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Imię i nazwisko autora rozprawy: Piotr Sebastian Szulczewski
Dyscyplina naukowa: Budowa i Eksploatacja Maszyn

ROZPRAWA DOKTORSKA

Tytuł rozprawy w języku polskim: Metoda identyfikacji zbioru parametrów i charakterystyk decydujących o bezpieczeństwie statków towarowych w stanie uszkodzonym w oparciu o kryteria oceny ryzyka

Tytuł rozprawy w języku angielskim: A method of identification of a set of parameters and characteristics of decisive impact on safety of cargo ships in damaged conditions based on the risk assessment criteria

Promotor *Podpis*	Drugi promotor *Podpis*
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Gdańsk, rok 2016

GDAŃSK UNIVERSITY
OF TECHNOLOGY
OCEAN ENGINEERING AND
SHIP TECHNOLOGY

The author of the PhD dissertation: Piotr Sebastian Szulczewski
Scientific discipline: Budowa i Eksploatacja Maszyn (Building and Operation of Machineries)

DOCTORAL DISSERTATION

Title of PhD dissertation: A method of identification of a set of parameters and characteristics of decisive impact on safety of cargo ships in damaged conditions based on the risk assessment criteria

Title of PhD dissertation (in Polish): Metoda identyfikacji zbioru parametrów i charakterystyk decydujących o bezpieczeństwie statków towarowych w stanie uszkodzonym w oparciu o kryteria oceny ryzyka

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Gdańsk, year 2016

Załącznik nr 2/1
do Zarządzenia Rektora PG nr 5/2015 z 10 lutego 2015 r.

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Autor rozprawy doktorskiej: Piotr Szulczewski

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[2] Ustawa z dnia 27 lipca 2005 r. Prawo o szkolnictwie wyższym: Rozdział 7 Odpowiedzialność dyscyplinarna doktorantów, Art. 226.

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The author of the PhD dissertation: Piotr Szulczewski

I, the undersigned, agree/~~do not agree~~* that my PhD dissertation entitled:

A method of identification of a set of parameters and characteristics of decisive impact on safety of cargo ships in damaged conditions based on the risk assessment criteria

may be used for scientific or didactic purposes.[1]

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[2] Act of 27th July 2005, Law on Higher Education: Chapter 7, Criminal responsibility of PhD students, Article 226.

Załącznik nr 3/1
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OPIS ROZPRAWY DOKTORSKIEJ

Autor rozprawy doktorskiej: Piotr Sebastian Szulczewski

Tytuł rozprawy doktorskiej w języku polskim: Metoda identyfikacji zbioru parametrów i charakterystyk decydujących o bezpieczeństwie statków towarowych w stanie uszkodzonym w oparciu o kryteria oceny ryzyka

Tytuł rozprawy w języku angielskim: A method of identification of a set of parameters and characteristics of decisive impact on safety of cargo ships in damaged conditions based on the risk assessment criteria

Język rozprawy doktorskiej: angielski

Promotor rozprawy doktorskiej: Mirosław Gerigk

Data obrony:

Słowa kluczowe rozprawy doktorskiej w języku polski: hydromechanika, bezpieczeństwo, stateczność awaryjna, transport, ryzyko, projektowanie statków, eksploatacja statków

Słowa kluczowe rozprawy doktorskiej w języku angielskim: hydromechanics, safety, damage stability, transport, risk, design of ships, operation of ships

Streszczenie rozprawy w języku polskim: Rozprawa jest poświęcona bezpieczeństwu statków w stanie uszkodzonym. Została w niej przedstawiona analiza wybranego modelu stanu awaryjnego, polegająca na uszkodzeniu poszycia i wtargnięciu wody do kadłuba statku. W pracy znalazła się krytyka istniejącej metody zawartej w przepisach konwencji SOLAS 2009 oceny bezpieczeństwa statków, oraz wnioski z możliwego do zastosowania alternatywnego modelu, który odpowiada wynikom z tej metody.

Zaprezentowana alternatywa dla metody zawartej w SOLAS 2009 jest przeznaczona do optymalizacji bezpieczeństwa już na etapie projektowym. Jednocześnie jednym z celów przy projektowaniu metody była łatwość w jej implementacji w czasie eksploatacji, dla oficerów na statkach, i dla projektantów.

Streszczenie rozprawy w języku angielskim: The dissertation covers the subject of safety of ships in damaged condition. In this dissertation, the analysis of the model state of emergency, which consists of damage to the shell and the ingress of water into the ship's hull, were presented and described in detail. In addition the work contains a critique of the existing, in many ways equivalent methods included in the regulations of SOLAS 2009 assessment and the conclusions of a possible application of the alternative method.

The presented in the dissertation alternative to the method included in SOLAS 2009 was designed to optimize safety at the design stage. Concordantly one of the objectives of the designed method was the ease in its implementation during ships operation, for officers on ships and for naval architects.

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DESCRIPTION OF DOCTORAL DISSERTATION

The Author of the PhD dissertation: Piotr Szulczewski

Title of PhD dissertation: A method of identification of a set of parameters and characteristics of decisive impact on safety of cargo ships in damaged conditions based on the risk assessment criteria

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Language of PhD dissertation: English

Supervision: DSc. Mirosław Gerigk, Professor of Gdańsk University of Technology

Date of doctoral defense:

Keywords of PhD dissertation in Polish: hydromechanika, bezpieczeństwo, stateczność awaryjna, transport, ryzyko, projektowanie statków, eksploatacja statków

Keywords of PhD dissertation in English: hydromechanics, safety, damage stability, transport, risk, design of ships, operation of ships

Summary of PhD dissertation in Polish: Rozprawa jest poświęcona bezpieczeństwu statków w stanie uszkodzonym. Została w niej przedstawiona analiza wybranego modelu stanu awaryjnego, polegająca na uszkodzeniu poszycia i wtargnięciu wody do kadłuba statku. W pracy znalazła się krytyka istniejącej metody zawartej w przepisach konwencji SOLAS 2009 oceny bezpieczeństwa statków, oraz wnioski z możliwego do zastosowania alternatywnego modelu, który odpowiada wynikom z tej metody.

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The presented in the dissertation alternative to the method included in SOLAS 2009 was designed to optimize safety at the design stage. Concordantly one of the objectives of the designed method was the ease in its implementation during ships operation, for officers on ships and for naval architects.

*) delete where appropriate.

“*A good decision is based on knowledge and not on numbers*”

- Plato

Preface

This Thesis is the result of work carried out for a PhD degree. The Matlab code used for visualization of the method presented is a modified code used by Mr Martin Martinussen for his Thesis at NTNU University. The largest modifications included changed calculation parameters, damping coefficient calculations and hull geometry generation codes program implementation. The major modifications to the code are added to this work as appendices.

The work has been carried out under supervision of Prof. Miroslaw Gerigk. The Author would like to thank his family, companies Anglo Eastern and Brookes Bell as well as the Professors from University of Technology Gdansk with whom I had the pleasure to work with for help in preparation of this work.

Dedicated to:
유 정민

Table of Contents

Terminology:

A_{xx} -	total added mass coefficient
A_{WP} -	water-plane area
b_{BK} -	breadth of bilge keel
B -	beam of ship or barge
B_{xx} -	total roll damping coefficient
B_{e} -	eddy making damping coefficient
B_{f} -	skin friction damping coefficient
B_{L} -	lift effect damping coefficient
B_{w} -	damping from free surface waves (radiation)
C_{xx} -	stiffness matrix
C_{B} -	block coefficient of the ship
C_{M} -	mid-ship section coefficient
D -	draft
F_k -	force component, where $k = 1, 2, ..., 6$, or “s”
F_{n} -	Froude number
g -	gravitational acceleration
$H_{1/3}$ -	average of the 1/3 highest waves (taken as significant wave height)
I -	total moment of inertia
KG -	distance from the keel to the c.g.
L -	lateral dimension of the ship
M -	wave exciting moment
OG -	vertical distance (positive upward) from SWL to c.g.
Φ -	amplitude of roll motion (in degrees)
S -	wetted surface area
T_n -	wave period
t -	time
U -	forward speed (or current)
V -	ship displaced volume
η -	kinematic viscosity of water
ρ -	water density
ω -	wave frequency

1.Introduction

Evaluation of ship safety is a complex problem. There are numerous factors influencing a risk for safety of passengers, crew, cargo and the environment a floating structure moves in.

Current methods of evaluating the safety of ships are based on specific rules and regulations that include analysis of damaged ship stability. For various types of ships specific criteria have been developed and later improved or modified. These criteria were developed not only through modifications of required parameters of righting arm curves, but also by changes in damage scenarios used in this analysis. A range of currently used methods is optimized for ships of different size and purpose. There are different safety requirements for passenger ships, bulk carriers, chemical tankers, liquefied gas tankers or special purpose ships. Not meeting the specified in the above mentioned requirements criteria for stability and/or unsinkability classifies ships as dangerous, and adequate ship design modifications become necessary. In the last century there have been numerous attempts to widen the scope of safety evaluation. Some of these attempts have been considered in the process of improving rules and regulations, while others have been rejected and remain in the sphere of t theoretical studies now. Consequently, analysis of the safety of most ships in damaged conditions remains prescriptive and is based on a set of criteria based on analysis of a righting arm. For selected vessels the PSA (Probabilistic Safety Assessment) has been implemented however, elements of previously established prescriptive methods of evaluating the ship safety were employed.

