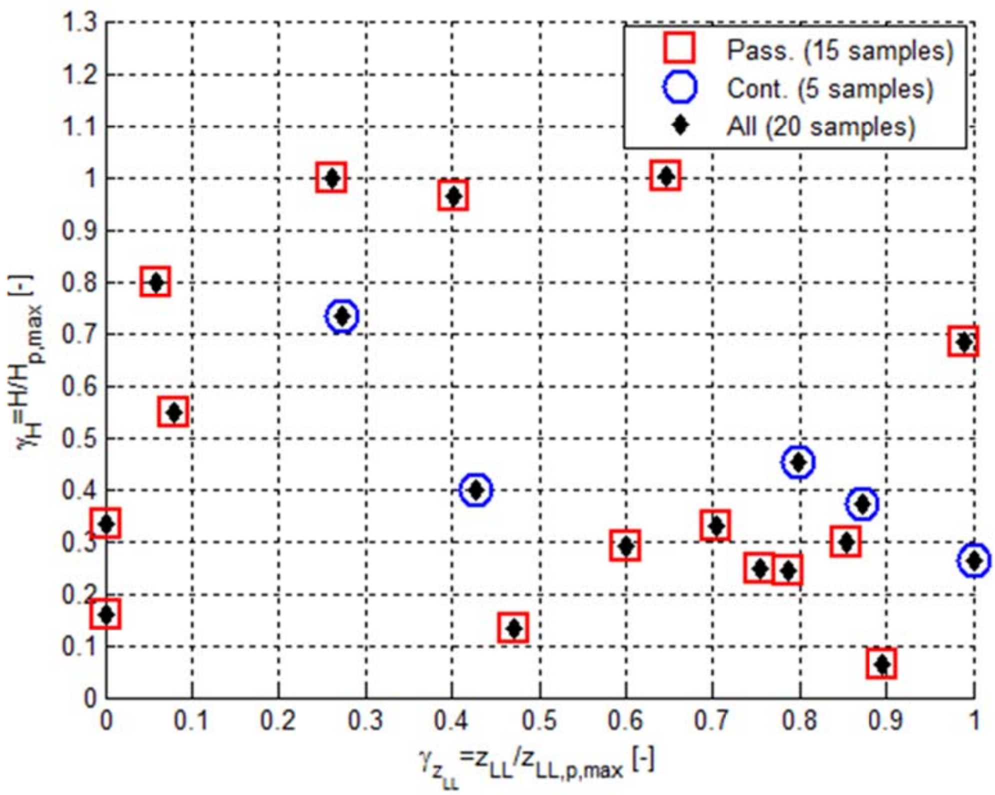

Figure 39: Scatter plot of normalised vertical extent of damage versus normalised vertical position of lower limit of damage from ship bottom.

Looking at Figure 39 it can be noticed that the normalisation procedure has reduced the observable dependence between the vertical extent of damage and the vertical position of the lower limit of the damage. The analysis of the sample data in Figure 39 indicates that there is no strong evidence for rejecting the hypothesis that the random variables γ_H and $\gamma_{z_{LL}}$ are statistically independent [2]. From a practical point of view, and considering the limited availability of data for drawing more sophisticated modelling, it is therefore reasonable to consider γ_H as independent of $\gamma_{z_{LL}}$. To complete the modelling, it is therefore necessary to determine a model for the marginal distribution of γ_H.

As a simplified model for the distribution of γ_H, a parametric trapezoidal distribution is considered in the interval $[0,1]$. The generic functional form of a parametric trapezoidal distribution in $[0,1]$ can be written as:

$$
\begin{aligned}
& cdf_{\gamma_H}(\gamma_H = x) = x \cdot \left[1 + 6 \cdot \left(\alpha_1 - \frac{1}{2}\right) \cdot (x-1)\right] \\
& pdf_{\gamma_H}(\gamma_H = x) = \frac{d}{d\gamma_H} cdf_{\gamma_H}\Big|_{\gamma_H = x} = 1 + 12 \cdot \left(\alpha_1 - \frac{1}{2}\right) \cdot \left(x - \frac{1}{2}\right) \\
& x \in [0,1] \;\; ; \;\; \alpha_1 \in \left[\frac{1}{3}, \frac{2}{3}\right]
\end{aligned}
\qquad (27)
$$

There is only one controlling parameter of the distribution (27), namely α_1 as shown in (27). Values of α_1 at the boundaries (1/3 and 2/3) correspond to triangular distributions, while the value 0.5 correspond to a uniform distribution. A direct least square fitting of the model (27) has been performed on the estimated cumulative distribution of γ_H using a simple exhaustive search in the range $\alpha_1 \in \left[\frac{1}{3}, \frac{2}{3}\right]$. All data, i.e. passenger vessels and container vessels, have been used. The result from the least square fitting provides, as optimum parameter, the following value of α_1:

$$
\alpha_1 = (\alpha_1)_{\text{fit-cdf}} = \frac{1}{3} \qquad (28)
$$

which is on the boundary of the allowed range for α_1, and actually corresponds to a triangular distribution for γ_H.

A comparison between the cumulative distribution obtained from the data and the distribution obtained from the fitting is reported in Figure 40. It can be noticed that the modelling of the distribution of γ_H as a triangular distribution is a good representation of the actual data.

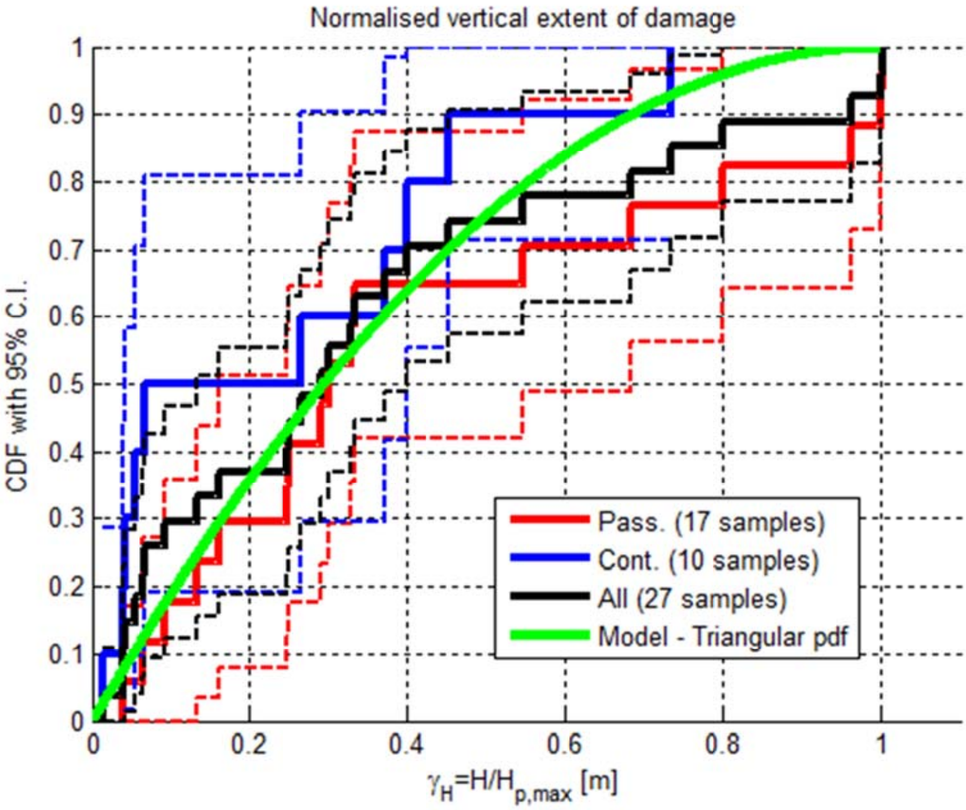

Figure 40: Comparison between distribution of normalised vertical extent of damage and model based on a triangular distribution.

In accordance with the reported analysis, a triangular distribution can be considered to be a reasonably supportable model for the random variable γ_H in the range $[0,1]$. Transforming γ_H back to the dimensional vertical extent of damage, it is therefore possible to define the conditional distribution of H_p given a specified vertical position of the lower limit of damage from the ship bottom, $z_{LL,p}$. The following modelling is then obtained for the conditional distribution of the vertical extent of potential damage (H_p), given the vertical position of the lower limit of potential damage from the ship bottom ($z_{LL,p}$):

$$
cdf_{H_p|z_{LL,p}}\left(H_p = x \middle| z_{LL,p}\right) = \left(\frac{x}{H_{p,\max}\left(z_{LL,p}\right)}\right)\cdot\left[1+6\cdot\left(\beta_{1,H}-\frac{1}{2}\right)\cdot\left(\left(\frac{x}{H_{p,\max}\left(z_{LL,p}\right)}\right)-1\right)\right]
$$

$$
pdf_{H_p|z_{LL,p}}\left(H_p = x \middle| z_{LL,p}\right) = \frac{d}{dH_p} cdf_{H_p|z_{LL,p}}\left(H_p \middle| z_{LL,p}\right)\Bigg|_{H_p = x} =
$$

$$
= \frac{1}{H_{p,\max}\left(z_{LL,p}\right)}\cdot\left[1+12\cdot\left(\beta_{1,H}-\frac{1}{2}\right)\cdot\left(\left(\frac{x}{H_{p,\max}\left(z_{LL,p}\right)}\right)-\frac{1}{2}\right)\right] \quad (29)
$$

$$
\beta_{1,H} = \frac{1}{3} \;;\; H_{p,\max}\left(z_{LL,p}\right) = \min\left\{H_{am} \;,\; h_{ul} + T_{ship} - z_{LL,p}\right\}
$$

$$
H_{am} = 7.5m \;;\; h_{ul} = 6.6m \;;
$$

$$
H_p = x \in \left[0, H_{p,\max}\left(z_{LL,p}\right)\right]
$$

It is important to underline that the modelling in (29) represents a conditional distribution model for the random variable H_p given a specified value for the random variable $z_{LL,p}$, and not a marginal distribution model.

8.6.6.3 Joint distribution of lower limit and vertical extent of damage

Following the analysis and modelling of the marginal distribution of vertical position of lower limit of damage from the ship bottom, and the analysis and modelling of the conditional distribution of the vertical extent of damage, it is then possible to provide a modelling for the joint probability density function of $z_{LL,p}$ and H_p. Combining (20) and (29), the modelling takes the following form:

$$
pdf_{z_{LL,p},H_p}\left(z_{LL,p} = x, H_p = y \middle| T_{ship}\right) = pdf_{H_p|z_{LL,p}}\left(H_p = y \middle| z_{LL,p}\right)\cdot pdf_{z_{LL,p}}\left(z_{LL,p} = x\right) =
$$

$$
= \frac{1}{H_{p,\max}\left(z_{LL,p}\right)}\cdot\left[1+12\cdot\left(\beta_{1,H}-\frac{1}{2}\right)\cdot\left(\left(\frac{y}{H_{p,\max}\left(z_{LL,p}\right)}\right)-\frac{1}{2}\right)\right]\cdot\frac{1}{z_{LL,p,\max}\left(T_{ship}\right)}
$$

$$
z_{LL,p,\max}\left(T_{ship}\right) = \min\left\{\beta_{1,\zeta}\cdot \mathrm{T}_{ship} \;,\; \mathrm{T}_{ship} + \beta_{2,\zeta}\right\} \;;
$$

$$
H_{p,\max}\left(z_{LL,p}\right) = \min\left\{H_{am} \;,\; h_{ul} + T_{ship} - z_{LL,p}\right\} \;; \quad (30)
$$

$$
\beta_{1,\zeta} = 1.4 \;;\; \beta_{2,\zeta} = 3.2m \;;
$$

$$
\beta_{1,H} = \frac{1}{3} \;;\; H_{am} = 7.5m \;;\; h_{ul} = 6.6m \;;
$$

$$
z_{LL,p} \in \left[0, z_{LL,p,\max}\left(T_{ship}\right)\right]
$$

$$
H_p \in \left[0, H_{p,\max}\left(z_{LL,p}\left(T_{ship}\right)\right)\right]
$$

A graphical representation of $H_{p,\max}\left(z_{LL,p}\right)$ as given by the modelling (30) for different ship draughts is reported in Figure 41.

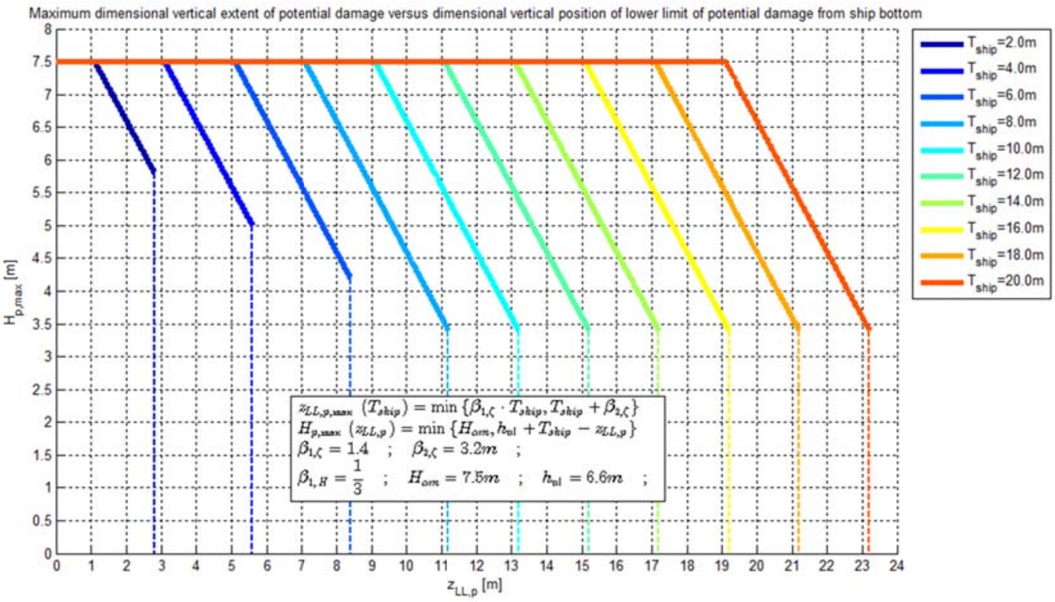

Figure 41: Graphical representation of maximum dimensional vertical extent of potential damage versus dimensional vertical position of lower limit of potential damage from ship bottom, as given by the proposed modelling, for different reference ship draughts.

8.6.7 Damage penetration

The modelling of damage penetration from the available database is particularly difficult. Indeed, the available database contains only a few quantitative data regarding the damage penetration suffered in the accidents. The very large majority of data, when available, is associated with qualitative indications.