It is a standard now to design cargo ships for optimised efficiency in terms of travel cost per cargo unit. Consequently, designing ships is based on optimising ship designs for speed or fuel consumption at given/attainable cargo capacities. Stability of ships in damaged conditions is not a design target in this process and remains a limiting factor in realising the above described goal. One example of this compromise may be a removal of additional structure barriers, bulkheads or decks, that protect the ship from uncontrolled ingress of water after damage. Such structures increase the weight of the ship , lower the cargo capacity and may compromise efficient cargo allocation. This may be contradictory to maintaining a desired level of safety. The cargo ship design is a highly optimised process where the survivability of the ship , and hence the safety of the crew and cargo, and the protection of the environment, are seen only as factors limiting the increase in economic efficiency.

Consequently the author is inclined to believe that there is a need for developing improved methods of evaluating the safety of cargo ships that would quantify and assess the ship safety more comprehensively and further allow for a more direct comparison of ship designs safety-wise so that safety could become one of the goals of design process. This newly developed method will not only have to allow for effective determination of ship safety, but also should meet expectations of various industries. The author is of the opinion that it is very likely that a new method which fundamentally differs from the existing rules would not meet some of the industry expectations. Ergo, it is of uttermost importance that the new method proposed hereunder for identification of important from safety perspective parameters utilises our up-to date experience, knowledge and the data for gradual implementation of new propositions to the existing design methods and the methods of evaluating safety of ships in damaged conditions.

This paper presents advantages and drawbacks of the existing methods and shows an alternative approach which, when further verified and evaluated, could serve as a useful tool for designers and ship operators alike.

2. Evaluation of the state of knowledge on damaged ships safety assessment as per the SOLAS 2009 Convention.

This chapter of the paper summarizes current legislation responsible for assessing safety of ships in case of collision or any other causes of vessels being subjected to flooding of compartments, and briefly presents the previous regulations that have led to formulation of the latest method presented in SOLAS 2009 Convention.

The current rules responsible for assessment of the safety of ships by improvement of their stability parameters in damaged conditions are divided into several categories. In the past it was found that it is inefficient and unjustifiable to apply identical rules to ships that serve different purpose or/and are of very different size.

The principal standards for damaged ships stability assessment are derived from the IMO Conventions, Codes and Resolutions (Table 1).

Document with requirements:	Ships to which the requirements apply:	Date of coming into force in the current shape
International Convention on Load Lines 1966 (ICLL) as amended	ships of length not less than 100 m., engaged on international voyages, except where defined by SOLAS 2009, fishing vessels, ships of war and pleasure yachts.	3/II/2000
International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) as amended	ships carrying liquefied gases in bulk	1/VII/1986
International Convention for the Prevention of Pollution from Ships (MARPOL) as amended	ships carrying oil and/or oil products	2/X/1983
International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk (IBC Code) as amended	ships carrying dangerous chemicals in bulk	1/VII/1986
International Convention for the Safety of Life at Sea (SOLAS)	passenger ships carrying more than 12 passengers and cargo ships that carry cargo on deck of gross tonnage 500 and above.	1/I/2009
The Guidelines for the Design and Construction of Offshore Supply Vessels (OSV Guidelines - Resolution MSC.235(82))	offshore supply vessels of length above 24 m., but less than 100 m.	1/XII/2006
International Code of Safety for High-Speed Craft (HSC Code – MSC.36(63) as amended)	high speed crafts as defined by the HSC Code	1/I/1996
Code of Safety for Special Purpose Ships (SPS Code - resolution A.534(13) as amended)	special purpose ships of gross tonnage larger than 500 and carrying more than 12 special personnel	13/V/2008
Mobile Offshore Drilling Units Code (A.414(XI) as amended)	mobile offshore drilling units	1/I/2012

Table 1. List of Documents about requirements for stability of ships in damaged conditions

Out of the documents listed in Table 1 only the Code of Safety for Special Purpose Ships (SPS Code) as amended and International Convention for the Safety of Life at Sea (SOLAS) as amended introduce requirements based on a probabilistic approach. The remaining documents refer to entirely deterministic approach based on the application of theoretical damages of selected, described geometries vessels have to survive by maintaining values of metacentric heights and righting arm curves of described in these documents. These properties serve as representations of survivability potential of vessels in expected weather conditions.

At present, the only types of ships the probabilistic methods are applied to are the following :

- Passenger ships
- Ro-Ro, Ro-Pax ships and car carriers
- Cargo ships that carry cargo on deck
- Special purpose ships

Consequently, it is important to underline that the probabilistic method defined in selected documents shown in Table 1 is applied to a relatively small part of the worldwide merchant fleet in operation. The reasons for the limited application of probabilistic approach are related to the structure of the method and the assumptions made during its development.

2.1 Probabilistic method background and structure of determining required levels of safety included in IMO A.265 (VIII).

The first attempt to introduce the probabilistic safety assessment (PSA) concept to ship design on a large scale was made in 1973. On the 20th of November 1973, a new resolution A.265(VIII) [1] with the probabilistic safety assessment method for passenger ships was adopted. The main motivation for the development of a new method was to increase the safety of passengers on passenger ships. Before the method was adopted, it was assumed that most damages passenger ships sustain in operation occur in their forward part . Hence it seemed prudent to develop new criteria concept that would force the designers to improve the subdivision of passenger vessels by taking into account their operational experience rather than the check stability after the application of a theoretical damage of predefined extent anywhere in the length of examined ship designs.

The method included in Resolution A.265(VIII) [1] was developed with the use of results of two series of model tests in simulated real weather conditions (waves only) [2]. These tests revealed that the observed ship models behaviour was linked to a significant wave height generated by obtaining the values of freeboards and ship models metacentric heights in particular sea state conditions. On the basis of these results, adequate mathematical relationship was formulated and included in the shape of stability criteria (Figure 1).

The method was invented for application to passenger ships only and its application for the ship design was not mandatory, but rather a voluntary alternative to the deterministic approach [1]. In the probabilistic method, the numerical value of the required level of safety and consequently, the provided degree of ship safety was defined as a function of subdivision length of the ship and the number of passengers the ship is allowed to carry (1).

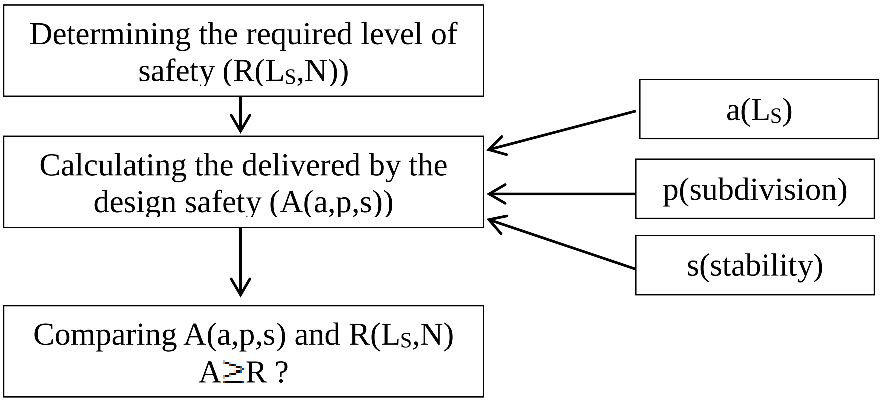


Figure 1. The structure of probabilistic method of assessment of safety defined in A.265

It is worth underlining that this required and, as a consequence of the comparison R>A (Figure 1), delivered by the ships designed against this method degree of safety is a function of the two above mentioned parameters only. Hence, the method introduced a logic that a ship needs to provide a greater degree of safety when carrying a larger number of persons and a smaller one, if it carries fewer persons. In addition, it is known from the formula for the required level of safety (1) [1] that the increase in steepness of required subdivision index curve becomes less visible with an increase in both the subdivision length and the number of passengers on-board ships. This raises questions as to the equivalent behaviour of function "A" (2) defined as Attained Subdivision Index for ships in function of parameters of the "R" function. In other words, without having access to detailed statistical parameters used for preparation of the shape of the "R" function, numerous questions arise: whether or not there isa practical correlation between functions "A" and "R" and if yes, what is the degree and shape of such correlation, whether it is rational to compare them with each other in this form and, if meeting the requirements from this regulation actually increases the safety of ships in operation. The behaviour of function for the "R" coefficient in the currently valid methods, with taking into account the above mentioned correlation degree of the changeable parameters in both functions "A" and "R" is further discussed in Chapter 3.

It is worth noting that smaller ships may have a smaller potential for providing the same degree of safety (when subjected to any type of damage to the original structure and of the same magnitude) than larger vessels. It seems to be a natural conclusion from the above observation that it is unwise to expect vessels of smaller size to provide the identical degree of safety to that larger vessels have.

$$R = 1 - \frac{1000}{4L_S + N + 1500} \tag{1}$$

2.2 Attained Subdivision Index defined in IMO A.265 (VIII)

The representation of the attained level of safety called Attained Subdivision Index (“A”) is defined as:

$$A = \sum aps \tag{2}$$

The three components of “A” factor (2) represent probability of damage related to the position against the length of ship (“a”), the effect of change in the longitudinal extent of damage only on the probability of flooding a compartment or compartments (“p”) ,and the evaluation of the floating condition after the vessel sustains a considerable damage (“s”) [1].

The function of “a” parameter describes the place where the damage is most likely to occur and quantifies the importance of the area under consideration with a certain factor. As a result from the calculation of this factor the impact on the final result of damage in the forward area of a ship is increased by a numerical value of 1.2. As it was derived from operational experience the rule developers enhanced the probability of damage multiple times in the forward area compared with the aft area. Consequently, the significance of damage in the most aft area of a ship was reduced from a factor of 1 down to 0.4 (minimum). The formula was made up in such a way that regardless of the vessels length, the overall area below and above value 1 of the curve along the entire length of ship is equal and therefore, the mean average value of the “a” factor along the subdivision length of a ship remains equal to one (Figure 2).

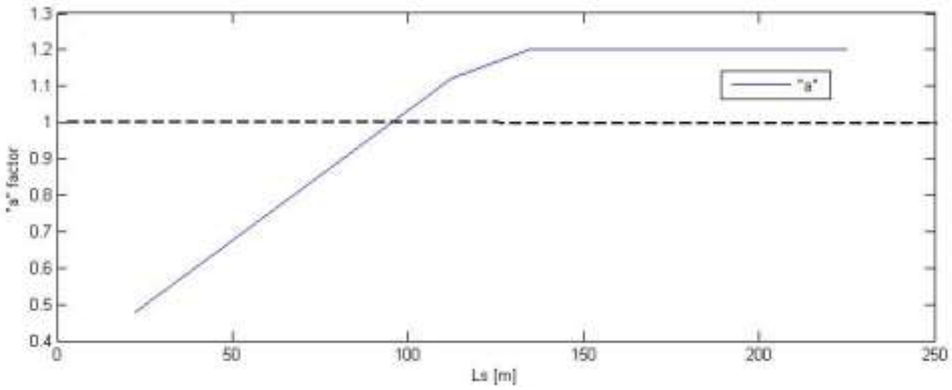


Figure 2. Example shape of “a” function against length of ship – as defined by A.265 (VIII)

In the A.265 (VIII) method function “p” is intended to describe the variation in the longitudinal extent of damage on probability, provided that single or multiple zone damages occur. The value of “p” factor significantly increases with an increase of the ratio of length of watertight compartment or a group of compartments under consideration to the subdivision length. At the same time, the scale of this increase is reduced with an increase of this ratio (Figure 3).

As a consequence, the value of “p” factor for every identical damage scenario will significantly increase if two watertight compartments are damaged instead of one and will increase even more if 3 compartments are damaged over the same length. Additionally, since multiple zone damages are taken into consideration, there may be a significant difference in subdivision which leads to the same value of p factor (Figure 4).

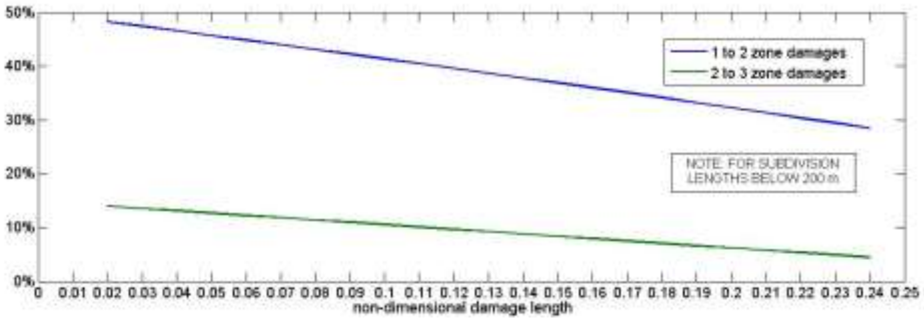


Figure 3. The percentage increase of value of "p" factor for 2 zone damage compartments and 3 zone damage compartments against the ratio of the length of compartment, or group of compartments to subdivision length of vessel.

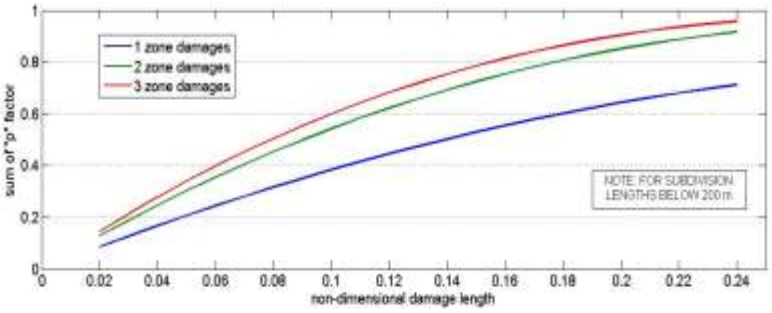


Figure 4. The theoretical sum of values of "p" factor for total number of cases at length of compartment or group of compartments to subdivision length ratios in practical range of (0,02 to 0,24) for 1, 2 and 3 zone damages.

In the method included in A.265 (VIII) also the "r" reduction factor which represents the influence of wing tank (if fitted) on the variation in the extent of damage is defined. Since it does not change the principal logic behind the method, the author has decided not to describe it in greater detail.

The last factor from the formula for the A-factor (2) is the "s" factor that evaluates stability and the floating position of the vessel in the final stage of flooding. The "s" factor was defined as a multiplication of the final metacentric height after damage, and the ratio of "effective mean damage freeboard" [1] to the breadth of the ship which is reduced by the tangent of ship angle of heel due to asymmetrical flooding (3).

$$s_i = 4.9 * \left[\left(\frac{F_1}{B_2} - \frac{\tan\theta}{2}\right)(GM_R - MM_S)\right]^{\frac{1}{2}} \tag{3}$$

As the rule specifies that the value of "effective mean damage freeboard" [1] is not to be taken greater than twenty percent of breadth of the ship, the value of the ratio between the "effective mean damage freeboard" [1] and the breadth of the ship may be within the <0,0,2> range. The "s" factor formula correlates the final metacentric height value with the freeboard after damage and consequently in an indirect way, with the roll motion amplitude. This correlation was determined by mathematical analysis and from experimental and statistical data [2]. The result from the formula for the “s” factor is that the tangent trigonometric function of the heeling angle divided by two will attain values in this range for heeling angles between 0 and approx. 21,8 degrees, and that the corrected metacentric height to compensate for the reduction from the heel more than 0,21 meter. Consequently, regardless of stability parameters representation in shapes of metacentric heights or/and the subdivision arrangements, if the final floating condition is with the heel of approx. 21,8 degrees, the ship will attain the “A” factor equal to zero for the determined “a” and “p” partial damage scenario coefficients. On the other hand, if a vessel has the ratio of “effective mean damage freeboard” to breadth of 0,2 and the final heel angle after damage equals zero, the corrected metacentric height that allows the “s” parameter function to remain equal to one must be more than; 0,21 meter.

In rule [1], the final “s” factor taken into equation is defined as a sum of the “s” factors calculated at different drafts and multiplied by certain coefficients between 0 and 1 representing the probability of their occurrence.

2.3 Method included in SOLAS 90 for safety assessment and determination of required safety level.

In 1998, as a consequence of intensive research a revision of probabilistic rules was implemented into a new regulation from SOLAS also known and hereafter referred to as SOLAS 90 [3]. In these regulations, the rules for passenger ships defined by A.265 (VIII) [1] were significantly amended. Also, for the first time, this concept of evaluation of safety of ships in damaged conditions was adapted to cargo ships. Although included also in SOLAS, a provision was made that under certain conditions the new probabilistic method can only be regarded as an alternative to demonstrating the degree of safety of ships in accordance with the regulations from the International Convention on Load Lines ([4] – Reg. 27). Also, the rule was not applicable to special purpose ships, crude oil tankers, gas and chemical tankers, and offshore supply vessels if they fit definitions of such types of ships given in applicable regulations (Table 1).

The new rule [3] was made applicable to vessels constructed (the definition of term “constructed” – [3]) between July 1998 and October 2010. As the method was considered very complex for the computation models and engineering practices available then, the use of the probabilistic method for cargo ship construction was made voluntary and its effect was limited.

The structure of the SOLAS 90 method was derived from the method introduced in IMO A.265 (VIII) for passenger ships (Figure 2) and followed the same logic. Accordingly, the attained subdivision index to the level of ship safety was compared with the required one calculated on the basis of statistical data and was a function of the subdivision length of vessels (4).

$$R = (0.002 + 0.0009 L_S)^{\frac{1}{3}} \tag{4}$$

By making the “R” (Required Subdivision Index) a third degree square root function of the subdivision length, the increase of this factor became significantly smaller with the mean increase of subdivision length of ships when compared with the method introduced by the IMO A.265 (VIII) discussed above. In order to determine whether this can be compared on a like for like basis, a detailed analysis of the formula for “A” Attained Subdivision Index was made and is presented in the next parts of this Paper.

2.4 Attained Subdivision Index as defined by SOLAS 90 Convention

The attained level of safety (represented by “A”) in this method is defined as a sum of multiplication of “p_i” and “s_i” factors that represent the probability that only a compartment or a group of compartments under consideration are subjected to flooding and the probability of survival of vessels after such a damage, respectively (5).

$$A = \sum p_i s_i \tag{5}$$

Compared with the IMO A.265 (VIII), the attribute “a” was removed from the equation as a separate factor and repositioned to become a part of the equation for the “p_i” factor (6).

$$p_i = ap \tag{6}$$

Although added as function of different shape, the resulting values of “a” component from the formula for the “p_i” were identical to the ones from IMO A.265 (VIII) method (Figure 2). However, the formula for the probability defined by factor “p_i” changed for the aft-most and forward-most compartments and was defined by functions that allowed the probability for a damage sustained in these areas of the ship to be increased relative to the length of these compartments.