In particular, from the whole database, a total of 30 samples are present, for which some information is available regarding the damage penetration. However, among these 30 cases, only for 2 cases (1 passenger vessel in a grounding accident and 1 container vessel in a contact accident), an explicit quantification of the damage penetration was given in the accident background information. For only 3 cases (1 passenger vessel in a contact accident and 2 container vessels both in contact accidents) it was possible to gather sufficient background information to allow a sufficiently reliable quantification of the penetration. For all the other 25 cases (18 passenger vessels, 17 contacts/1 grounding; 7 container vessels, 6 contacts/1 grounding) a quantification of the penetration from the available background information was not possible, and in all such cases the damage was indicated, in the accident reports and/or other sources, as a damage with a relatively small penetration. Typically, the damage was qualitative referred to as "gash", "tear", "crack" or "minor". Although this type of indication is not giving a quantitative indication of the damage penetration, it nevertheless inform about the fact that the damage penetration was somewhat "small", although the concept of "small" cannot be precisely and uniquely defined.

As a result, summarising the available 30 samples, and indicating with B_{ship} the breadth of the vessel:

- For 25 cases the penetration can be qualitatively categorised as "small";
- For 2 cases the penetration is clearly provided and it corresponds to $2.91m / 0.082 B_{ship}$ (passenger vessel) and $2.44m / 0.061 B_{ship}$ (container vessel);
- For 3 cases the penetration was quantitatively estimated, corresponding to $0.7m / 0.033 B_{ship}$ (passenger vessel), $0.5m / 0.018 B_{ship}$ (container vessel) and $0.5m / 0.027 B_{ship}$ (container vessel).

It is evident that, with the reported availability of data, it is necessary to develop a modelling based on a significant level of subjective judgement. Herein, therefore, the following reasoning has been followed.

First of all, it is observed that damage penetration, as measured, can safely be considered to correspond to the penetration of "potential damage".

Then, as a first modelling step, it was assumed that a damage with "small penetration" can be considered to be a damage with a penetration equal or smaller than a value of $B_{ship} / 30$. Under this assumption, the probability that a damage penetration is (equal or) smaller than $B_{ship} / 30$ can be estimated from the available data as:

$$\begin{aligned} &\Pr\left\{L_y / B_{ship} \le 1/30\right\} = 0.93 \quad \left[0.78, 0.99\right]_{95\% CI} \\ &\Pr\left\{L_y / B_{ship} < 1/30\right\} = 0.90 \quad \left[0.73, 0.98\right]_{95\% CI} \end{aligned} \qquad (31)$$

In one case, indeed, the penetration reported in the database is exactly equal to $B_{ship} / 30$. Taking a conservative approach, in the probabilistic model, it is therefore assumed that the probability of a damage having a penetration equal to or smaller than $B_{ship} / 30$, can be fixed to 0.90.

Regarding the extreme damage penetration, the maximum damage penetration observed from the database is $2.91m / 0.082 B_{ship}$. For the sake of conservativeness, it could be considered appropriate to limit the maximum damage penetration to a dimensionless value close to the maximum observed one. Herein, a relevant maximum penetration is therefore considered to be $B_{ship} / 10$.

Considering the limited availability of data, for damage penetrations in the range $\left[0, B_{ship}/30\right[$ and $\left]B_{ship}/30, B_{ship}/10\right]$, it is assumed that a uniform distribution can be used.

Such simplified modelling can therefore be graphically summarised as reported in Figure 42. It is worth mentioning that the average damage penetration associated with such model corresponds to $\frac{13}{600}B_{ship} \cong 0.0217B_{ship}$.

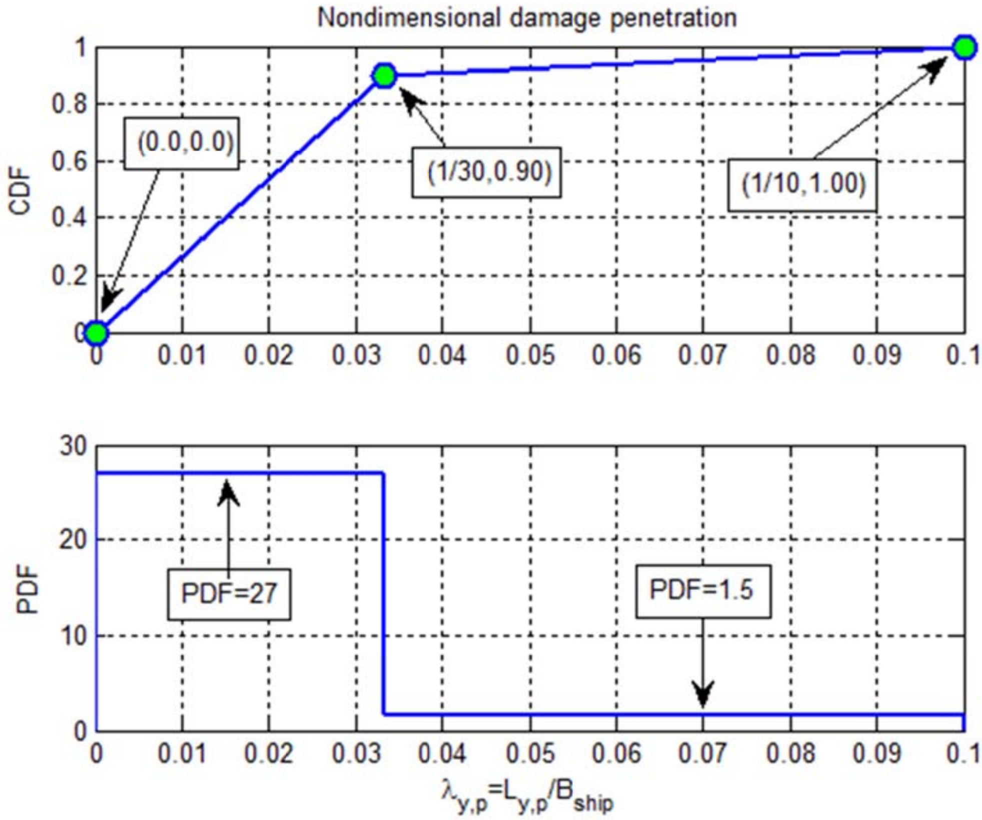

Figure 42: Distribution for nondimensional potential damage penetration.

The analytical description of the described model, as reported in Figure 42, can be given, equivalently, in dimensionless or dimensional form. The nondimensional representation is as follows:

$$cdf_{\lambda_{y,p}}\left(\lambda_{y,p}=x\right)=\begin{cases}\frac{\alpha_1}{\alpha_2}\cdot x & \text{for } x\in\left[0,\alpha_2\right]\\ \frac{1-\alpha_1}{\alpha_3-\alpha_2}\cdot\left(x-\alpha_2\right)+\alpha_1 & \text{for } x\in\left[\alpha_2,\alpha_3\right]\end{cases}$$

$$pdf_{\lambda_{y,p}}\left(\lambda_{y,p}=x\right)=\begin{cases}\frac{\alpha_1}{\alpha_2} & \text{for } x\in\left[0,\alpha_2\right[\\ \frac{1-\alpha_1}{\alpha_3-\alpha_2} & \text{for } x\in\left]\alpha_2,\alpha_3\right]\end{cases} \quad (32)$$

$$\alpha_1=0.90\ ;\ \alpha_2=\frac{1}{30}\ ;\ \alpha_3=\lambda_{y,p,\max}=\frac{1}{10}\ ;\ x\in\left[0,\alpha_3=\lambda_{y,p,\max}\right]$$

The dimensional representation is as follows:

$$cdf_{L_{y,p}}\left(L_{y,p}=x\right)=\begin{cases}\frac{\alpha_1}{\alpha_2}\cdot\frac{x}{B_{ship}} & \text{for } x\in\left[0,\alpha_2\cdot B_{ship}\right]\\ \frac{1-\alpha_1}{\alpha_3-\alpha_2}\cdot\left(\frac{x}{B_{ship}}-\alpha_2\right)+\alpha_1 & \text{for } x\in\left[\alpha_2\cdot B_{ship},\alpha_3\cdot B_{ship}\right]\end{cases}$$

$$pdf_{L_{y,p}}\left(L_{y,p}=x\right)=\begin{cases}\frac{\alpha_1}{\alpha_2}\cdot\frac{1}{B_{ship}} & \text{for } x\in\left[0,\alpha_2\cdot B_{ship}\right[\\ \frac{1-\alpha_1}{\alpha_3-\alpha_2}\cdot\frac{1}{B_{ship}} & \text{for } x\in\left]\alpha_2\cdot B_{ship},\alpha_3\cdot B_{ship}\right]\end{cases} \quad (33)$$

$$\alpha_1=0.90\ ;\ \alpha_2=\frac{1}{30}\ ;\ \alpha_3=\frac{L_{y,p,\max}}{B_{ship}}=\frac{1}{10}\ ;\ x\in\left[0,\alpha_3\cdot B_{ship}=L_{y,p,\max}\right]$$

At this stage, similarly to what was done in case of analysis of damage length, it is worth recalling that the data available in the database are associated to contacts of the vessel with rocks, with fixed object and with floating objects, resulting in side damages. For this reason, it might be the case that the developed modelling could be shifted towards smaller damages compared to the case of an ideal database containing only grounding cases.

For the sake of comparison, the present modelling for side damage penetration is therefore compared with one of the models developed in GOALDS for the damage penetration in case of bottom grounding damages [8], and, specifically with the approach indicated as "ship-size-dependent". This model is indeed characterised by a ship-size-dependent maximum damage penetration which scales nonlinearly with the ship breadth. In terms of nondimensional damage penetration, the GOALDS model is as follows:

$$
\begin{aligned}
& cdf_{\lambda_{z,p}}(x)=\frac{\alpha_1\cdot x}{x+\lambda_{z,p,\max}\cdot(\alpha_1-1)} \\
& pdf_{\lambda_{z,p}}(x)=\frac{\lambda_{z,p,\max}\cdot\alpha_1\cdot(\alpha_1-1)}{\left[x+\lambda_{z,p,\max}\cdot(\alpha_1-1)\right]^2} \\
& \lambda_{z,p,\max}=\lambda_{z,p,\max}(B_{ship})=\frac{L_{z,p,\max}}{B_{ship}}=\min\left\{\frac{k_{MB}}{B_{ship}^{(1-\alpha_B)}},\frac{T_{ship}}{B_{ship}}\right\} \text{ with } B_{ship} \text{ and } T_{ship} \text{ in } [m] \\
& \alpha_1=1.170 \;;\; \alpha_B=0.636 \;;\; k_{MB}=0.503
\end{aligned}
\tag{34}
$$

where the dimensionless damage penetration is indicated as $\lambda_{z,p}$ because the GOALDS modelling refers to bottom grounding damages having a vertical penetration, i.e. a penetration parallel to the z-axis of the vessel. Herein, instead, it is assumed that the damage is occurring on the side of the vessel, this meaning that the penetration is assumed to occur orthogonal to the ship centreplane and, hence, parallel to the y-axis of the vessel.

Assuming that $k_{MB}\cdot B_{ship}^{\alpha_B}>T_{ship}$, which is typically the case for non-small vessels [8], the GOALDS modelling (34) is compared with the model in Figure 42 for three representative ship breadths, namely 21.0m, 32.2m and 40.0m. Results of this comparison are shown in Figure 43. From the reported results it can be seen that the present model for side damage penetration is characterised by a smaller maximum dimensionless penetration and, as a consequence, by overall smaller dimensionless penetrations compared to the GOALDS model developed for bottom grounding damages.

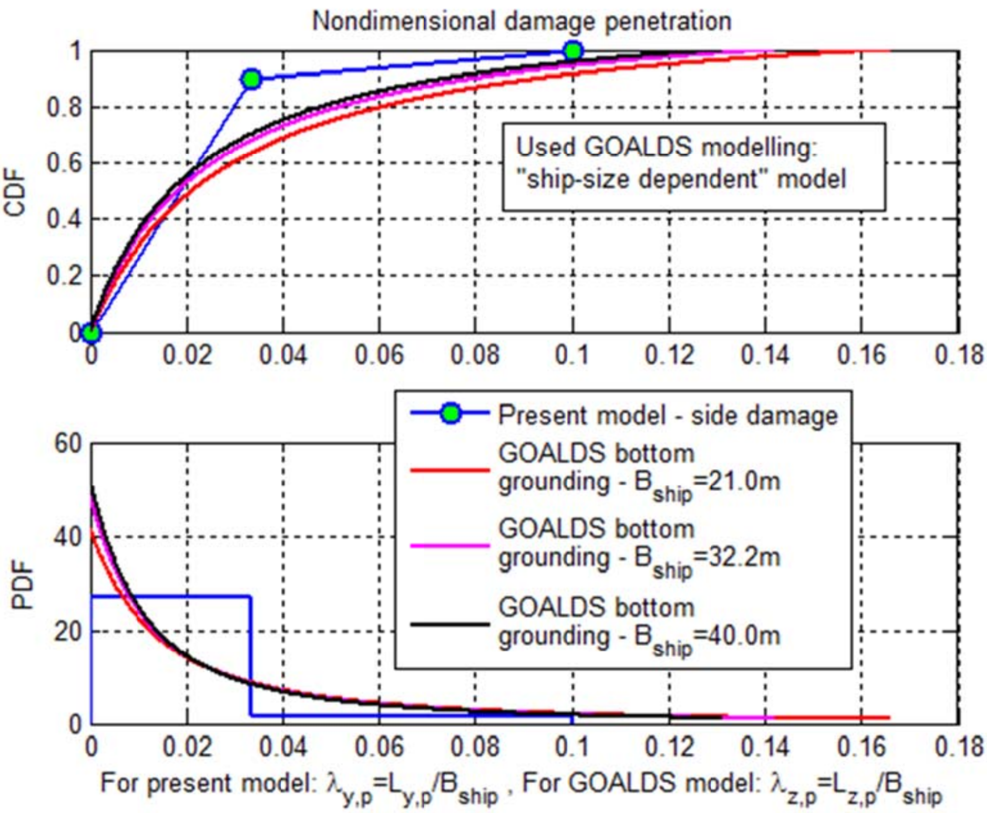

Figure 43: Comparison of distribution for nondimensional potential damage penetration. Present model versus GOALDS ship-size-dependent model for bottom grounding.

8.6.8 Vertical position of waterline for the determination of the damage penetration surface

In order to actually generate the damage starting from the ship geometry and the variables characterising the damage position and extent, it is necessary to set the reference waterline for the determination of the damage penetration surface by specifying the variable z^*. Such variable cannot be determined from the database and it only plays the role of an auxiliary variable for a proper geometrical modelling of the damage.