Component “p” from the “p_i” formula (6) is structured in a different way than in the first probabilistic method from IMO A.265 (VIII) [1] and is no longer a function of the length of the considered compartment to the subdivision length ratio, but is defined by a predefined damage extent that is a function of subdivision length. The consequence of this change in the definition is that the density of transverse subdivision of ships may be directly determined by the formula included in the “p” component definition [5]. Practical experience gained by the author from using the SOLAS 90 probabilistic method for determining safety of ships seems to indicate that survivability formulated by “s” factor (described below) for all single zone damages will not guarantee meeting the requirements. Hence, it is very likely that vessels designed with the use of this method have to provide survivability after a number of two zone damage scenarios. In general, the method claims that survivability of two zone damage compartments greatly enhances the contribution of the “p_i” to the final result (Figure 5).

Consequently, and very much in accordance with the results from numerous calculations, the contribution from the provided survivability as defined by the “s” factor for two zone damage in the most forward and the second most forward compartment is that it may determine the final value of “A” factor in the range of up to 40% its final value. On the other hand, a benefit from providing a two zone damage compartment survivability in the aft area of the ship is little or almost non-existent when it comes to the final result. On most of the cargo ships, the machinery area is between aft terminal and forward machinery bulkhead. One of the potential outcomes of such rule structure may be that the little impact on the final result of the damage in the aft area would not encourage providing a full watertight standard to the aft machinery bulkhead.

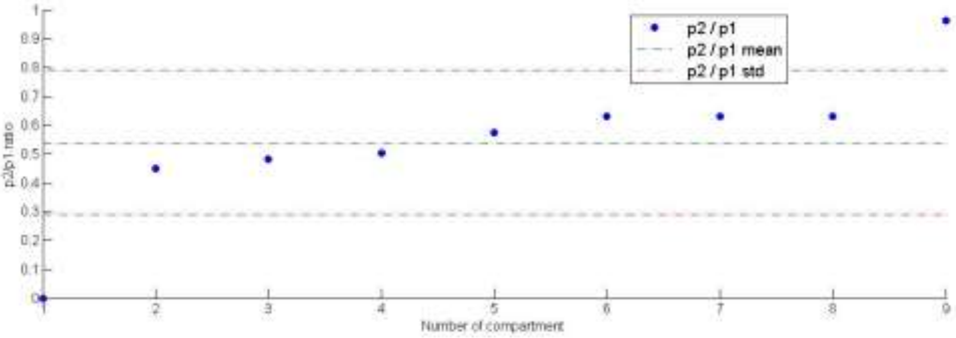


Figure 5. Averaged (from sample lengths) percentage difference in “p_i” factor between two zone and one zone damages redistributed at the same length (Ls = 225m)

Just like in the regulations of A.265 (VIII) (1), also the “r” reduction factor that represents the influence of wing tank (if fitted) on the variation of the extent of damage is defined and introduced as a separate calculation formula.

In the SOLAS 90 [2] method, apart from a significant change in the calculation of “p_i” factor described above, a markedly different approach to calculation of “s_i” factor is presented. Described by the IMO A.265 (VIII) [1], the correlation between metacentric height after flooding and remaining freeboard providing sufficient stability in certain weather conditions was replaced by a correlation between the maximum positive righting arm value (after damage) with a range of positive righting levers beyond the angle of equilibrium and the final equilibrium angle of heel. In this method, it is no longer the lack of sufficient remaining freeboard that determines the value of “s” factor, but it is the value of maximum righting arm, the positive range of righting arm and the angle at which immersion happens of weathertight openings (7).

$$s = C\sqrt{0.5(GZ_{max})(range)} \qquad (7)$$

For calculations for the cargo ships, the value of righting arm is not to be taken as higher than 0.1, and the range of positive righting arm should not exceed 20 degrees. The value of C parameter is directly linked to the value of final angle of heel. The final value of “s_i” factor is then obtained by summation of half of “s” factors calculated by the formula (7) for two load lines: the deepest subdivision load line and the partial load line as defined by rule [2].

2.5 SOLAS 2009 – structure and modified required level of safety

The SOLAS 90 method was voluntarily applicable to vessels for which the keels were laid till 1/1/2009. After an intensive research, a first attempt to introduce a mandatory PSA -based method of safety assessment to the construction of cargo ships was made to corroborate with coming into force the new SOLAS 2009 Convention in 1/1/2009. According to the SOLAS 2009, such a method was to be mandatorily used to the same types of ships for which the probabilistic method of the SOLAS 90 was voluntarily applicable. Practical experience gathered from the industrial implementation of the method presented in the SOLAS 90 together with an extensive research and accumulation of statistical data has led to the revision of both the required level of safety (represented by "R") and the evaluation of subdivision and stability. Although the principle logic of evaluation of safety remained very similar to that originally presented in the IMO A.265 (VIII) (Figure 1), substantial changes were introduced to the way the "p_i" and "s_i" factors are calculated.

$$R = 1.0 - \frac{128.0}{L_S + 152.0} \tag{8}$$

The formula for Required Subdivision Index (8) was significantly changed, but remained a function of Subdivision Length [6] only. Consequently, and very much like in the previous method, the required level of safety of the ship will increase with the growing length of it. In the new method, the mean value of Required Subdivision Index is significantly larger than that determined by the method that was in use before 2009. To have a better understanding whether the designs safety was improved one must first look into the details of calculation of attained level of safety, defined as "A" by the same general formula as previously (5).

2.6 Attained Subdivision Index defined by the currently valid SOLAS 2009 Convention

In the method presented in the SOLAS 2009, the "p_i" factor accounting for the probability that a compartment or a group of compartments are flooded was redefined (9) and the factor "a" defined in the SOLAS 90 was entirely removed from the equation. Furthermore, the "r" factor accounting for the transverse extent of damage has been introduced.

$$p_i = p(x1_j, x2_j) * \left[r(x1_j, x2_j, b_k) - r(x1_j, x2_j, b_{k-1}) \right] \tag{9}$$

The main formula for the "p" is described as a function of 2 variables only, i.e. the longitudinal extent of damage and the ratio of this extent to Subdivision Length [6]. For example, for single zone damages and 2 zone damages the values of the "p" factor remain almost entirely constant (and equal up to the ratio of about 0,16) for the subdivision length range between 100 and 260 meters, but are adjusted above this range (Figure 6).

Practically, considering 1-zone damages only, if the number of subdivision zones for which the "p" is calculated increases, the value of the sum of "p" for one zone damages along the subdivision length will decrease, which is mainly related to the fact that the derivative of "p" function is a second order polynomial of the length of compartment under consideration (Figure 7).

If the values of the "p" (Figure 7) are further multiplied by the theoretical number of compartments possible within the subdivision length, the weight of a compartment at a given subdivision length may be derived (Figure 8). Although defined by a very complex function and a set of conditions, the "p" factor remains a function of 2 variables only: the subdivision length of the ship and the longitudinal extent of compartment under consideration.

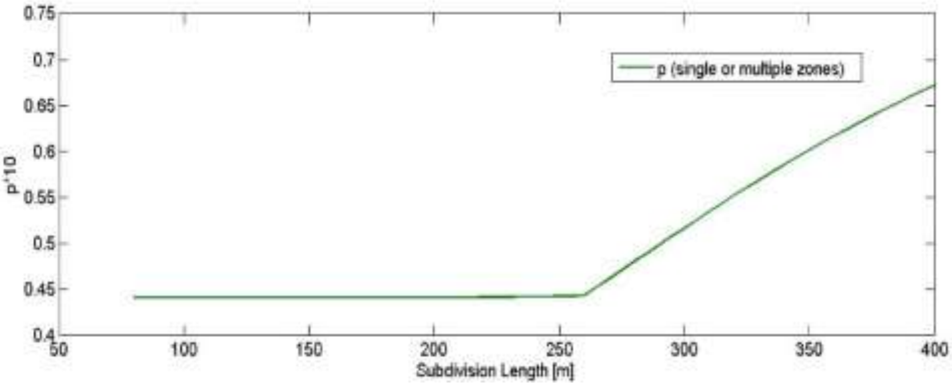


Figure 6. Trend in change in "p" factor for one and two zone damage compartments in function of subdivision length as defined by SOLAS 2009 (length of one/two zone damage = constant = 0.1 L_S)

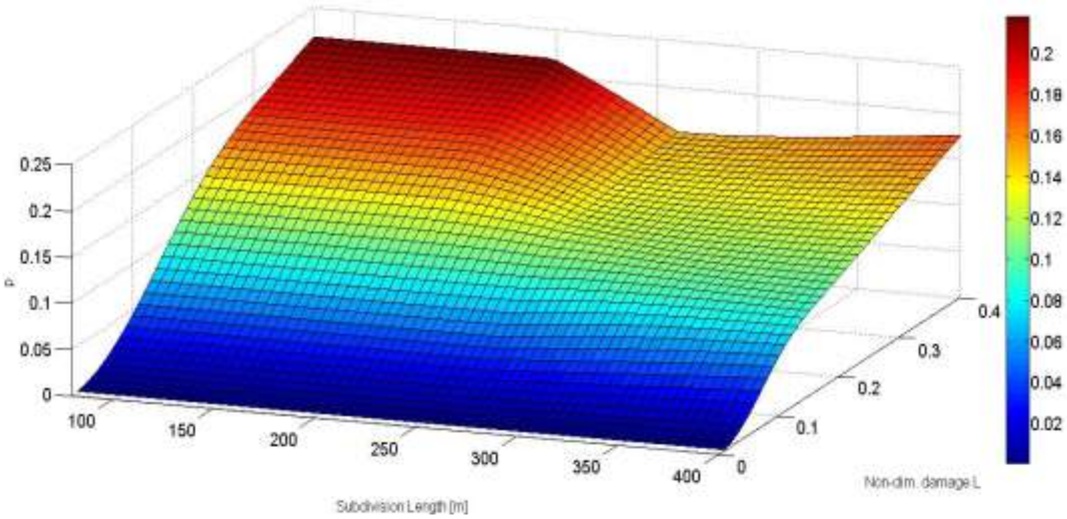


Figure 7. Trend in change in "p" factor for one zone damage compartments in function of non-dimensional length of damage zone and Subdivision Lengths as defined by SOLAS 2009

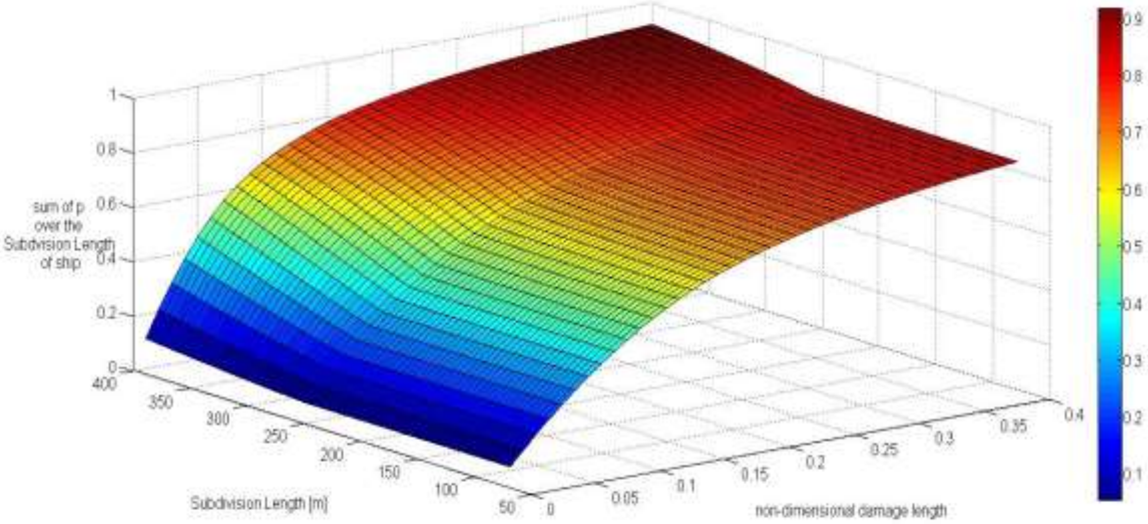


Figure 8. Trend in change in sum of "p" factor subdivision zones along the entire length of ship for one zone damage compartments in function of non-dimensional length of damage zone for various Subdivision Lengths as defined by SOLAS 2009.

The values of the "p" factor for two- and -three zone damages are defined analogically to the way presented in the SOLAS 90 method (10).

$$p_i = p(x1_j, x2_{j+1}) * [r(x1_j, x2_{j+1}, b_k) - r(x1_j, x2"_{j+1}, b_{k-1})] - p(x1_j, x2_j) * [r(x1_j, x2_j, b_k) - r(x1_j, x2_j, b_{k-1})] - p(x1_{j+1}, x2_{j+1}) * [r(x1_{j+!}, x2_{j+1}, b_k) - r(x1_{j+!}, x2_{j+1}, b_{k-1})] \quad (10)$$

Similarly to formula (10), any presentation of the results of "p" factor calculation for two zone damage compartments can only be obtained through a reduction of results from corresponding single zone damages (Figure 9). The value of "p_i" factor for a determined length of compartment remains constant regardless of whether it is a single zone or multiple zone damage case for a large range of damage length. In this range, another benefit from 2-zone damages is derived from a generation of new damage scenarios that were non-existent without transverse subdivision boundaries (Figure 10). The sum from 2 (and more) subdivision zones will hence be greater than that from single zone damages alone. Similarly to the presentation of results for 1-zone damage cases (Figure 8), the relationship between a damage length and the calculated probability of damages for different subdivision lengths of vessels can be summarized in a graph (Figure 11).

The calculation method of the "p" factor for aftermost and foremost compartments changes, and its result for a commonly met range of length of compartment to subdivision length ratio is of increased contribution to the final result.

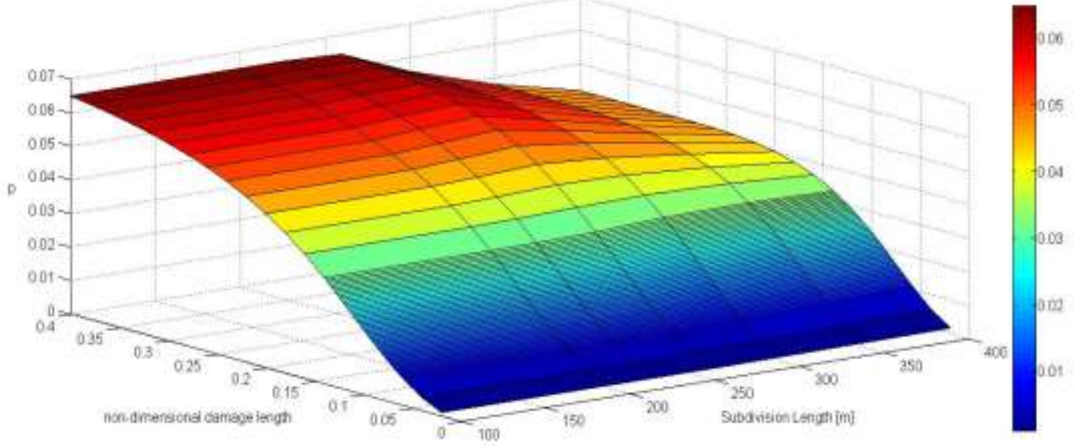


Figure 9. Trend in change in "p" factor for two zone damage compartments in function of non-dimensional length of two zone damage zone for various Subdivision Lengths as defined by SOLAS 2009

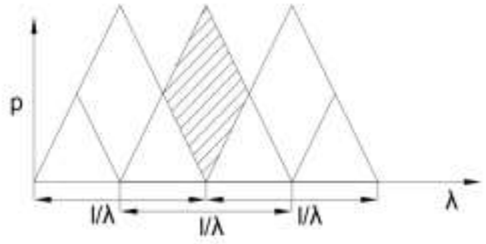


Figure 10. Illustration of unit additional contribution to the sum of "p" factor for two zone damage compartments in function of length of two zone damage zone for various Subdivision Lengths as defined by SOLAS 2009

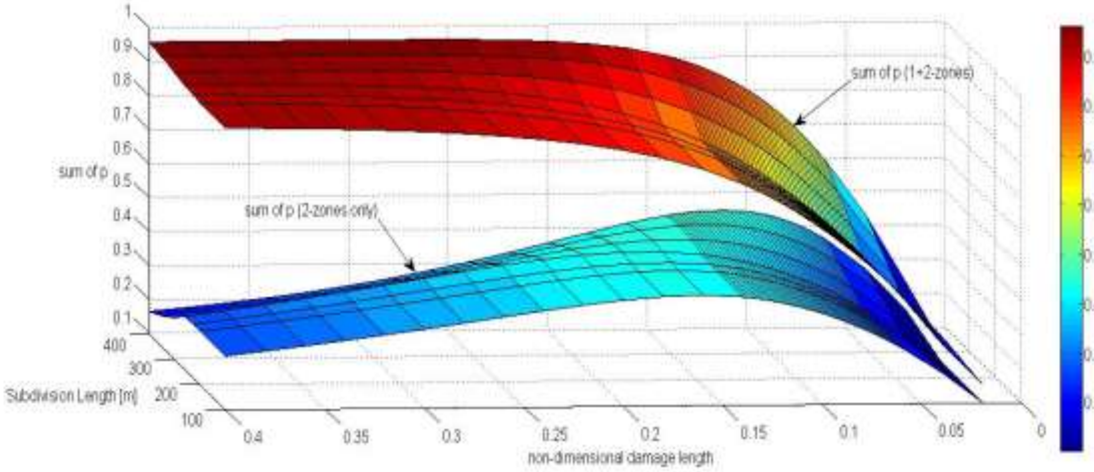


Figure 11. Trend in change in sum of "Σp" factor subdivision zones along the entire length of ship for one and one+two zone damage compartments in function of non-dimensional length of damage zone (L/λ) for various Subdivision Lengths as defined by SOLAS 2009

The “r” factor contributing to the final “p_i” value accounts for the transverse penetration of damage and is defined as a function of the length of damage and the transverse penetration extent (11).

$$r(x1,x2,b) = 1 - (1 - C) * \left[1 - \frac{G}{p(x1,x2)}\right] \tag{11}$$

The value of this factor is also adjusted for aftermost and foremost compartments and reflects the “p” factor calculation and hence depends, to a small degree, on the subdivision length of ships. The “r” factor value increases if the assumed transverse penetration is larger and equal to 1; if the transverse penetration is equal to a half of the breadth of a ship and applied anywhere in the length of a ship. The most common range of “r” factor values in function of compartment length and for different penetration levels can be illustrated on a graph (Figure 12).