As a result, the specification of z^* is linked with a subjective choice based on expert judgement. Considering the typical shape of vessels, which tend to show an increase of breadth as the draught increases, it could be considered suitable, as a first tentative, to set:

$$z^* = z_{LL,p} + H_p \tag{35}$$

i.e. to set the vertical position of the reference waterline at the waterline corresponding to the upper limit of the damage. However, it might happen that the vertical position at z^* is above the top of the hull to be used for the geometrical generation of the damage (note that the buoyant hull can differ from the hull used for the definition of the damage). For this reason, if the uppermost ship vertical abscissa is at a position z_{top}, it is necessary to specify appropriate rules to handle the following cases:

- Damage completely above z_{top}, i.e.

$$z_{LL,p} > z_{top} \tag{36}$$

- Damage partially above z_{top}, i.e.

$$\begin{aligned} & z_{LL,p} < z_{top} \\ & z_{LL,p} + H_p > z_{top} \end{aligned} \tag{37}$$

Considering all the approximations involved in the modelling, and considering the fact that the modelling is intended to provide a tool for relative comparisons among vessels, it could be reasonable to use a practical approach where z^* is limited to z_{top}, i.e.:

$$z^* = \min\left\{z_{LL,p} + H_p \ , z_{top}\right\} \tag{38}$$

Such approach is reasonable especially for the case reported in (37), while it is more questionable for cases of the type described in (36). However, for the cases described by (36), i.e. the case of damages extending vertically completely above z_{top}, it is likely that the buoyant part of the vessel is not affected or marginally affected, irrespective of the assumption used. In addition, the probability associated with cases of the type (36) is likely quite low, which makes likely small (or negligible) the effect of assumptions influencing the behaviour of the method for cases of the type (36). As a result, the approach stated in (38) could be considered as a reasonable practical tool, to be subject, however, to further considerations and testing.

At the same time, of course, more sophisticated approaches could be used to provide a more physical transversal positioning of the damage also in complex geometries. For instance, it could be possible to take into account the envelope of the projection on the XY plane of the ship side in the region of damage. However, such approaches are likely to be computationally much more expensive due to the larger requirements of geometrical operations.

A further possibility, could be to mix the above approaches with a random generation of z^* in the range $\left[z_{LL,p}, z_{LL,p} + H_p\right]$, for instance, according to a uniform distribution.

However, for typical ship geometries, both underwater and above water, as already said, the approach (38) could be considered as a reasonable practical tool, to be subject, however, to further considerations and testing.

8.6.9 Probabilistic model conditional to the occurrence of water ingress

The probabilistic model developed so far is representative of measured extent of side hull breaches due to contact/grounding. However, the modelling does not explicitly deal with whether water ingress occurs or not through the damaged area.

Although it is clear that water ingress occurs whenever the damage is (at least partially) below the waterline, the situation can be less clear when the hull breach extends fully above the waterline. Damages extending fully above the waterline are actually modelled by the probabilistic model reported in the previous sections. In particular, the damaged area fully extends above the waterline whenever the vertical position of the lower limit of the damage ($z_{LL,p}$) is higher than the ship draught T_{ship} (see (20)).

In accordance with (20), the maximum value of $z_{LL,p}$ is $z_{LL,p,\max} = \min\left\{1.4 \cdot \mathrm{T}_{ship}\ ,\ \mathrm{T}_{ship} + 3.2m\right\}$. As a result, the lower limit of the damage can be at positions reaching, for sufficiently large reference ship draughts, up to 3.2m above the waterline.

The question then, is whether damages starting high above the waterline shall be assumed to lead to water ingress or not. In general, the higher the vertical position of the lower limit of the damage, the less likely it is the water ingress.

Of course, a deterministic limit separating cases with water ingress from cases without water ingress cannot be uniquely identified, due to the general uncertainty, the variability of the environmental conditions, the simplifications involved in the basic modelling. However, herein we assume that, as a simplified practical approach, a threshold vertical position of the lower limit of damage, say $z_{LL,p,WI}$, can be defined for practical applications such that, whenever $z_{LL,p} > z_{LL,p,WI}$, water ingress does not occur.

Such type of assumption has been borrowed from the Stockholm Agreement stability assessment [30]. Indeed, in the Stockholm Agreement, accumulation of water due to wave effects is not to be taken into account on the ro-ro deck whenever the residual freeboard is larger than a specified value, which is taken as 2m. Therefore, indications from the Stockholm Agreement would suggest to take a value for $z_{LL,p,WI}$ of the order of the ship draught plus 2m[10].

Assuming that a value for $z_{LL,p,WI}$ is properly defined, the event of water ingress, E_{WI} , can be consequently defined as:

---

[10] It should be noted that, since Stockholm Agreement considers collision damages always extending below the waterline, the 2m residual freeboard threshold applies to the ship after flooding of the damaged compartments without accounting for water possibly accumulated on the ro-ro deck. On the contrary, for the case considered herein of side damages due to grounding/contact extending entirely above the waterline, the 2m distance of the lower point of damage is measured from the intact waterline.

$$E_{WI} = \{\text{water ingress}\} = \{z_{LL,p} \le z_{LL,p,WI}\} \tag{39}$$

The next aim is to determine the distribution of damage characteristics conditional to the occurrence of the event "water ingress" E_{WI}. For the specific case of the modelling developed herein, this is straightforward because all the variables, with the exception of $z_{LL,p}$ and H_p, are mutually statistically independent. Therefore, the occurrence of the event E_{WI} only influences the joint distribution of $z_{LL,p}$ and H_p. Furthermore, the joint distribution of $z_{LL,p}$ and H_p is given, in the reference model coming from historical data, in terms of the marginal distribution of $z_{LL,p}$ and of the conditional distribution of H_p given $z_{LL,p}$. This situation allows to determine the probabilistic model conditional to water ingress, by simply defining the conditional distribution of $z_{LL,p}$ given the occurrence of water ingress.

According to the above, the conditional distribution of $z_{LL,p}$ given the occurrence of water ingress can be determined as:

$$\begin{aligned} & cdf_{z_{LL,p}|E_{WI}}\left(z_{LL,p} = x \middle| E_{WI}\right) = \Pr\left\{z_{LL,p} \le x \middle| \text{water ingress}\right\} = \frac{cdf_{z_{LL,p}}\left(z_{LL,p} = x\right)}{cdf_{z_{LL,p}}\left(z_{LL,p} = z_{LL,p,WI}\right)} \\ & x \in \left[0, \min\left\{z_{LL,p,\max}, z_{LL,p,WI}\right\}\right] \end{aligned} \tag{40}$$

From (40), the conditional probability density function follows as:

$$\begin{aligned} & pdf_{z_{LL,p}|E_{WI}}\left(z_{LL,p} = x \middle| E_{WI}\right) = \frac{d}{dx} cdf_{z_{LL,p}|E_{WI}}\left(z_{LL,p} = x \middle| E_{WI}\right) = \frac{pdf_{z_{LL,p}}\left(z_{LL,p} = x\right)}{cdf_{z_{LL,p}}\left(z_{LL,p} = z_{LL,p,WI}\right)} \\ & x \in \left[0, \min\left\{z_{LL,p,\max}, z_{LL,p,WI}\right\}\right] \end{aligned} \tag{41}$$

It is to be noted that the conditional distribution of vertical damage extent, $pdf_{H_p|z_{LL,p}}\left(H_p = y \middle| z_{LL,p}\right)$, is not affected by the conditioning.

As a result, the joint distribution of vertical damage position and vertical extent of damage can be written as:

$$pdf_{z_{LL,p},H_p|E_{WI}}\left(z_{LL,p} = x, H_p = y \middle| T_{ship}, E_{WI}\right) = pdf_{H_p|z_{LL,p}}\left(H_p = y \middle| z_{LL,p}\right) \cdot pdf_{z_{LL,p}|E_{WI}}\left(z_{LL,p} = x \middle| E_{WI}\right) \tag{42}$$

Such considerations have general value, irrespective of the functional form of the distribution of the vertical position of the lower limit of damage. However, for the specific probabilistic model under consideration, the introduction of the conditioning to the occurrence of water ingress (event E_{WI}) is obtained by simply replacing (20) with (in dimensional form):

$$
\begin{aligned}
& cdf_{z_{LL,p}}\left(z_{LL,p}=x \middle| E_{WI}\right)=\frac{x}{z_{LL,p,UL}} \; ; \; pdf_{z_{LL,p}}\left(z_{LL,p}=x \middle| E_{WI}\right)=\frac{1}{z_{LL,p,UL}} \\
& z_{LL,p,\max}=\min\left\{\beta_{1,\zeta}\cdot \mathrm{T}_{ship} \; , \; \mathrm{T}_{ship}+\beta_{2,\zeta}\right\} \\
& z_{LL,p,WI}=\mathrm{T}_{ship}+\beta_{3,\zeta} \; ; \; z_{LL,p,UL}=\min\left\{z_{LL,p,\max} \; , \; z_{LL,p,WI}\right\} \\
& \beta_{1,\zeta}=1.4 \; ; \; \beta_{2,\zeta}=3.2m \; ; \; \beta_{3,\zeta}=2.0m \; ; \; T_{ship} \text{ in [m]} \\
& z_{LL,p}\in\left[0, z_{LL,p,UL}\right]
\end{aligned}
\qquad (43)
$$

It is worth noticing that in (43) both parameters $\beta_{2,\zeta}$ and $\beta_{3,\zeta}$ are explicitly maintained although, in the specific case, the presence of both the parameters is, in principle, redundant, and it would be equivalent to just use their minimum value in defining the upper limit of $z_{LL,p}$. However, it has been herein decided to keep both parameters in order to keep, explicitly, the conceptual separation between:

- The limit $z_{LL,p,\max}$, which comes from the statistical analysis of historical data, irrespective of the occurrence of water ingress;
- The limit $z_{LL,p,WI}$ which controls the assumptions regarding the occurrence or not occurrence of water ingress.

8.6.10 Summary of the probabilistic model

In this section, the probabilistic modelling of side damage characteristics is summarised. For uniformity, in this summary, all the random variables are described, through the associated cumulative distribution and probability density function, in dimensional form. The model is intended to be applied to passenger vessels. It is also reminded that the modelling has been developed considering a dataset containing accidents data from both grounding and contacts. Moreover, the model is assumed to be a probabilistic model for side damage characteristics, conditional to the occurrence of water ingress.

Firstly, it is recalled that the dimensional random variables describing the damage positioning and extent are assumed to be the following ones:

- Indicator for the side of damage: ind_{side} [-] (+1: port side ; −1: starboard side)
- Longitudinal position of forward end of damage: X_F [m];
- Longitudinal extent of potential damage, i.e. potential damage length: $L_{x,p}$ [m];
- Transversal extent of potential damage, i.e. potential damage penetration: $L_{y,p}$ [m];
- Vertical position of lower limit of potential damage: $z_{LL,p}$ [m];
- Height of potential damage above its lower limit, i.e. vertical extent of potential damage: H_p [m];

The following variables, in the model, are assumed to be statistically independent from the others:

- Indicator for the side of damage: ind_{side} [-] ($+1$: port side ; -1: starboard side)
- Longitudinal position of forward end of damage: X_F [m] ;
- Longitudinal extent of potential damage, i.e. potential damage length: $L_{x,p}$ [m] ;
- Transversal extent of potential damage, i.e. potential damage penetration: $L_{y,p}$ [m] ;

On the other hand, the two following random variables are assumed to be statistically dependent on each other, but statistically independent from the previous ones:

- Vertical position of lower limit of potential damage: $z_{LL,p}$ [m] ;
- Height of potential damage above its lower limit, i.e. vertical extent of potential damage: H_p [m] ;

As a result, for the variables ind_{side} , X_F , $L_{x,p}$ and $L_{y,p}$ it is sufficient to provide the corresponding marginal cumulative distribution and marginal probability density function.

On the other hand, for the variables $z_{LL,p}$ and H_p it is necessary to provide a modelling of the joint probability density function. To this end, the modelling is provided as follows:

- For $z_{LL,p}$ a model is provided for the marginal cumulative distribution and marginal probability density function;
- For H_p a model is provided for the conditional cumulative distribution and conditional probability density function, where the conditioning is with respect to $z_{LL,p}$.

Such a description is indeed sufficient, because the joint probability density function of $z_{LL,p}$ and H_p can be obtained by multiplying the marginal probability density function of $z_{LL,p}$ and the conditional (with respect to $z_{LL,p}$) probability density function of H_p .

Implicit in the model is the conditioning with respect to the occurrence of water ingress (event E_{WI}). Water ingress is assumed to occur whenever the lower limit of the damage is not higher than a specified threshold above the waterline.

The distributions of the random variables describing the damage positioning and extent of a side damage are summarized in the following (Table 37 to Table 40).

Table 37: Probability mass function (PMF) of the variable defining the side of the damage. Passenger vessels.

Quantity	Indicator for the side of the damage
	ind_{side} [-] ($+1$: port side damage; -1: starboard side damage)
$PMF(x)$	$\Pr\{ind_{side} = +1\} = \Pr\{\text{port side damage}\} = \alpha_1$ $\Pr\{ind_{side} = -1\} = \Pr\{\text{starboard side damage}\} = 1-\alpha_1$
Parameters	$\alpha_1 = 0.5$
Support	$ind_{side} \in \{-1,+1\}$
Notes	An equal probability is assumed for the damage to occur on the port or starboard side of the vessel.

Table 38: Distributions of variables defining the longitudinal position of the forward end of potential damage and of the longitudinal extent of potential damage (potential damage length) . Passenger vessels.

Quantity	Longitudinal position of forward end of potential damage	Longitudinal extent of potential damage (potential damage length)
	X_F [m]	$L_{x,p}$ [m]
$CDF(x)$	$\alpha_1 \cdot \frac{x}{X_{F,\max}} + (1-\alpha_1) \cdot \left(\frac{x}{X_{F,\max}}\right)^{\alpha_2}$	$\frac{\alpha_1 \cdot \left(\frac{x}{L_{x,p,\max}}\right)^2 + \alpha_2 \cdot \left(\frac{x}{L_{x,p,\max}}\right)}{\left(\frac{x}{L_{x,p,\max}}\right) + (\alpha_1 + \alpha_2 - 1)}$
$PDF(x)$	$\frac{1}{X_{F,\max}} \left[\alpha_1 + \alpha_2 \cdot (1-\alpha_1) \cdot \left(\frac{x}{X_{F,\max}}\right)^{(\alpha_2 - 1)}\right]$	$\frac{\alpha_1 \cdot \left(\frac{x}{L_{x,p,\max}}\right)^2 + (\alpha_1 + \alpha_2 - 1) \cdot \left(2 \cdot \alpha_1 \cdot \left(\frac{x}{L_{x,p,\max}}\right) + \alpha_2\right)}{L_{x,p,\max} \cdot \left[\left(\frac{x}{L_{x,p,\max}}\right) + (\alpha_1 + \alpha_2 - 1)\right]^2}$
Parameters	$\alpha_1 = 0.325$; $\alpha_2 = 3.104$; $X_{F,\max} = L_{ship}$	$\alpha_1 = -0.03886$; $\alpha_2 = 1.124$; $L_{x,p,\max} = 0.632 \cdot L_{ship}$
Support	$X_F \in \left[0, X_{F,\max}\right]$	$L_{x,p} \in \left[0, L_{x,p,\max}\right]$
Notes	This model corresponds to the GOALDS model developed for bottom grounding damages for non-full ships [8].	As a possible alternative, the GOALDS model developed for bottom grounding damages for non-full ships [8], could be used. The GOALDS model follows the same functional form, but with the following parameters: $\alpha_1 = 0.231$; $\alpha_2 = 0.845$; $L_{x,p,\max} = 1.000 \cdot L_{ship}$

Table 39: Distribution of the variable defining the transversal extent of potential damage (potential damage penetration). Passenger vessels.