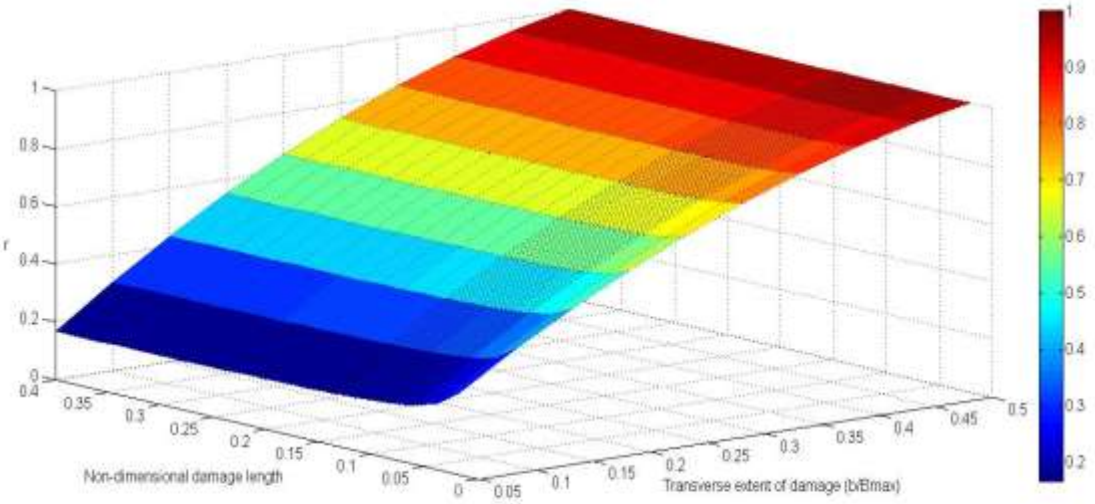


Figure 12. Approximate range of “r” factor value in function of transverse penetration to mean breadth of a ship and length of compartment under investigation at constant subdivision length 198m.
(influence of subdivision length of ship variation on result considered minor and disregarded)

The SOLAS 2009 method also defines the horizontal extent of damage that had not been taken into consideration in previous methods. The horizontal watertight boundaries above the waterline are to be taken into account by multiplying the attained “p_i” formula by “v_m” factor described by a simple linear function of the horizontal boundary height above the baseline and the draught specific for the investigated condition. According to the formula for the Attained Subdivision Index (5), the “p_i” index specific for a given damage scenario must be multiplied by the “s” factor. Factor “s” varies with attained stability parameters of ships for particular damage scenarios as defined by factor “p_i”. The method for obtaining the value of this factor has substantially changed in the SOLAS 2009 rules.

In general the “s_i“ is defined as the minimum of the values presented (12):

$$s_i = minimum\{s_{intermediate,i}, s_{final,i}, s_{mom,i}\} \tag{12}$$

For cargo ships however, only the “$s_{final,\, i}$” is taken into consideration. The formula for “$s_{final,\, i}$” (13) is a function of stability parameters of vessels at the final stage of flooding and is different from what had been previously applied in the SOLAS 90 method (7).

$$s_{final,i} = K * \left[\frac{GZ_{max}}{0.12} * \frac{Range}{16}\right]^{\frac{1}{4}} \tag{13}$$

In both cases above, if values of either GZ*max* or “Range” are larger than the denominatives, the values for calculations are not to be taken greater than these denominatives. Consequently, there is no additional benefit for the value of “s” factor from the values of the above mentioned stability parameters being greater than the values stipulated in the above equations. The “K” factor in the equation for “s” (13) is a function that determines the final maximum allowable degree of heel after sustaining a damage and is only to be taken as “1” if it is less than 25 degrees and 0 if it is more than 30 degrees. In other cases, it is to be taken as a function of the difference between the maximum allowable angle of heel and the actual angle. (Figure 13)

$$K = \sqrt{\frac{\theta_{max} - \theta_e}{\theta_{max} - \theta_{min}}}$$

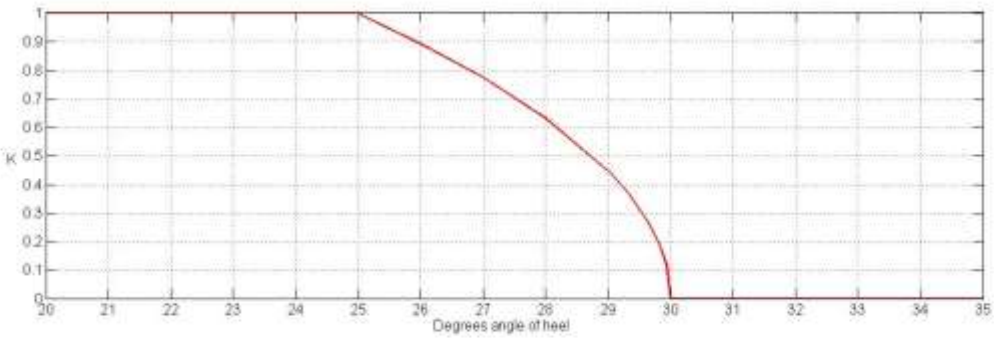


Figure 13. The function for “K” factor as defined by SOLAS 2009 and the shape of the curve.

The criteria usually responsible for the final outcome of determination whether a ship is safe or not are those responsible for checking whether a sufficient range of positive righting lever curve is provided. For cargo ships, for which the SOLAS 2009 method is used, the rules defined by ICLL 66 (as amended) or SOLAS 90 were previously applicable (with the exception of special purpose ships). The required stability parameters by these three methods are presented below (Table 2).

Figure 14 shows a graphical representation of “s” factor values for different initial parameters. Incidentally, the result of such a low value of righting arm as 0.1 meter from theoretical calculations is highly improbable and practically there may a be very little difference between the 0,1 and 0,12 meters limit.

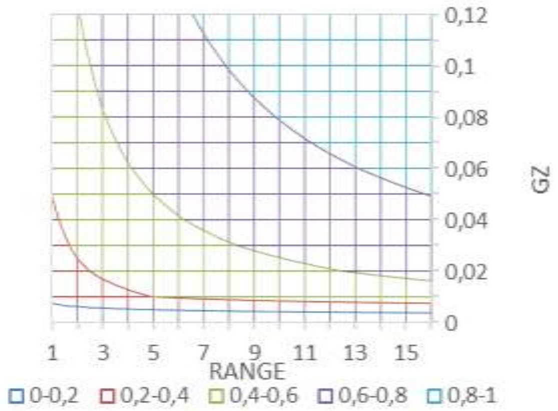


Figure 14. The value of attained s-factor for various stability parameters from SOLAS 2009

"s" factor as defined in SOLAS 2009	"s" factor as defined in SOLAS 90	ICLL 66 as amended requirements
$s_{final,i} = K * \left[\frac{GZ_{max}}{0.12} * \frac{Range}{16}\right]^{\frac{1}{4}}$	$s = C\sqrt{0.5(GZ_{max})(range)}$	1) Final angle of heel to be less than 15 or at maximum 17 degrees 2) The range of positive stability righting lever curve to be at least 20 degrees 3) The minimum value of righting arm within the range as described in Point 2) above to be 0.1 m. (the metacentric height in the final floating condition is positive) 4) The area under the righting lever curve within the range as described in point 2) to be not less than 0.0175 m*rad.

Table 2. comparison of the required stability parameters for cargo ships by three methods

The "C" factor value obtained from SOLAS 90 method is described by an identical equation to the "K" factor as presented in the SOLAS 2009 method (Figure 13).

The final value of "A" (accounting for the attained level of safety) which is to be taken for comparison against the required safety level represented by "R" is taken as a sum (14) of the mean values obtained from calculations from damage cases to both ship sides and for different drafts: The subdivision draft (usually corresponding to the deepest subdivision draft), the partial draft, being calculated by an adequate formula [6] and the light service draft (usually corresponding to the lightest draft the vessel may operate in e.g. light ballast draft).

$$A = 0.4A_s + 0.4A_p + 0.2A_l \qquad (14)$$

The value of attained safety level for cargo ships, calculated for any of the above mentioned drafts, is in no case to be less than 0,5 multiplied by the required level of safety.

From the presented summary, one may draw a conclusion that the probabilistic method has changed significantly and that the three presented versions thereof take a different approach to the probability of a damage allocation and survivability estimation. It is also evident that basic assumptions, such as that of significance factors for different initial conditions and calculation methodology, have changed during the process of the method development. At the same time, the required level of safety of cargo ships remained a function of subdivision length only.

3. Critical analysis of state of knowledge on used alternative methods of evaluating safety of damaged cargo ships based on the concept of Probabilistic Safety Assessment.