Quantity	Transversal extent of potential damage (potential damage penetration)
	$L_{y,p}$ [m]
$CDF(x)$	$\begin{cases} \frac{\alpha_1}{\alpha_2} \cdot \frac{x}{B_{ship}} & \text{for } x \in \left[0, \alpha_2 \cdot B_{ship}\right] \\ \frac{1-\alpha_1}{\alpha_3-\alpha_2} \cdot \left(\frac{x}{B_{ship}} - \alpha_2\right) + \alpha_1 & \text{for } x \in \left[\alpha_2 \cdot B_{ship}, \alpha_3 \cdot B_{ship}\right] \end{cases}$
$PDF(x)$	$\begin{cases} \frac{\alpha_1}{\alpha_2} \cdot \frac{1}{B_{ship}} & \text{for } x \in \left[0, \alpha_2 \cdot B_{ship}\right[\\ \frac{1-\alpha_1}{\alpha_3-\alpha_2} \cdot \frac{1}{B_{ship}} & \text{for } x \in \left]\alpha_2 \cdot B_{ship}, \alpha_3 \cdot B_{ship}\right] \end{cases}$
Parameters	$\alpha_1 = 0.90$; $\alpha_2 = \frac{1}{30}$; $\alpha_3 = \frac{1}{10}$; $L_{y,p,\max} = \alpha_3 \cdot B_{ship}$
Support	$L_{y,p} \in \left[0, L_{y,p,\max}\right]$
Notes	The cumulative distribution is piecewise linear, while the probability density function is piecewise constant and discontinuous in $x = \alpha_2 \cdot B_{ship}$. As a possible alternative, the GOALDS model developed for bottom grounding damages for non-full ships [8], could be used, especially in case the GOALDS model is used for the potential damage length.

Table 40: Distributions of variables defining the vertical position of lower limit of potential damage from ship bottom, and of vertical extent of potential damage, conditional to the occurrence of water ingress. Passenger vessels.

Quantity	Vertical position of lower limit of potential damage	Quantity	Vertical extent of potential damage
	$z_{LL,p}$ [m]		H_p [m]
$CDF\left(x \mid E_{WI}\right)$	$\frac{x}{z_{LL,p,UL}}$	$CDF\left(x \mid z_{LL,p}\right)$	$\left(\frac{x}{H_{p,\max}\left(z_{LL,p}\right)}\right)\cdot\left[1+6\cdot\left(\beta_{1,H}-\frac{1}{2}\right)\cdot\left(\left(\frac{x}{H_{p,\max}\left(z_{LL,p}\right)}\right)-1\right)\right]$
$PDF\left(x \mid E_{WI}\right)$	$\frac{1}{z_{LL,p,UL}}$	$PDF\left(x \mid z_{LL,p}\right)$	$\frac{1}{H_{p,\max}\left(z_{LL,p}\right)}\cdot\left[1+12\cdot\left(\beta_{1,H}-\frac{1}{2}\right)\cdot\left(\left(\frac{x}{H_{p,\max}\left(z_{LL,p}\right)}\right)-\frac{1}{2}\right)\right]$
Parameters	$z_{LL,p,\max}=\min\left\{\beta_{1,\zeta}\cdot \mathrm{T}_{ship}\ ,\ \mathrm{T}_{ship}+\beta_{2,\zeta}\right\}$ $z_{LL,p,WI}=\mathrm{T}_{ship}+\beta_{3,\zeta}$; $z_{LL,p,UL}=\min\left\{z_{LL,p,\max}\ ,\ z_{LL,p,WI}\right\}$ $\beta_{1,\zeta}=1.4$; $\beta_{2,\zeta}=3.2m$; $\beta_{3,\zeta}=2.0m$; T_{ship} in [m]	Parameters	$\beta_{1,H}=\frac{1}{3}$; $H_{p,\max}\left(z_{LL,p}\right)=\min\left\{H_{am}\ ,\ h_{ul}+T_{ship}-z_{LL,p}\right\}$ $H_{am}=7.5m$; $h_{ul}=6.6m$;
Support	$z_{LL,p}\in\left[0,z_{LL,p,UL}\right]$	Support	$H_p\in\left[0,H_{p,\max}\left(z_{LL,p}\right)\right]$
Notes	This model provides the marginal cumulative distribution and marginal probability density function of $z_{LL,p}$ conditional to the occurrence of water ingress (event E_{WI}).	Notes	This model provides the conditional cumulative distribution and conditional probability density function of H_p, and the conditioning is with respect to $z_{LL,p}$.

The joint probability density function of H_p and $z_{LL,p}$, for a given ship draught T_{ship} [m], conditional to water ingress (event E_{WI}) is given by:

$$pdf_{z_{LL,p},H_p \mid E_{WI}}\left(z_{LL,p}=x, H_p=y \mid T_{ship}, E_{WI}\right)= pdf_{H_p \mid z_{LL,p}}\left(H_p=y \mid z_{LL,p}\right)\cdot pdf_{z_{LL,p} \mid E_{WI}}\left(z_{LL,p}=x \mid E_{WI}\right)=$$

$$=\frac{1}{H_{p,\max}\left(z_{LL,p}\right)}\cdot\left[1+12\cdot\left(\beta_{1,H}-\frac{1}{2}\right)\cdot\left(\left(\frac{y}{H_{p,\max}\left(z_{LL,p}\right)}\right)-\frac{1}{2}\right)\right]\cdot\frac{1}{z_{LL,p,UL}\left(T_{ship}\right)}$$

8.7 The Probabilistic framework

8.7.1 Attained Subdivision Index

According to the probabilistic framework, the assessment of the survivability of a ship in damaged condition is based on the comparison of an "Attained" Subdivision Index A with a "Required" index R, specified by the regulation for the given ship. This procedure, used for the case of collision accidents is adopted also in the present study for the case of grounding and contact accident. An appropriate formulation for the calculation of the Required index will be developed in Task 3, based on the analysis of the results for the A index for a series of passenger ships, and the elaboration of the envisaged risk control options. A procedure, developed for the calculation of the Attained Index for grounding accidents will be outlined in the following.

A separate Attained Index is calculated for each damage type: $A_{GR,B}$ and $A_{GR,S}$, corresponding to bottom and side damages respectively. At the end, it is of course possible to come up with a single Attained Index for grounding and contact accidents, equal to the weighted average of $A_{GR,B}$ and $A_{GR,S}$:

$$A_{GR} = w_b A_{GR,B} + w_s A_{GR,S} \quad (44)$$

where w_b and w_s are appropriate weighting factors, equal to the frequencies of occurrence of bottom and side damages, given the occurrence of a grounding or contact accident. According to the collected data in the accidents databases, the following values were calculated for w_b and w_s:

$$w_b = 0.333 \quad (45)$$

$$w_s = 1 - w_b = 0.667 \quad (46)$$

The above values for w_b and w_s are obtained considering the entire sample of accidents in the data base for passenger ships, i.e. considering both accident types (groundings and contacts) and all types of passenger ships (i.e. RoPax, RoPax Rail, cruise and pure passenger ships). According to the data presented in Table 21 and Table 22, the total number of accidents resulting to side or bottom breaches is equal to 48 and 24 respectively (ws=66.7% / wb=33.3%), when considering both types of accidents and all types of passenger ships. Considering only the grounding accidents, and all types of passenger ships, the corresponding figures are 10 side damages vs. 24 bottom damages (ws=29.4% / wb=70.5%). Considering only contact accidents, a breach to the side was reported in 38 cases, while there was no breach to the bottom of the ship (ws=100% / wb=0%).

Following SOLAS 2009, each one of the Attained Subdivision Indices, $A_{GR,B}$ and $A_{GR,S}$ is obtained by the summation of three partial indices, calculated for three draughts, d_s, d_p and d_l:

$$A_j = 0.4A_{js} + 0.4A_{jp} + 0.4A_{jl} \quad (47)$$

In the above equation, index j stands for GR,B or GR,S, corresponding to bottom or side damages, while A_{js}, A_{jp} and A_{jl} correspond to the partial indices at the three draughts d_s, d_p and d_l respectively. The three draughts d_s, d_p and d_l correspond to the subdivision, partial and lightest draught, defined in SOLAS 2009 for the damaged stability calculations in case of collision accident. In the calculation of the partial indices, the level trim shall be used for the deepest subdivision draught and the partial subdivision draught. The actual service trim shall be used for the light service draught.

Each partial index is a summation of contributions from all damage cases taken in consideration, using the following formula:

$$\mathrm{A} = \sum p_i s_i \quad (48)$$

where:

- i represents each compartment or group of compartments under consideration;
- p_i accounts for the probability that only the compartment or group of compartments under consideration is flooded[11];
- s_i accounts for the probability of survival after flooding the compartment or group of compartments under consideration.

8.7.2 The probability of survival

The probability of survival s_i in case of either bottom or side damage is calculated as follows:

$$s_i = \min\left(s_{intermediate,i}, s_{final,i} \cdot s_{mom,i}\right) \quad (49)$$

where:

[11] In principle, different p-factors should be calculated for each of the three draughts (subdivision, partial and lightest draught). However, since the generation of the damage cases might be quite time consuming, particularly in case a very large number of hull breaches is to be generated, it was decided to generate the damage cases and calculate the corresponding p-factors only for the subdivision draught, and use the same also for the partial and lightest draught. The methodology, however, can be applied also by considering draught dependent p-factors.

$s_{intermediate,i}$ is the probability to survive all intermediate flooding stages until the final equilibrium stage.

$s_{final,i}$ is the probability to survive in the final equilibrium stage of flooding.

$s_{mom,i}$ is the probability to survive heeling moments.

These probabilities are calculated according to the same procedure outlined in SOLAS 2009 for collision accidents of passenger ships. In addition, particularly for RoPax and RoPax-Rail ships, the possibility of calculating the s-factor according to the SLF 55 formulation, in case when a vehicles space is flooded, is implemented.

8.7.3 Probability of flooding a group of compartments

Up to this point, the probabilistic framework, developed in Task 3 for grounding and contact accidents, is to a large extent analogous to the one defined in SOLAS 2009 for collision accident. The probability of flooding a particular group of compartments p_i however, is calculated according to an innovative procedure, the so called "direct approach", which is completely different from the traditional "zonal approach" used in SOLAS 2009.

The 'traditional' zonal approach is based on the development of formulas/procedures for the calculation of the probability of flooding of a specific compartment or group of compartments. In addition, the development of software tools for the identification of the damage cases is required. Following a similar procedure with the one used for the collision damages also in the case of groundings/contacts, a subdivision table should be introduced, listing the various boundaries (decks, transverse bulkheads, longitudinal bulkheads), used to subdivide the ship in watertight compartments. Then, each compartment could be placed with respect to the subdivision table, and finally the damage cases should be identified. This procedure has been successfully applied for collision damages; however its applicability to the case of grounding damages is expected to be considerably more complex.

An alternative to the above procedure would be to use the so-called "direct approach". According to this approach, a large number of hull breaches are defined each one with an associated probability of occurrence. For each defined hull breach, the corresponding watertight compartments that become open to the sea are identified. By grouping different hull breaches leading to the same (set of) compartments open to the sea, it is possible to define a limited set of flooding conditions, which are typically called "damage cases" in the framework of probabilistic damage stability assessment in SOLAS 2009. Summing up the probabilities associated to all breaches leading to the same damage case, it is possible to determine the probability associated with that specific damage case, i.e. the "p-factor".

Therefore, the determination of the "p-factor" is linked to the methodology of generation of hull breaches. The probabilities of occurrence of such single hull breaches must be properly linked with the underlying damage characteristics' distributions. The generation of the hull breaches can be either random (e.g. Monte Carlo), or deterministic (systematic discretization). In both cases, the actual “p-factor” for each damage case is obtained from the mentioned procedure when the number of hull breaches is large enough.

8.7.4 Zonal vs. Direct approach

Each of the two methods has a series of advantages and disadvantages:

1. Zonal approach:

   - The traditional zonal approach is already used in the SOLAS regulations, therefore is already familiar to both designers and regulators (and also to software developers) and could be easily accepted for the calculation of the p-factors of grounding accidents.
   - The zonal approach may be applied, provided that adequate formulas for the calculation of the p-factors are available. New formulas for the calculation of the p-factors need to be developed, whenever improved damage statistics are available.
   - Damaged stability calculations based on the zonal approach require developing of software tools for the identification of the damage cases, i.e. all possible combinations of watertight compartments that may become open to the sea as a result of a hull breach.
   - The main disadvantage of the zonal approach is based on some crude simplifying assumptions (i.e. both the hull form and the damaged compartments are assumed to be box-shaped). As a result, its accuracy is questionable in case of realistic hull forms. In case of collision accidents, the errors introduced by this approximation were considered to be of acceptable magnitude. However, in case of grounding, such errors can be quite larger and can prevent the use of such an approach.

2. Direct Approach:

   - The direct approach is relatively new; therefore it might take additional effort to introduce it to the designers and regulators.
   - On the other hand, the direct approach is very flexible and can be readily adapted in case that in the future new and improved damage statistics are available.
   - No simplifications are required, regarding the shape of the hull or the damaged compartments.
   - Due to the inherent simplicity of the direct approach, there will be no need for lengthy and complicate explanatory notes to specify the appropriate treatment of complex, or unconventional internal geometries.
   - If the direct approach is selected, then the development of software for the analysis of grounding accidents is straightforward, since the damage cases are ‘automatically’ developed during the process. Therefore there will be no need for developing additional software tools that would be otherwise necessary, in order to identify the full set of damage cases.

Based on the above, it was decided that in Task 3 the direct approach will be applied for the calculation of the p-factors, for the cases of bottom and side damages due to grounding and contact accidents.

8.8 Development of the Software Tool

8.8.1 General description of the tool

In order to confirm the developed models and experience the use of these during the design process, a tool was developed for this based on the NAPA software. This tool allows a user to generate damages and calculate an index to measure the impact on the design.

The tool developed is included in a purpose built compilation of the NAPA software that have been distributed only among the project participants. Whether the tool will become a permanent part of NAPA or not depends on the outcome of this project, and how the results are received by the international community.

Designers participating to the project have the possibility to use the tool on existing designs, with some modification, and evaluate the impact of the developed grounding analysis on their designs. If a designer already has a compartmentation model suitable for damage calculations, the calculation setup is fairly simple and user input limited in order to limit the variations of the results submitted for further analysis (see Figure 44).