This part of the paper examines the behaviour of functions included in SOLAS 2009 Convention and used in calculating the safety of ships in damaged conditions. Access to statistical data originally used by the rule developers in determining the "R" factor for a method included in the SOLAS 2009 Edition, and to accidents at sea data gathered for the GOALDS [7,8] and by the Maritime Administration Investigation Branch (MAIB) [9] allowed the author to develop mathematical calculation algorithms for evaluating the first method introduced with regulation A.265 (VIII) (for passenger ships only), the method for cargo ships from SOLAS 90, and the currently valid one from SOLAS 2009, and to compare them with other rules applicable to ships of different types to which the requirements from SOLAS 2009 do not apply.

According to the researchers who have for many years worked gathering comprehensive statistical data from various Flag Administrations under which many vessels operate, the data kept by Flag Administrations or/and made available to the public is not as detailed or complete as one might expect from statistical assessments [10]. This alone may be an indicator suggesting that the sample ships selected for the purpose of validation of the formula for the required level of safety for an entire population of ships may not be accurate [2,11-13].

The based on statistical investigations final formula used for calculation of the required level of safety (8) was prepared under certain assumptions and can be now described as follows:

- It does not consider different aspects of operation of ships of different types.
- The acceptance criterion was set to be on the basis of comparison with the results from the calculation of attained level of safety described by formula (14) for a sample population of existing ships carefully selected under certain assumptions.
- The required level of safety is described by the required subdivision index (8) and is solely a function of the subdivision length of the vessel. (arithmetical increase with the value of subdivision length) (addressing prescriptive requirement from SOLAS).
- The required level of safety is a number.

3.1 R – Required Subdivision Index

The ships used in the process of devising a formula for the required safety level of ships [14] were chosen for unclear reasons and on the basis of unverified in the available publications assumptions. From the available information today we know that the selected sample consisted of ships submitted by representatives of various countries and the attention was focused on covering a range of vessel lengths that the future regulation was supposed to apply to [15]. There have been numerous attempts to modify the sample of ships and to change the final shape of the formula for the required level of safety for the selected sample of ships, but the final result was that "(…) the group was essentially evenly divided between the R formula based on regression analysis of SLF 47 sample ship calculation results (…)" – [14].

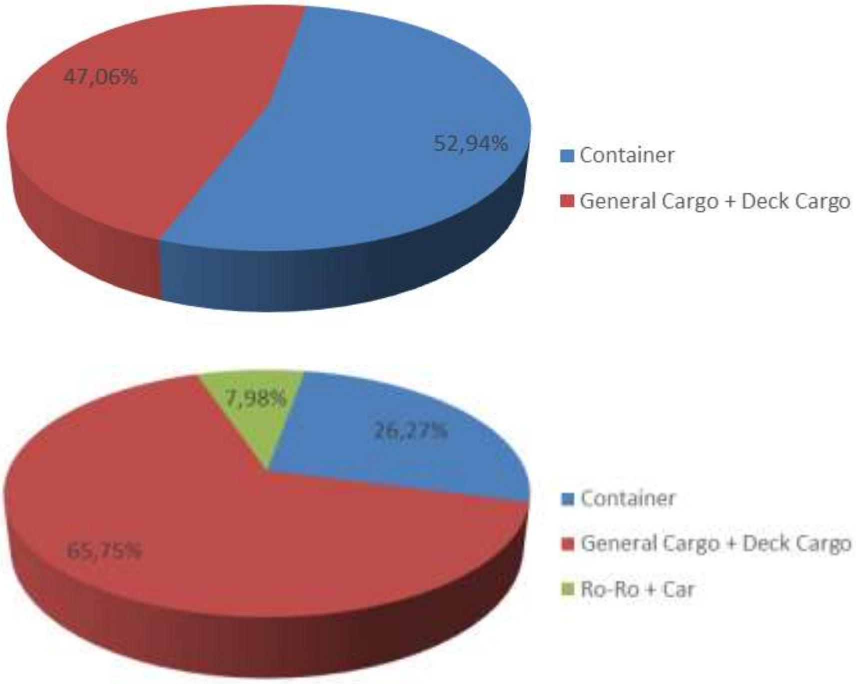


Figure 15. No. of ships used for the preparation of SOLAS2009 "R" factor formula by type (assumption that 1 Bulk carrier offered a possibility of caring cargo on deck) (TOP) against no. of ships in the worldwide fleet of GT>500 for which the method found its application [16]. The selected sample corresponds far better to the tonnage of worldwide fleet.

Subdivisions of container ships and bulk carriers are as indicated in Chapter 2 of this paper very different and for the mathematical reasons presented there may lead to fundamentally different results. Therefore, it seems reasonable to present the impact of different ship types and their length on the final Required Subdivision Index "R" formula results.

In accordance with the official publications [14], only one criterion for the actual selection of (used as representation of) statistical population (sic!) of ships for determining the required level of ship safety is known for sure, i.e. all the ships taken into account had to comply with the previous rules included in the SOLAS 90 Regulations. In addition, it is known that one car carrier and two ro-ro ships were ignored in the process of building this equation because their impact on the final result was considered too big ([14], influential variables – [16]). Accordingly, only the results for one bulk carrier, seven general cargo ships and nine container ships were considered in building up a regression formula. A partial residual decomposition was made that showed correlation of R to A; it is presented on the graph below (Figure 16). The standard error is estimated at 0.035.

The size and shape of the sample corresponds to the distribution of tonnage of the worldwide fleet subjected to the new regulations rather than the number of ships (Figure 15). At the same time, the attained average values for the majority of larger vessels (Container Ships) used for the preparation of the formula are above the newly prepared required value of Subdivision Index “R” and so decrease the required value, particularly for these larger vessels (Figure 16). The fact to remember is that the “R” value was prepared with the use of only three types of ships, and that the SOLAS 2009 found its application to a much larger number of types of ships. The actual, physical correlation between the “A” and “R” values for these other ships has not been taken into account, which fully justifies one to question the results from this method for these ships [17,18].

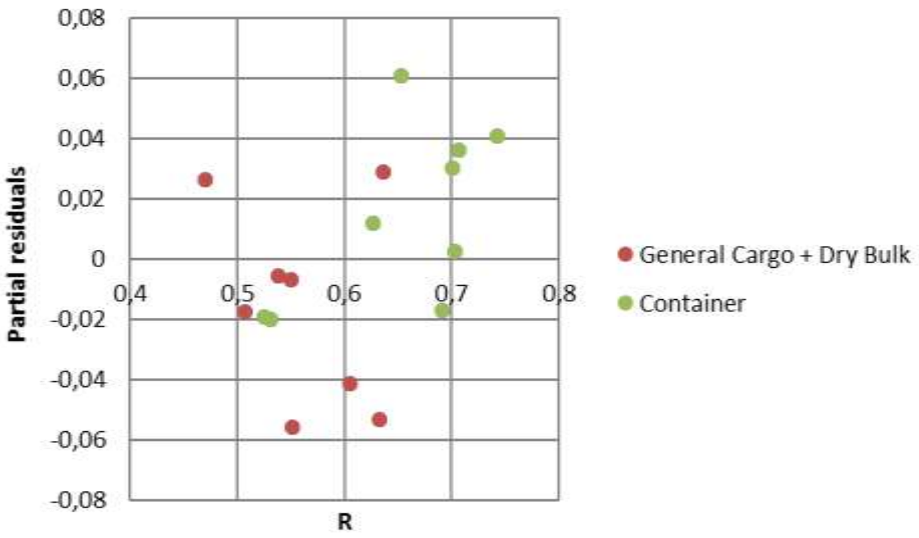
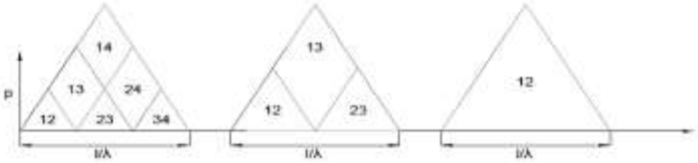


Figure 16. Residual analysis in regression of the population of ships used for preparation of the Required Subdivision Index “R” formula. Average existing General Cargo and Dry Bulk Carriers obtained values below the new required value, average from Container Ships obtained values above.

As explained in Chapter 2 of the paper, the formula for a “p” factor is a function of the non-dimensional length of damage and the subdivision length of a vessel only. In order to present the results of sensitivity analysis, a finite-difference approximation method was applied to determine the sensitivity of the formula for “p” factor independent of changes in Subdivision Length and Non-dimensional damage extent.