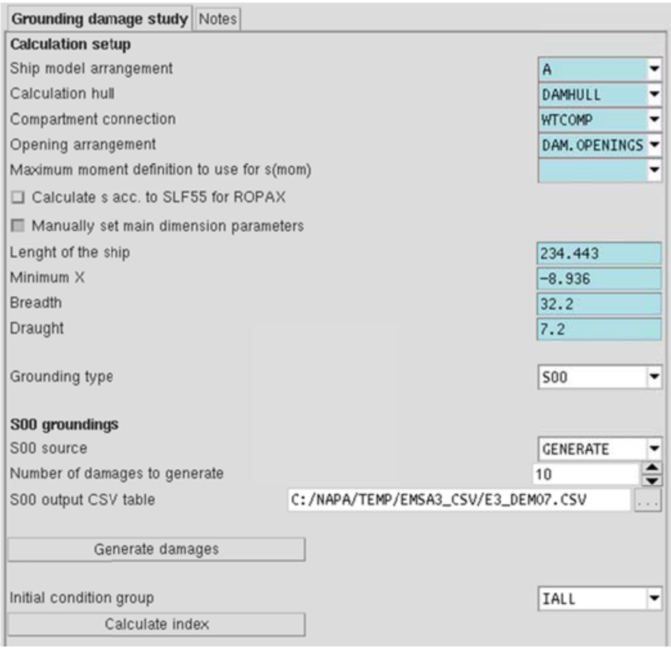

Figure 44: Layout of the developed grounding calculation tool in NAPA.

8.8.2 Modelling guidelines

8.8.2.1 Arrangement and calculation hull

The calculation requires a body representing the buoyant hull (calculation hull) and a ship model arrangement containing the watertight spaces that can provide buoyancy.

The definition of the grounding damages is done through penetration. In order to avoid non-contact cases, the ship model arrangement selected should match the calculation hull. In principle there are two alternatives for this:

- Exclude all appendages from the hull, such as rudders and propeller shafts as they are normally not modelled as rooms in the ship model arrangement
- Include all appendages that are in the calculation hull, also to the ship model arrangement with a suitable permeability. Note that a permeability PERM=0 cannot be used as NAPA will assume this is incorrect and switch it to PERM=1 instead. For these cases a very small permeability should be used instead (e.g. PERM=0.0001).

From a safety point of view it is recommended to use the first of the above alternatives, so that appendages are not allowed to provide protection to the hull from the grounding damages.

8.8.2.2 Influence of piping and valves

For cases where tanks have valves or piping connected to them which can cause a progressive flooding as a result of the damage, the approximate location of this piping can be modeled as a dummy room (included in the WT arrangement and connected to the tank) with a close to zero permeability. This can then help in analyzing the non-damageable zones used for normal index calculation in SOLAS 2009. The tank will then also be made open to the sea if the piping is damaged.

The smallest PERM value that can be given to a compartment in NAPA appears to be 0.000001.

8.8.2.3 Cross-flooding connections

For side grounding damages (type S00) a normal modelling of cross-flooding connections is adequate. For bottom grounding (type B00) damages, a more detailed modelling may be required to ensure that a damage that occurs between tanks can result in a damage to the cross flooding device and flooding of the tanks/voids it connects. This could e.g. be done by modelling the cross-flooding device as an own room, connected (one way only) to the side tanks (Figure 45).

	CONN	COMP	OPEN	STAGE	OPENING	WTCOMP	CLASS
1	R040203	R040204	Y	CROSS	CROSS1		
2	R040204	R040203	Y	CROSS	CROSS1		
3	R040203	R040204	Y	CROSS	CROSS2		
4	R040204	R040203	Y	CROSS	CROSS2		
5	R100202	R100203	Y	CROSS	CROSS3		
6	R100203	R100202	Y	CROSS	CROSS3		
7	R100202	R100203	Y	CROSS	CROSS4		
8	R100203	R100202	Y	CROSS	CROSS4		
9	R100104	R100105	Y	CROSS	CROSS5		
10	R100105	R100104	Y	CROSS	CROSS5		
11	R110101	R110102	Y	CROSS	CROSS6		
12	R110102	R110101	Y	CROSS	CROSS6		
13	R110201	R110202	Y	CROSS	CROSS7		
14	R110202	R110201	Y	CROSS	CROSS7		

Figure 45: Example of cross-flooding connections.

8.8.2.4 A-class connections

A-class bulkheads should be modelled the normal way, and the calculation will automatically populate the A-class stages for the damages (Figure 46).

	CONN	COMP	STAGE	CLASS
1	R080203	WTC1	ACLASS	A
2	WTC1	R080203	ACLASS	A
3	R080204	WTC1	ACLASS	A
4	WTC1	R080204	ACLASS	A
5	WTC2	R090203	ACLASS	A
6	R090203	WTC2	ACLASS	A
7	R090204	R090203	ACLASS	A
8	R090203	R090204	ACLASS	A
9	R090205	R090204	ACLASS	A
10	R090204	R090205	ACLASS	A

Figure 46: Example of A-class connections.

8.8.2.5 Custom setup for cross or A-class connections

As some designers do not use the conventional way of defining cross connections or A-class bulkheads in their designs, an additional feature has been built in into the tool. The tool will read the STAGE alternatives from the selected compartment connection (CCONN) table and automatically include all of them in the damage generation using the following logic:

- The primary damage (caused by the distributions) is in stage 1
- All other stages found in the CCONN table, apart from stage CROSS or stage ACLASS, are sorted alphabetically and added as optional stages to the damage after stage 1
- Stage CROSS is automatically added as an optional stage to the damage after the previous stages if stage=CROSS is found in the CCONN table
- Stages #<nr> (if applicable) are automatically populated based on the connections with class A in the CCONN table and included at the end of the damage definition

8.8.2.6 Up-flooding connections

Especially for the bottom groundings (type B00), it is necessary to model all routes for up-flooding, staircases, lift and escape trunks, hatches, etc. Otherwise, the results may be too optimistic. The recommended way is to add these into the compartment connection (CCONN) table. Note that possible A-class boundaries and cross-flooding connections need to be handled separately (Figure 47).

	CONN	COMP	OPEN	STAGE	OPENING	WTCOMP	CLASS
1	R030101	R030202					
2	R030202	R030101					
3	R040101	R040205					
4	R040205	R040101					
5	R050101	R050201					
6	R050201	R050101					

Figure 47: Example of up-flooding connections in CCONN* table, note that each connection is defined on two rows (two way connections).

8.8.2.7 Progression of water on the bulkhead deck

When the water level reaches the bulkhead deck, the impact on the ship becomes much more difficult to predict and time domain simulations should preferably be used for good results. Therefore, unless a simulation is performed, the model should be equipped with unprotected openings that are not participating in any progressive calculations on the bulkhead deck. These openings will effectively block any progression of water from one zone to another by setting s=0 when the opening is immersed.

8.8.3 The probabilistic model for generating damages

The grounding calculation tool in NAPA includes the probabilistic model, as presented earlier in this report, to produce the geometric values and create the CSV source table independently. In the tool the user is therefore presented with two alternatives for generating the damages;

- populate random damages using NAPA alone; or,
- by reading an already filled-in CSV table with the geometric values used as the base for the damage definitions

To better support the research work in this study, if the data is populated in NAPA, the user can change the number of damages to be generated using the tool interface.

The probability for all generated damages is the same (1/n), but damages that do not breach any compartments are considered not part of the total number of damages. The probability for a single damage is therefore re-normalised based on the number of cases breaching one or more compartments.

8.8.4 Geometry and damage extents

The dimension of the damage is governed by the populated values (based on the probabilistic model) in the CSV table. These values are then transformed into actual ship-coordinates and a penetrating box is created for each damage (Figure 48). Using the penetrating box in a temporary damage definition, the breached compartments are identified and recorded. Any group of damages, breaching the same set of compartments, are then considered unique and given the probability of all contributing damages. Only unique damage cases are then re-generated and sorted into the database for the index calculation.

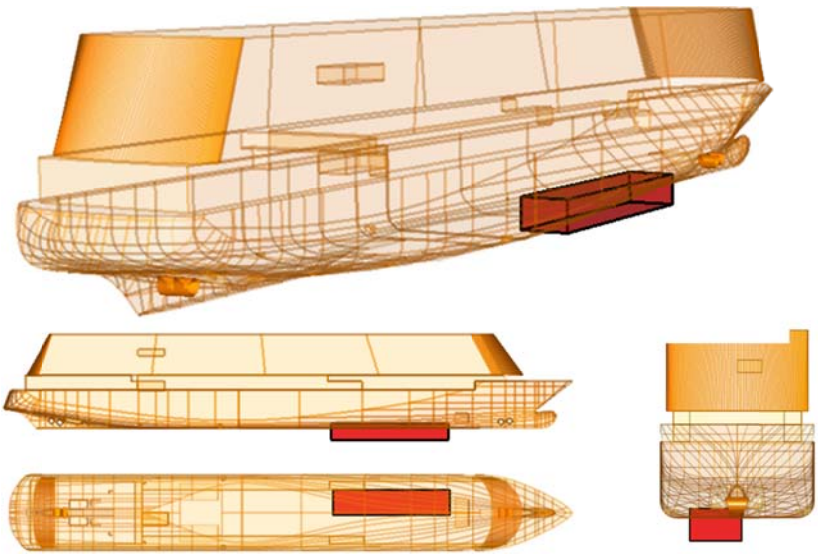

Figure 48: An example of a bottom (B00) grounding.

The side (S00) damages requires a shaped surface as the penetration limit (Figure 49), and in order to reduce the number of surfaces generated and simplify the amount of different geometries, a 1 cm tolerance was introduced for the waterline height and the penetration depth. As a result, the once generated surfaces can then be reused for the following damages and some performance boost can be gained.

Due to practical reasons in the program, the minimum penetration for the grounding damages and minimum dimensions for the penetrating box are set to 1 or 2 mm.

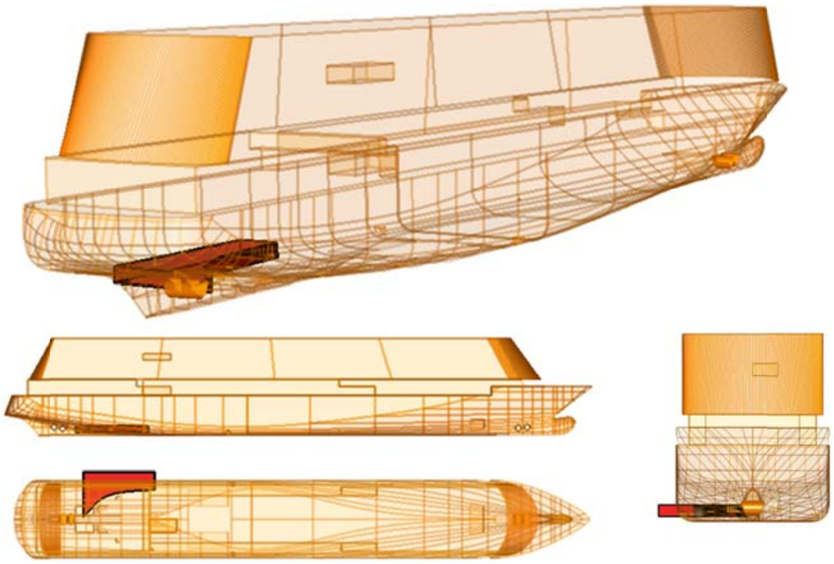

Figure 49: An example of a side (S00) grounding.

8.8.5 Damage definition and progressive flooding

To calculate an s-value according to SOLAS 2009, cross flooding connections and A-class structures also need to be considered. The grounding damage calculation tool supports the normal definition of these in NAPA, but also (as requested by some designers) an alternative method for including progressive flooding constructed using multiple stages. The tool will identify all stages named in the compartment connection, sort them alphabetically and add them in this order to the damage after the first (primary) stage. After this, the normal CROSS and A-class stages will be populated to the end of the damage.

8.8.6 Index calculation

Once the damages have been defined, an initial conditon group can be selected and the initial condition / damage combinations can be calculated. Based on the calculation results, the s-values are listed, multiplied with the probabilities and weight coefficients (as for the initial conditions in SOLAS 2009) to produce the index contribution for each case separately. These index contributions are then summed for the final total index and are listed. Also individual indexes are listed for the individual initial conditions.

For RoPax ships, SDC 1 agreed on a modification to the s_{final} formula (based on a proposal in SLF 55) and this alternative calculation of the s-factor is also available in the tool. If this s-formula is chosen, the designer must also name the roro cargo holds in the tool interface.

8.9 Risk Model

8.9.1 High-Level Event Sequence

High-level event sequences and risk models for the various accident types have been already discussed in the first interim report of Task 1 of the present study. In Task 3, the high-level event sequence and the risk model for grounding accidents have been revisited, in order to take into account an additional parameter that was introduced in Task 3, with decisive impact on the survivability of passenger ships, i.e. the type of damage:

a) bottom damage (type B00) and

b) side damage (type S00).

The high-level event sequence for grounding accidents for both Cruise and RoPax ships (Figure 50) considers the following events:

1. **Area of Operation**. Two alternatives are foreseen: the accident takes place either within or outside a Terminal Area. In the latter case, Limited Waters and Open Sea are combined in one area (Other) and treated together, since it is expected that the consequences of a grounding accident would be similar in both areas.
2. **Area of the hull in contact with the sea bottom**. The following two alternatives are considered: the ship touches the sea bottom with the bottom or the side of the hull surface.
3. **Type of the sea bottom** (Hard/Soft). In case the ship touches the sea bed with the side of the hull surface, the sea bottom is assumed always hard, therefore the corresponding node in the risk model is omitted.
4. **Hull breach** (Yes/No). In case of soft bottom, the probability of hull breach is set equal to zero. In case of hard sea bottom, the probability of hull breach is calculated, based on the available data from grounding accidents.
5. **Water Ingress** (Yes/No). In case of a hull breach due to bottom damage (type B00), water ingress takes place with a probability of 100%, therefore the corresponding node in the risk model is omitted. In case of a hull breach due to side damage (type S00), water ingress might take place or not, depending on the position of the lower limit of the breach with respect to the water line[12].
6. **Staying aground** (Yes/No). If immediately after the accident the ship stays aground, then no fatalities are assumed[13].
7. **Afloat** (Yes/No). If the ship does not stay aground, two alternatives are considered: a) it may remain afloat, with a probability assumed equal to the corresponding A-Index or, b) it may sink or capsize, with a probability assumed equal to 1-A[14].

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[12] In 8.6.9 (Probabilistic model conditional to the occurrence of water ingress), it is assumed that no water ingress occurs in case of side damage if the height of the lower limit of the breach from the base line exceeds a threshold limit equal to the ship's draught plus 2.0 m. Therefore, the probability of water ingress could be calculated from the probabilistic model, which has been developed combining grounding and contact accidents. However, in the current Risk Model, the calculation of the probability of water ingress in case of side damage is based on the available data from grounding accidents only. Based on the available data,, the probability of water ingress has been set equal to 100% regardless of the area of operation (either in terminal areas or in limited waters and open sea).

[13] Even if after saying aground, the ship becomes subsequently afloat again, either by its own means or with external assistance, it is assumed that its condition has been evaluated to ensure that there is no risk of sinking or capsizing and/or the passengers have been safely evacuated.

[14] In case of a grounding in terminal areas or in limited waters, if the ship becomes afloat immediately after the accident and does not lose its propulsion and maneuvering capability, the master may have the option of voluntary beaching the ship, in order to avoid sinking or capsizing. It might be argued therefore, that in this case the probability of avoiding a ship loss is higher than the corresponding A-Index.

8. **Consequences.** In case the ship sinks or capsizes, the number of fatalities is calculated as a percentage of POB (Persons on Board). The procedure for the calculation of fatalities is described in 8.9.2.

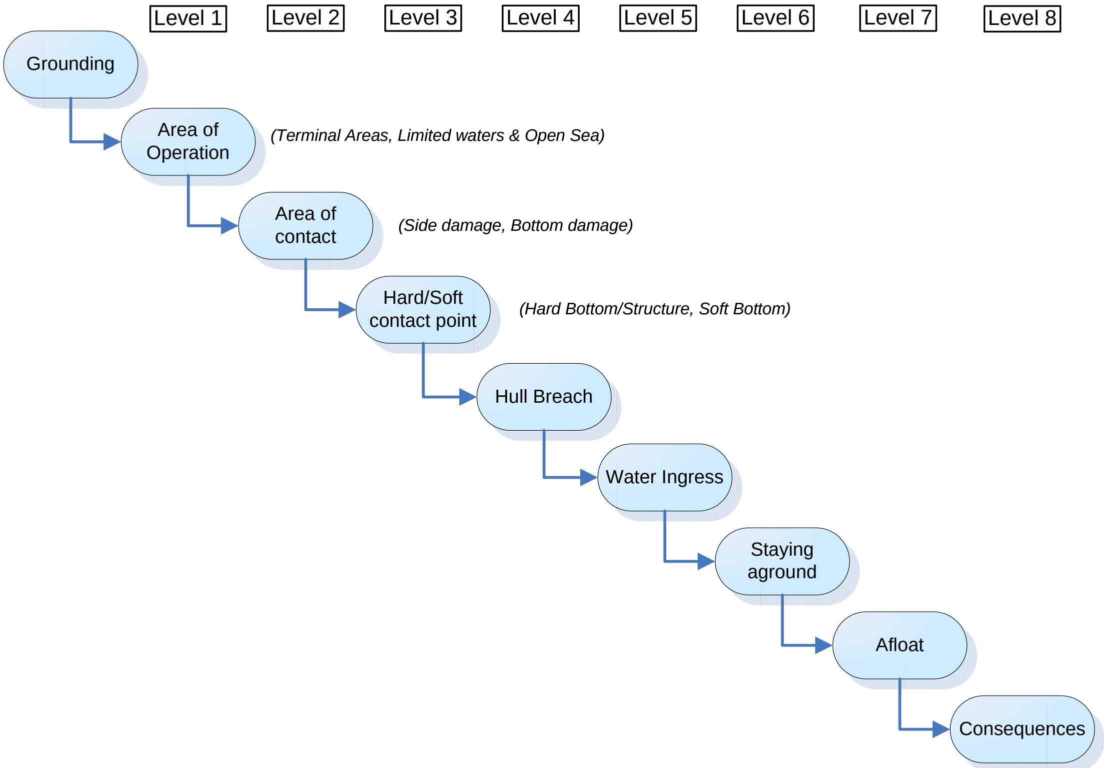

Figure 50: High-level event sequence for grounding of Cruise and ROPAX ships

8.9.2 Quantitative Risk Model for Grounding Accidents

The same Risk Model for Grounding Accidents is used for both types of ships, RoPax and Cruise ships with the following two differences:

- Initial accident frequencies are determined separately for each ship type.
- The probability of fast sinking is set equal to 18% for Cruise ships and 50% for RoPax ships.

The above probabilities of fast sinking of Cruise and RoPax ships were initially so defined in the GOALDS project on the basis of sample simulations and considering relevant historical data, and were also used in Task 1 of the present study ([31], [32]). Slow sinking is generally associated with progressive flooding, while capsizing, as a result of loss of transverse stability may take place quite fast. However, even in case of capsizing, this could also take place at a later stage, for example as a result of wave action, shift of cargo (in case of RoPax ships), or progressive flooding. What is of primary importance at this point is not the actual mechanism leading to the loss of the ship, but the time available for an orderly evacuation of the passengers and crew. The of probabilities of fast sinking of Cruise and RoPax ships proposed in GOALDS were kept unchanged also in Task 3; however, it should be noted that a 50% probability of fast sinking of RoPax ships, *particularly in case of bottom damages* seems to be excessively high. For RoPax ships, with a continuous watertight subdivision deck located much higher than the maximum possible height of bottom penetration, and with a relatively small number of up-flooding openings, it is expected that the probability of fast sinking should be quite small. Appropriate values for the probability of fast/slow sinking will be discussed and agreed by the partners during the elaboration of Subtask 3.c. In the meantime, it was decided to keep the GOALDS values in the risk model, at least in this phase of the study, and to investigate the impact of different probabilities of fast sinking in the sensitivity studies. It should be noted that the results for the Potential Loss of Life presented in this report are provisional, based on two empirical formulae proposed in GOALDS for the estimation of the A-Index for grounding accidents. The final results, based on the actual A-Index calculated according to the developed procedure will be presented in the final report of Task3, where the revised probability of fast/slow sinking will be used.

For the calculation of consequences in case the ship sinks or capsizes, the number of fatalities is calculated as follows:

- 80% of POB (Persons on Board) fatalities in case of fast sinking/capsizing in limited waters or in the open sea;
- 5% of POB fatalities in case of slow sinking/capsizing, or in case the accident takes place in terminal areas.

The percentage of fatalities (80% in case of fast sinking and 5% in case of slow sinking) were introduced in GOALDS, regardless of the area of the accident, while in Task 1 of the present study ([32]) it was decided to use the 5% percentage of fatalities in case the accident takes place in terminal areas, without distinguishing between fast/slow sinking. This is because it is considered that harbour infrastructure will enable immediate activation of emergency response forces, and also because the limited water depth in comparison with the ship's dimensions will protect the ship from being completely flooded and foundered.

Initial accident frequencies are determined considering the fleet at risk data for the period from 2000 to 2013[15] (only IACS classed ships) and ship losses during the same period of time due to grounding accidents, recorded in the accident data base for passenger ships described in chapter 8.4.2. Therefore, the full set of criteria for the selection of accidents, to be used for the calculation of initial frequencies are:

- Ship types: Cruise and Pure Passenger ships, <u>OR</u> RoPax and RoPax-Rail;
- Casualty time period: 2000-2013;
- GT ≥ 1,000;
- ≥ 80 m length;
- Built ≥ 1982;
- IACS classed;

[15] Accidents before the year 2000 and non-IACS classed ships are excluded to minimize the possibility of under-reporting.

- Accident type: serious;
- Froude number ≤ 0.5 – to eliminate HSC from the study.

The results with respect to casualties and frequencies (casualties per ship-year) are summarised in Table 41. The corresponding data for contact accidents[16] are also reported. The corresponding fleet at risk is equal to 2763 ship-years for cruise and pure passenger ships and 5328 ship-years for RoPax and RoPax Rail.

Table 41: Number of casualties and calculated accident frequencies for Cruise and RoPax ships (Groundings and Contacts)

	Cruise ships		RoPax ships	
	Casualties	Frequencies	Casualties	Frequencies
Groundings	26	9.73E-03	37	6.94E-03
Contacts	22	8.23E-03	86	1.61E-02

The dependent probabilities within the risk model are calculated merging the available data from both ship types (Cruise and RoPax ships). To this end, casualties reported in the groundings database for passenger ships described in chapter 8.4.2 for the period of time from 1990 to 2013 are used, including also non-IACS ships. All accidents in the database reported as non-serious have been excluded. The full set of criteria for the selection of accidents, to be used for the calculation of initial frequencies are:

- Ship types: Cruise and Pure Passenger ships, AND RoPax and RoPax-Rail;
- Casualty time period: 1990-2013;
- GT ≥ 1,000;
- ≥ 80 m length;
- Built ≥ 1982;
- IACS and non-IACS classed ships;
- Accident type: serious;
- Froude number ≤ 0.5 – to eliminate HSC from the study.

The risk model developed in Task 3 for grounding accidents of RoPax ships is presented in Figure 51. The corresponding risk model for grounding accidents of Cruise ships is presented in Figure 52. In these models, the probability of sinking should be estimated using the attained subdivision index A, calculated separately for bottom or side damages.

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[16] In the NTUA-SDL Casualty database used in Task 3, a grounding event is defined as an accident for which the vessel is going aground, or hitting/touching shore or sea bottom or underwater objects (wrecks, etc.), including hitting a submerged rock, whereas contact events are assigned to accidents when the ship had an impact on a fixed installation or object, which extends over the surface level (like a pier or higher extending rock), or impact on a floating object (barge, container etc.). Thus, the Costa Concordia accident is herein classified as powered grounding.

It should be reminded at this point that *the probabilistic model for the side damage characteristics, which is used for the calculation of the corresponding A-index, is based on data from both grounding and contact accidents*. As a result, it is possible that the model developed herein, exhibiting a distribution of the potential damage length shifted towards shorter damages (Figure 31), could be in this respect non-conservative. However, with the presently available data it is not possible to develop a better model based only on grounding accidents. In this respect, it might be considered reasonable to apply the modelling for the damage length that was developed in GOALDS for bottom damages, also in the case of side damages, or to consider the possibility of an intermediate model between the one developed herein for side damages and the one developed in GOALDS.

At the same time, it should be noted that the simplification of using an "equivalent" damage, representing the envelope of the damaged region in case of multiple breaches, is a highly conservative approximation[17]. In addition, in case of grounding in terminal areas or in limited waters, if the ship does not remain aground and does not lose its propulsion and manoeuvring capability, the master usually has the option of voluntary beaching a ship that has sustained a major damage, in order to avoid sinking or capsizing. It might be argued therefore, that in this case the probability of avoiding a ship loss would be higher than the corresponding A-Index.

To some extent, it may be argued that the combined conservative impact of these two issues is expected to counteract the impact of using a probabilistic model that may predict smaller damage lengths, in comparison with a probabilistic model that would be based entirely on data from grounding accidents. Although it is of course not possible to quantify these counteracting contributions, it is expected that the results of damage stability calculations based on the proposed framework can be used as an acceptable comparative measure of the survivability of passenger ships in case of a grounding accident. The proposed formulation, as well as the corresponding software tool, being based on the "direct approach", is easily adaptable in case an improved sample of accidents, with sufficient quantitative data for the breach characteristics, will be available in the future. In such case, the simplification of the "equivalent" damage could be also replaced by a more advanced probabilistic model, allowing for multiple breaches.

[17] Replacing multiple breaches with the "equivalent" damage results in the flooding of all watertight compartments within the damage length, while in reality some compartments may remain intact. This simplification is penalizing ships of all sizes, but its impact is expected to be more severe in case of the larger ships, having an increased number of watertight compartments.

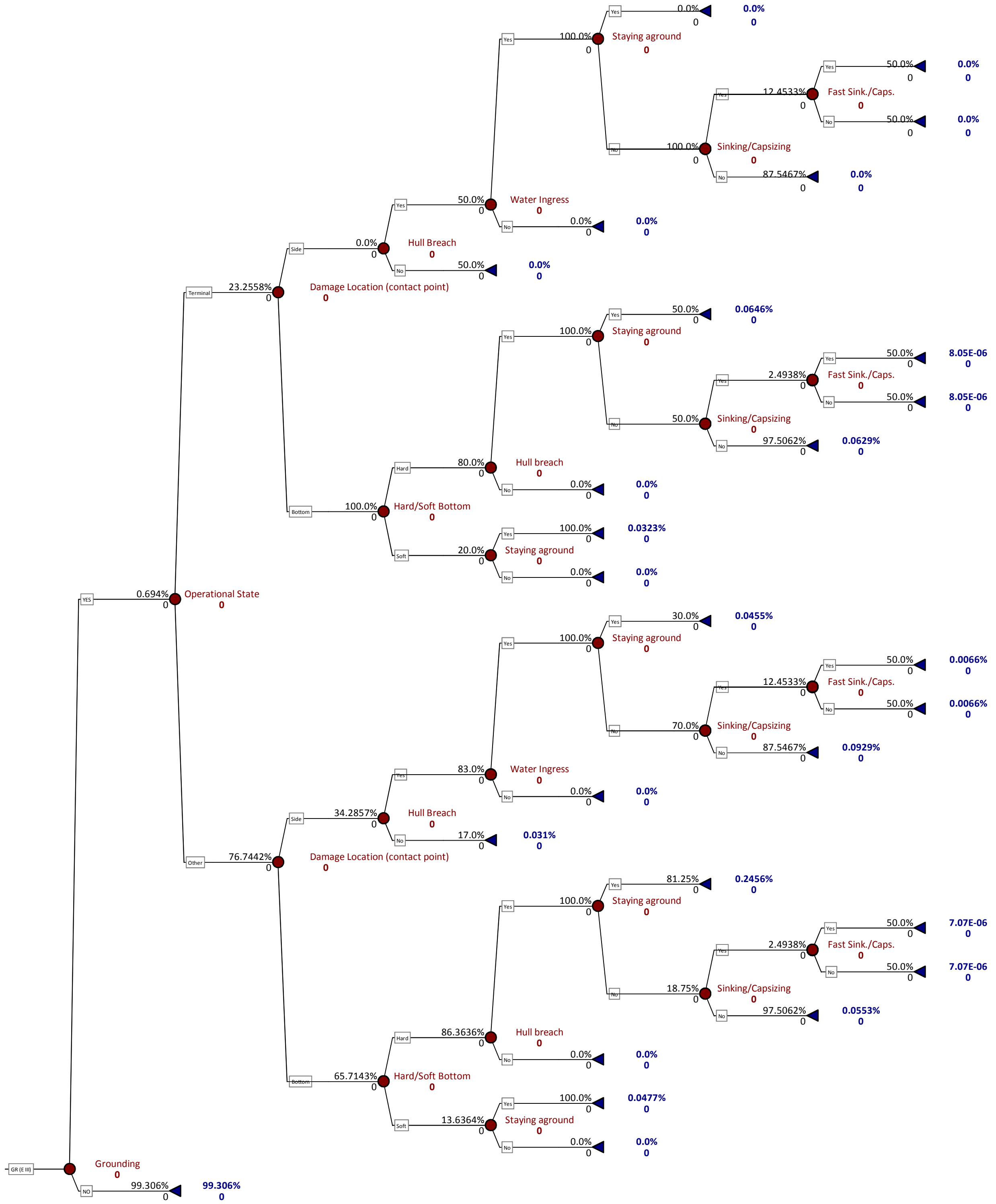

Figure 51: Risk Model for grounding accidents of RoPax ships

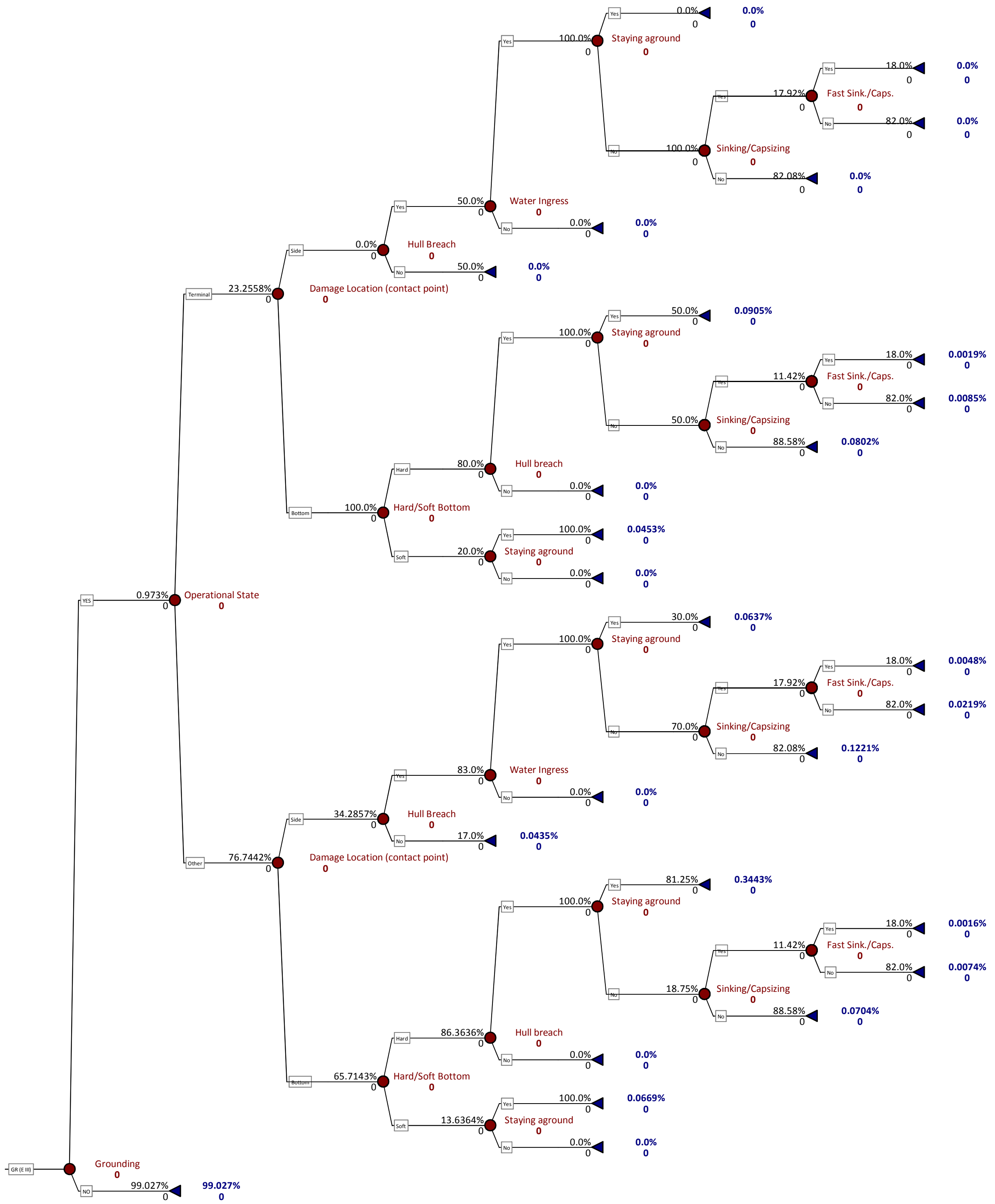

Figure 52: Risk Model for grounding accidents of Cruise ships

As shown in the risk models presented in Figure 51 and Figure 52, in case a grounding accident takes place, there is a 23.3% (resp. 76.7%) probability that the accident takes place in a terminal area (or in limited waters and open sea respectively).

1. Accidents in terminal areas

1.1. *Side accidents*. All the accidents in terminal areas were of the bottom damage type (100% probability). Therefore, in the branch of the risk model corresponding to side accidents in terminal waters, no values could be calculated for the dependent probabilities of hull breach, water ingress, and staying aground based on the available sample of accidents. However, for the sake of completeness, the following values were assumed: hull breach 50% 'Yes', water ingress 100% 'Yes', staying aground 100% 'No'. As long as the dependent probability of side damage in case of an accident in terminal areas remains zero, these assumptions have clearly no impact at all on the obtained results (the consequences are equal to zero).

1.2. *Bottom accidents*. In case of bottom accidents in terminal areas, a 20% probability of striking against a soft bottom is estimated. In this case no breach is assumed, and no consequences are calculated. The corresponding probability of striking against a hard bottom is therefore equal to 80%. In this case, based on the available data, the probability of a hull breach is set equal to 100%. The probability of water ingress in case of sustaining a hull breach at the bottom is always 100%; therefore the corresponding node is omitted. The probability of staying aground is set equal to 50%, in which case no consequences are assumed. If the ship does not remain aground, the probability of surviving is set equal to A_{GRB} (A-index for grounding accidents of type B00), in which case no consequences are assumed. In case the ship does not survive, the probability of fast sinking or capsizing is set equal to 18% for cruise ships and 50% for RoPax ships. A number of fatalities equal to 5% of POB is assumed in case of sinking/capsizing within terminal areas.

2. Accidents in limited waters and open sea

2.1. *Side accidents*. The dependent probability of side damages for accidents in limited waters and open sea is set equal to 34.3%. The dependent probability of a hull breach in case of side accidents in limited waters or open sea is set equal to 83%. The probability of water ingress is set equal to 100%, based on the available data. The probability that the ship remains aground (with no consequences to human life) is set equal to 30%. If the ship does not remain aground, the probability of surviving is set equal to A_{GRS} (A-index for grounding accidents of type S00), in which case no consequences are assumed. In case the ship does not survive, the probability of fast sinking or capsizing is set equal to 18% for cruise ships and 50% for RoPax ships. A number of fatalities equal to 5% (resp. 80%) of POB is assumed in case of slow (resp. fast) sinking/capsizing in limited waters or open sea.

2.2. *Bottom accidents*. The dependent probability of bottom damages for accidents in limited waters and open sea is set equal to 65.7%. The dependent probability of striking against a soft bottom in case of bottom accidents in limited waters or open sea is set equal to 13.6%. No consequences are assumed in this case. In case of striking against a hard bottom, the dependent probability of a hull breach is set equal to 100%. Since water ingress is an inevitable result of a hull breach in case of bottom damage, no such node is included in the risk model. The probability that the ship remains aground (with no consequences to human life) is set equal to 81.2%. If the ship does not remain aground, the probability of surviving is set equal to A_{GRB} (A-index for grounding accidents of type B00), in which case no consequences are assumed. In case the ship does not survive, the probability of fast sinking or capsizing is set equal to 18% for cruise ships and 50% for RoPax ships. A number of fatalities equal to 5% (resp. 80%) of POB is assumed in case slow (resp. fast) sinking/capsizing in limited waters or open sea.

8.9.3 Calculation of Potential Loss of Life for a series of passenger ships

The risk models presented in Figure 51 and Figure 52 will be used in Subtask 3.c for the calculation of the Potential Loss of Life (PLL) for a series of five passenger ships, studied in Task 1 ([31] and [32]) as well as for their five variants with increased damage stability characteristics, which have been evaluated to be cost effective. The probability of not sinking or capsizing will be estimated on the basis of the attained subdivision indices A_{GRB} and A_{GRS}, calculated separately for bottom or side damage types respectively.

In the meantime, the risk models have been applied to the five original designs, using two alternative empirical formulae proposed in GOALDS for the approximation of the grounding Attained Index A_{GR} based on the collision Attained Index A_{CN}:

$$A_{GR.GOALDS1} = A_{CN} + 0.1 \cdot (1 - A_{CN}) \qquad \text{(G.1)}$$

$$A_{GR.GOALDS2} = \begin{cases} A_{CN} + 0.1 & for \quad A_{CN} \le 0.9 \\ 1 & \text{else} \end{cases} \qquad \text{(G.2)}$$

The above formulae have been used herein for the approximation of A_{GR} both in case of bottom and side damages (A_{GRB} and A_{GRS}).

Selected data for the five passenger ships, used for the calculation of PLL are listed in Table 42. The average number of passengers for each ship is calculated using annual occupancy ratios selected in Task 1 of the EMSA 3 study ([31]). For cruise ships, the annual occupancy ratio is set equal to 90%, while for RoPax ships a value of 62.5% was used, based on the following seasonal ratios, provided by the project partners: 100% utilisation for 12.5% of the year, 75% utilisation for 25% of the year and 50% utilisation for the rest of the year. The persons on board (POB) have been calculated assuming the full number of crew and the average number of passengers, as estimated by the occupancy ratios. $A_{GR.GOALDS1}$ and $A_{GR.GOALDS2}$ in Table 42 stand for the approximation for A_{GR} derived by equations (G.1) and (G.2) respectively. The resulting PLL values, calculated by the Risk Models for grounding accidents presented in 8.9.2, based on $A_{GR.GOALDS1}$ and $A_{GR.GOALDS2}$ are included in Table 42, denoted as PLL_1 and PLL_2 respectively.

Table 42: Overview of sample ships

	Small Cruise Ship	Large Cruise Ship	Small RoPax	Medi-terranean RoPax	Baltic Ferry
Length BP (m)	113.70	294.64	95.50	172.40	232.00
GT	11,800	153,400	7,900	43,000	60,000
Passengers Max	316	5135	600	1600	3060
Passengers Av.	285	4622	375	1000	1875
Crew	162	1595	25	100	220
POB	447	6217	400	1100	2095
R	0.6978	0.8597	0.7214	0.778	0.83
A_{CN}	0.7202	0.8621	0.7740	0.8398	0.8592
$A_{GR.GOALDS1}$	0.7482	0.8759	0.7966	0.8558	0.8733
$A_{GR.GOALDS2}$	0.8202	0.9621	0.8740	0.9398	0.9592
PLL_1	0.0526	0.3607	0.0589	0.1148	0.1922
PLL_2	0.0376	0.1102	0.0365	0.0479	0.0619

The results from the calculation of PLL for the five sample designs are plotted versus the corresponding number of persons on board in Figure 53. Results based on equation (G.1) are denoted with square marks while those based on equation (G.2) with triangles. Results for RoPax ships are denoted by red colour, while those for cruise ships by blue colour.

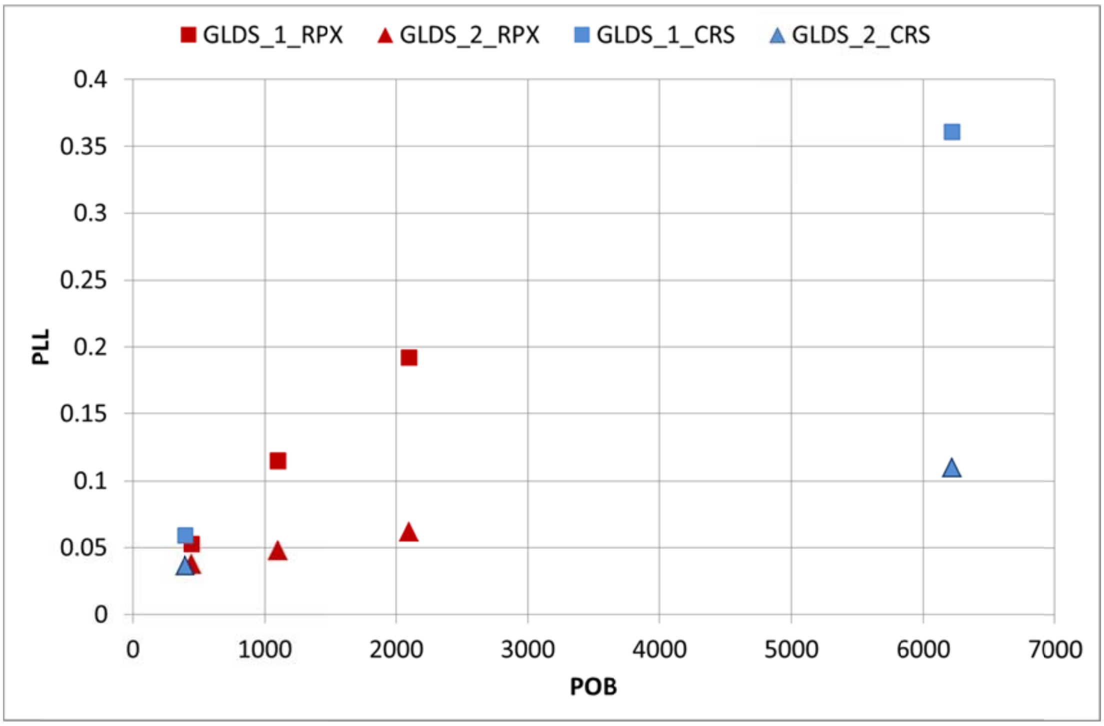

Figure 53: Results from the calculation of PLL vs POB for the 5 sample designs

8.9.4 Sensitivity analysis

In this section the sensitivity of the risk model is analysed, based on calculations with the small size cruise ship, the large cruise ship and the Baltic ferry.

The risk to persons on board in terms of PLL depends linearly on the initial accident frequency as well as on the number of persons on board (POB). Hence, an increase of the initial accident frequency or POB by 10% would lead to 10% increase of PLL.

Two more grounding accidents outside terminal areas[18] (i.e. in limited waters or in open sea) would have a marginal impact on the risk to human life. It would take ten more accidents outside terminal areas to have a noticeable impact on the PLL (approximately 2% increase on average). The corresponding results are summarized in the following table:

Table 43: Impact on PLL of additional accidents in limited waters or open sea

	PLL values based on A_{GR1}			PLL values based on A_{GR2}		
	Small cruise ship	Large cruise ship	Baltic Ferry	Small cruise ship	Large cruise ship	Baltic Ferry
Reference value	5.26E-02	3.61E-01	1.92E-01	3.76E-02	1.10E-01	6.19E-02
Two more accidents outside terminal	5.28E-02	3.62E-01	1.93E-02	3.77E-02	1.11E-01	6.22E-02
Ten more accidents outside terminal	5.36E-02	3.67E-01	1.97E-01	3.83E-02	1.12E-01	6.34E-02

In the terminal areas, no grounding accidents resulting to side damage are recorded in the database. One or two such accidents would have a marginal impact on the risk to human life. Even with five such accidents, the impact on PLL would be quite small (less than 1%). This is partly because fatalities in terminal areas in case of sinking or capsizing are always assumed equal to 5% of POB. The corresponding results are summarized in the following table:

Table 44: Impact on PLL of additional side damages in terminal areas

	PLL values based on A_{GR1}			PLL values based on A_{GR2}		
	Small cruise ship	Large cruise ship	Baltic Ferry	Small cruise ship	Large cruise ship	Baltic Ferry
Reference value	5.26E-02	3.61E-01	1.92E-01	3.76E-02	1.10E-01	6.19E-02
One side damage in Term. Area	5.28E-02	3.62E-01	1.92E-01	3.77E-02	1.11E-01	6.20E-02
Two side damages in Term. Area	5.29E-02	3.63E-01	1.93E-01	3.78E-02	1.11E-01	6.20E-02
Five side damages in Term. Area	5.32E-02	3.65E-01	1.93E-01	3.80E-02	1.11E-01	6.22E-02

[18] Whenever the sensitivity analysis is performed adding or subtracting a number of accidents of a certain type, the dependent probabilities within the Risk Models for Cruise or RoPax ships are updated accordingly, however, the initial frequency of grounding accidents remains unaffected.

The impact of one more accident in terminal areas, assuming bottom damage and soft bottom (therefore no water ingress and zero consequences) is considered next. The result would be a reduction of risk by approximately 1.6% for the two cruise ships and 0.7% for the RoPax. The corresponding results are summarized in the following table:

Table 45: Impact on PLL of one more accident in terminal areas, assuming bottom damage and soft bottom

	PLL values based on A_{GR1}			PLL values based on A_{GR2}		
	Small cruise ship	Large cruise ship	Baltic Ferry	Small cruise ship	Large cruise ship	Baltic Ferry
Reference value	5.26E-02	3.61E-01	1.92E-01	3.76E-02	1.10E-01	6.19E-02
Plus one accident in terminal areas + bottom damage and soft bottom	5.18E-02	3.55E-01	1.91E-01	3.70E-02	1.08E-01	6.14E-02

The impact of reducing the probability of hull breach from 100% to 95% and 90% in case of accidents in terminal areas, assuming bottom damage and hard bottom is considered next. In both cases, the reduction of the PLL is very small. The corresponding results are summarized in the following table:

Table 46: PLL values for reduced probability of hull breach for accidents in terminal areas, assuming bottom damage and hard bottom

	PLL values based on A_{GR1}			PLL values based on A_{GR2}		
	Small cruise ship	Large cruise ship	Baltic Ferry	Small cruise ship	Large cruise ship	Baltic Ferry
Reference value	5.26E-02	3.61E-01	1.92E-01	3.76E-02	1.10E-01	6.19E-02
95% probability of hull breach (terminal areas + bottom damage and hard bottom)	5.24E-02	3.59E-01	1.92E-01	3.74E-02	1.10E-01	6.17E-02
90% probability of hull breach (terminal areas + bottom damage and hard bottom)	5.21E-02	3.57E-01	1.91E-01	3.72E-02	1.09E-01	6.16E-02

The relative frequency of side / bottom damage in the risk model is equal to 0% side – 100% bottom in the terminal areas and 34.3% side – 65.7% bottom in limited waters and open seas. If a common (averaged) frequency of side – bottom damage would be used in both areas, the corresponding values would be 29% side – 71% bottom. The impact on risk would be a reduction of approximately 6%. The results for the three ships are summarized in the following table:

Table 47: PLL values based on a common (averaged) frequency of side – bottom damage for all accidents (both in and outside terminal areas)

	PLL values based on A_{GR1}			PLL values based on A_{GR2}		
	Small cruise ship	Large cruise ship	Baltic Ferry	Small cruise ship	Large cruise ship	Baltic Ferry
Reference value	5.26E-02	3.61E-01	1.92E-01	3.76E-02	1.10E-01	6.19E-02
Common side-bottom freq. in all areas	4.95E-02	3.40E-01	1.80E-01	3.54E-02	1.04E-01	5.78E-02

The impact of one more accident in limited waters or open sea, assuming side damage, water ingress and staying aground is considered next. The result would be a reduction of risk by approximately 5.5%. The corresponding results are summarized in the following table:

Table 48: PLL values for one more accident in limited waters or open sea, assuming side damage, water ingress and staying aground

	PLL values based on A_{GR1}			PLL values based on A_{GR2}		
	Small cruise ship	Large cruise ship	Baltic Ferry	Small cruise ship	Large cruise ship	Baltic Ferry
Reference value	5.26E-02	3.61E-01	1.92E-01	3.76E-02	1.10E-01	6.19E-02
Plus one accident in lim. waters or open sea + side damage, water ingress and staying aground	4.98E-02	3.41E-01	1.81E-01	3.56E-02	1.04E-01	5.84E-02

The impact of reducing the probability of water ingress from 100% to 95% and 90% in case of accidents in limited waters or open sea, assuming side damage and hull breach is considered next. The average reduction of the PLL is 3% (resp. 6%) in case of 95% (resp. 90%) probability of water ingress. The corresponding results are summarized in the following table:

Table 49: PLL values for reduced probability of water ingress (accidents in limited waters or open sea, assuming side damage and hull breach)

	PLL values based on A_{GR1}			PLL values based on A_{GR2}		
	Small cruise ship	Large cruise ship	Baltic Ferry	Small cruise ship	Large cruise ship	Baltic Ferry
Reference value	5.26E-02	3.61E-01	1.92E-01	3.76E-02	1.10E-01	6.19E-02
95% probability of water ingress (lim. waters or open sea, side damage and hull breach)	5.11E-02	3.50E-01	1.86E-01	3.65E-02	1.07E-01	5.99E-02
90% probability of water ingress (lim.waters or open sea, side damage and hull breach)	4.95E-02	3.39E-01	1.80E-01	3.54E-02	1.04E-01	5.80E-02

The impact of reducing the probability of water ingress from 100% to 95% and 90% in case of accidents in limited waters or open sea, assuming bottom damage and hull breach is considered next. The average reduction of the PLL is 1.7% (resp. 3.1%) in case of 95% (resp. 90%) probability of water ingress. The corresponding results are summarized in the following table:

Table 50: PLL values for reduced probability of water ingress (accidents in limited waters or open sea, assuming bottom damage and hull breach)

	PLL values based on A_{GR1}			PLL values based on A_{GR2}		
	Small cruise ship	Large cruise ship	Baltic Ferry	Small cruise ship	Large cruise ship	Baltic Ferry
Reference value	5.26E-02	3.61E-01	1.92E-01	3.76E-02	1.10E-01	6.19E-02
95% probability of water ingress (lim. waters or open sea, bottom damage and hull breach)	5.18E-02	3.55E-01	1.89E-01	3.70E-02	1.08E-01	6.08E-02
90% probability of water ingress (lim. waters or open sea, bottom damage and hull breach)	5.10E-02	3.49E-01	1.86E-01	3.64E-02	1.07E-01	5.98E-02

Finally, the impact of setting the probability of fast sinking equal to 10% or 30% is considered. It should be noted that for the cruise ships the probability of fast sinking used so far is 18%, therefore setting this probability to 30% corresponds to a 66.7% increase. On the other hand, for the RoPax ships the probability of fast sinking used so far is 50%, therefore both 10% and 30% probabilities correspond to a drastic reduction. Setting the probability of fast sinking equal to 10% would result in a reduction of PLL by 29% for the two cruise ships and by 67% for the RoPax ship. On the other hand, setting the probability of fast sinking equal to 30% would result in an increase of PLL by 44% for the two cruise ships and a reduction by 34% for the RoPax ship. The corresponding results are summarized in the following table:

Table 51: Impact of the probability of fast sinking on PLL values

	PLL values based on A_{GR1}			PLL values based on A_{GR2}		
	Small cruise ship	Large cruise ship	Baltic Ferry	Small cruise ship	Large cruise ship	Baltic Ferry
Reference value	5.26E-02	3.61E-01	1.92E-01	3.76E-02	1.10E-01	6.19E-02
10% probability of fast sinking	3.72E-02	2.55E-01	6.26E-02	2.66E-02	7.79E-02	2.01E-02
30% probability of fast sinking	7.57E-02	5.19E-01	1.27E-01	5.41E-02	1.59E-01	4.10E-02

8.9.5 Historical data of total losses due to groundings

In the following, a series of historical data of total losses due to groundings and associated consequences are described:

- Year 2000 – *EXPRESS SAMINA*: On Tuesday September 26, 2000, late afternoon, the Greek Passenger/Ro-Ro ferry Express Samina left the port of Piraeus heading to the island of Paros, the first on her route to the island of Lipsi. The vessel was reported carrying 533 persons on-board (472 passengers and 61 crewmembers), 17 trucks and 34 cars. While approaching the island of Paros, the ship deviated from the actual route and hit the rocks of Portes, located outside the entranceways to the port of Paros. The impact of the ship with the rocky islet was on the starboard side, resulting to three raking damages on the ship's outer shell, below and above the waterline level. Two of these damage openings were of particular significance for the flooding process, and the later sinking of the ship. The vessel sunk within half an hour, leading to death 80 passengers and crewmembers. The impact to regulatory framework was an extension of Stockholm Regional Agreement to the South European Waters. EU Directive 2003/25/EC. This accident is not included in the data used for the development of the Risk Model, since the ship was built before 1982.
- Year 2007 – SEA DIAMOND: On April 5, 2007, the Passenger ship SEA DIAMOND ran aground on a volcanic reef east of Nea Kameni, within the caldera of the Greek island of Santorini. Because of the impact, there was loss of watertight integrity, resulting to ship's listing up to 12 degrees, starboard side. The accumulation of water led to the ship sinking after 27 hours from the initial hitting, leaving two (2) passengers missing and presumed dead.
- Year 2008 – PRINCESS OF THE STARS: The RoPax ship PRINCESS OF THE STARS (built in year 1984) left the port of Manila on June 20, 2008, en route to Cebu City. While en route, the ship encountered the fierce winds and massive waves of Typhoon "Fengshen", which had been sweeping through the region, but were not expected to cross the ferry’s path. There was a reference that the vessel sustained engine failure and stranded. As a result, there was a loss of watertight integrity below the waterline and the ship capsized in South China Sea, with 523 reported fatalities and 308 missing persons. The circumstances of this accident are unclear with contradictory or controversial information being collected from various sources, whereas also the weather conditions were abnormal; therefore it may not be suitable to draw conclusions on the impact of grounding accidents on human life on the basis of this accident.
- Year 2009 – ARIAKE: The RoPax Ariake, travelling from Tokyo in high winds, developed a 22 degree list due to a large scale cargo shift induced by large rolling in stern quartering waves, ran aground and subsequently capsized at Mihama, Mie, Japan. All persons on board (7 passengers and 21 crewmembers) were safely rescued.
- Year 2012 – *COSTA CONCORDIA*: The Cruise vessel *Costa Concordia*, built in year 2004, struck on January 13, 2012, at about 9.45pm, a submerged rock in the Secca di Mezzo Canal, off the Isola del Giglio. It sustained severe damage to the port side of the hull near the engine room, took water leading to a black-out and complete power loss; she developed list to starboard side and in view of favourable weather conditions she drifted back to the shore and finally grounded, resting on her starboard side. Eventually, out of 3,229 passengers and 1,023 crew members known to have been onboard, merely 32 lives were lost in the accident.

The review of accidents identified only one ship loss as a result of a contact accident:

- Year 2007 – *EXPLORER*: On 23 November 2007, the Liberian registered, passenger vessel *EXPLORER*, sank in a position 25 miles southeast of King George Island. All 54 crewmembers and 100 passengers abandoned the ship safely. The vessel sank after striking ice and sustaining damage to the hull.

9 CONCLUSIONS

The harmonized probabilistic framework for ship survivability assessment following a damage – SOLAS 2009 – has represented an important step towards a more rational assessment of ship safety, compared to the previous deterministic damage stability regulations for passenger and cargo ships. At the same time, however, the SOLAS 2009 probabilistic framework explicitly addresses only side damages caused by a collision. Bottom damages caused by grounding are implicitly assumed to be dealt with by the deterministic approach in Chapter II-1, Regulation 9, "Double bottoms in passenger ships and cargo ships other than tankers", where minimum double bottom requirements are provided, and where deterministic bottom grounding damage characteristics are specified, to be used for survivability assessment in case of vessels with unusual bottom arrangements. As a result, side damages due to collision are addressed in a probabilistic way, while, at the same time, bottom grounding is addressed in a deterministic framework.

Such a situation could benefit from a harmonization, where bottom grounding damages are addressed in a probabilistic framework as well. To respond to this need, the EU-funded GOALDS project developed a probabilistic modelling for bottom grounding damage characteristics, with some preliminary indications for an actual implementation. Such modelling has then been re-evaluated and adapted in the framework of the present project, in order to develop a practically applicable tool for the determination of the probability of flooding of (groups of) compartment(s). Such tool can be combined with the assessment of survivability following a specific damage based on, e.g., the present SOLAS 2009 s-factor. The resulting framework is, therefore, able to address survivability after a bottom grounding damage through a fully probabilistic approach.

Nevertheless, as both historical data and also recent accidents show, grounding damages can result also in a damage on the side of the vessel. Damages on the side of the vessel can also be the result of the contact with fixed or floating objects. Presently, side damages within the SOLAS 2009 probabilistic framework, are associated only with the result of a collision.

Continuing on the line previously initiated in case of bottom grounding damages, the present analysis has been aimed at developing a fully probabilistic model for the geometrical characteristics of side damages due to grounding and contact. To this end, use has been made of historical data, some of them collected in the framework of previous projects, while others were added during the elaboration of the present project. Data have been scrutinised through exploratory data analysis, and analytical models for the distributions of the involved random variables have been developed. Probabilistic models have been provided, in particular, for:

- The side where the damage occurs;
- The longitudinal position of forward end of damage;
- The longitudinal extent of potential damage, i.e. potential damage length;
- The transversal extent of potential damage, i.e. potential damage penetration;

- The vertical position of lower limit of potential damage from the ship bottom;
- The height of potential damage above its lower limit, i.e. the vertical extent of potential damage;

It is important to note that, similarly to what was done also in the framework of the GOALDS project, in case of damages characterised by multiple holes, the variables referred above represent the overall extent of the part of the vessel affected by the damage, and not the extent of the single hole. Indeed, before analysing the data, multiple-hole damages have been substituted by “equivalent” damages, corresponding to the envelope of the damaged region of the vessel. Such approach has been considered to be an acceptable “equivalent” simplification for the determination of the probability of flooding of different compartments and when static ship stability is considered.

In the development of the models, attention has been given to try developing tools balancing simplicity and representativeness of the available data. Also, when possible, the functional form of the developed distribution models have been chosen in order to harmonize them with the models developed in GOALDS for bottom grounding damage.

The resulting modelling can be directly implemented in a procedure where damages are automatically generated, and an example procedure on how to perform this generation has been provided. This means that the model has direct practical applicability.

The distributions in the modelling have been kept in a parametric form, with characterising parameters appearing explicitly, in order to simplify possible modifications/corrections/tuning/updating. The scope, indeed, is to provide models which can be easily update as soon as new, better information are gathered.

The developed probabilistic model for damage characteristics has been embedded into an envisioned procedure for the determination of an “Attained Index”, similar to that already available in SOLAS 2009, but specific, now, for grounding accidents resulting in bottom or side damage. In such an envisioned procedure, p-factors are calculated by means of a “direct approach” (as a more flexible and updatable alternative to the more usual “zonal approach” utilised in the framework of SOLAS 2009), where a large number of hull breaches are generated in order to determine the probability of flooding a (group of) compartment(s), i.e. the p-factors. The conditional survival probability, “s-factor”, is then determined following the standard approach from SOLAS 2009 (or, as an alternative, the s-factor formulation from SLF 55 for RoPax ships).

It is thought that the present probabilistic modelling for survivability assessment to side and bottom grounding/contact damages, can help in filling the gap between the SOLAS 2009 probabilistic framework for survivability assessment following a side damage due to collision, and the deterministic requirements set in SOLAS Ch.II-1, Reg.9.

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