Using the probability density function property that for the graphical interpretation of partial probabilities (Figure 17) the total probability value for a certain damage length is irrespective of the partial lengths inside the zone under investigation and their number one can estimate the normalized local sensitivity coefficients to a mean value of 1.585% and with a standard error of 0.00173. At the same time, the function remains invulnerable to changes in subdivision length below 198m and its normalized local sensitivity coefficients remain much lower especially in view of the cargo ship design practice (Figure 18).



$$(\Delta_1 =>)p_{1234} = (\Delta_2 =>)p_{123} = (\Delta_3 =>)p_{12}$$

Figure 17. The visual representation of the probability "p" function property.

$$\tilde{S} = \left\{\frac{l/\lambda_j}{p_i}\frac{\delta p_i}{\delta l/\lambda_j}\right\}\begin{cases} l/\lambda, & < 0{,}2 \\ l/\lambda, & \geq 0 \end{cases}$$

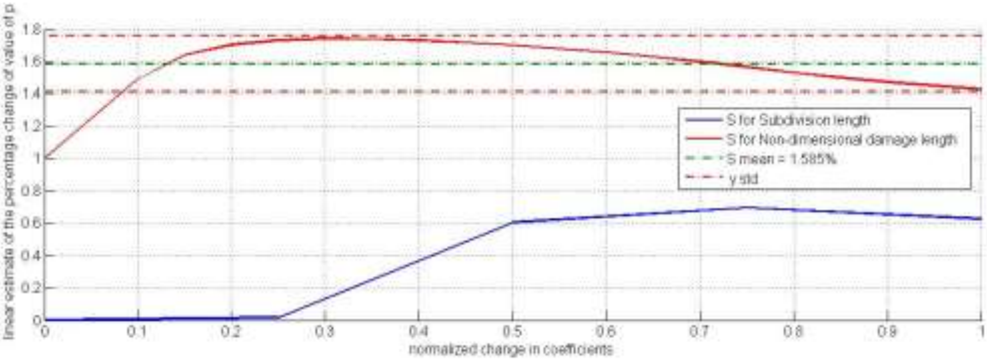


Figure 18. The normalized sensitivity coefficients of "p" component of "A" function for 2 changeable variables (subdivision length of ship (over 198m and below 400m), and non-dimensional damage length (over 0 and below 0,2).

The standard error of fitting the R curve to statistical data of 0.035 (3.5%) can be estimated as corresponding to a +/-2.21% of the average change in length of every examined longitudinal watertight space.

The author considers this to be a gross error that is well beyond the tolerance level. The coefficient "s" was not examined sensitivity-wise, because its values may be equal to 1 and 0 for many different physical floating conditions and thus introducing a large uncertainty to the sensitivity analysis.

The standards for the new method seem to have been set so that ships considered for the formulations of the requirements are the ships that had satisfactory results when examined from the damage stability perspective, but in accordance with the previous methods. The ships checked with methods of supposedly lower standards applicable before the SOLAS 2009 regulation in force would have to improve their results to meet the new requirements then. By introducing such a verification method one must wonder if it was taken into consideration that the future ships will not have to meet the old requirements and hence the old requirements will not have any impact on ship designs anymore. This observation is derived directly from the structure of stability assessment methods, which in many aspects is very different.

Comparison between the results obtained by the methods of SOLAS 2009 and 90 reveals that the values of attained “s” factor for almost the entire range of values are higher when coming from the formula of SOLAS 2009 than those coming from the SOLAS 90 (Figure 19).

Comparison between the two methods of SOLAS 2009 and SOLAS 90 (Figure 19 and Figure 20) also shows that the difference in the structure of both “p” and “s” factor cannot be transferred to a linear equation and hence the results cannot be easily transferred from one method to another. This may raise doubts to maintaining a desired level of safety for ships checked with one of this method and not the other.

3.2 - “p” factor

The “p” factor has been developed on the following assumptions:

- The non-dimensional damage size is independent of ship parameters such as deadweight, block coefficient, speed [16, 19, 20].
- The damage is a consequence of contact with another ship only [6, 19].
- Conclusions from statistics may be verified by model calculation analysis for 15 sample struck ships (in terms of damage) and 5 sample struck ships (in terms of energy) [20].
- Criteria for acceptable probability values are derived from risk analysis and the ALARP (As Low As Reasonably Possible) concept [20].

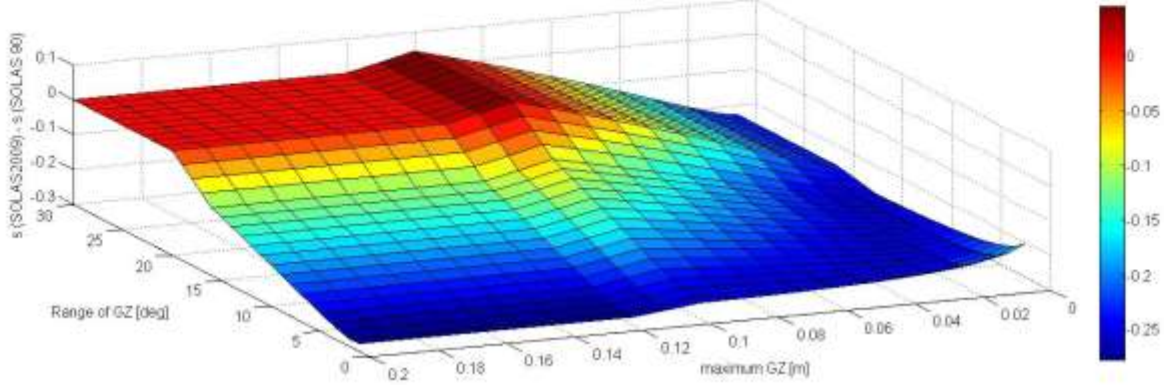


Figure 19. Values of “Δs” function between attained values from SOLAS 2009 and SOLAS 90 for 2 changeable variables (Righting arm range 0,12m to 0,2m is const.), Range of positive righting arm curve up to 30 deg.).

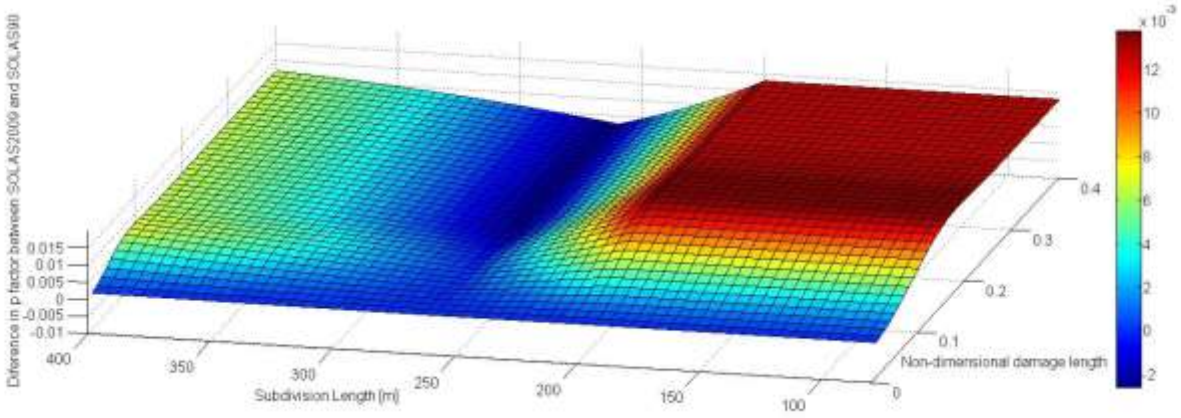


Figure 20. values of "Δp" function between attained values from SOLAS 2009 and SOLAS 90 for 2 changeable variables (l/λ up to 0,40); Range of length 80 – 400 m.

The original database for the preparation of the formula for the "p" as included in the IMO A.265 [1] was based on analysis of damages on which IMO had the data at that time and which were collected till 1960. The European Union project "HARDER" [13] aimed to increase the size of this database and obtain more data that would allow to prepare a more accurate formula. At the end of the project "HARDER", the total number of casualties grew to 2946 out of which 1069 came from IMO itself with the number of other casualties coming from both classification societies and one flag state (Germanisher Lloyd). The collected data was merged into a single database [20] which grew almost 3 times its original size. The databases were afterwards compared with each other in terms of many aspects thereof and one of the conclusions was that it was not possible to find a curve describing the probability of the longitudinal position of a collision that would fit these data with a reasonable regression factor or confidence level [20]. Therefore, a decision was made that after filtering damages in the most-forward 5% of the length of the ship no other relationship between location of the damage and the length of the ship will be added to the calculation [13].

Interestingly, this criteria development process was not published anywhere in the publically available literature to learn how the actual value of "p" had been calculated from statistical data and how it had been assigned to the one or more dimension (length) damages. One must wonder how the data on 2946 damages collected over a period of more than half a century can be transferred to the analysis relating to the total number of ships in that time and how to determine the significance levels related to the changeable with time size of statistical population of ships. Such statistical coefficients are nowhere to be found in the available publications. It is very difficult to obtain accurate data for such a long period of time and there is a high risk that various initial conditions may change and so give large variances to the data. Instead, a simple and general comparison can be made of the collected damage data with the specific statistical population of undamaged ships at a given time. For the purpose of critical analysis, the author decided to assume that an average life time of the ship in service (regardless of its type) is 15 years. Another assumption was made that the population of ships has remained constant in the last 15 years. Other assumptions were made that the SOLAS will become applicable to ships of more than 500 GT only and only the type of ships which SOLAS takes into consideration were considered. Further, it was assumed the collision data that was collected over a 50 year time period included all the damages that occurred in that period. It was also assumed that the frequency of damage occurrence is independent of the moment in time. Finally, the last assumption (as in SOLAS) was that only ship-to-ship collisions are taken into consideration.

Under the above mentioned assumptions the total number of ships is 40990 [14] and the number of recorded ship-to-ship collisions over a 15 year period of time is 244 which makes it possible that a ship was involved in a recordable incident with probability of 0,59% (0,0059). Assuming that a ship has already been in a collision situation, the graph below showing the recorded length of damage to the length between perpendiculars ratio is relevant to further statistical evaluation (Figure 21) [15,19,20].

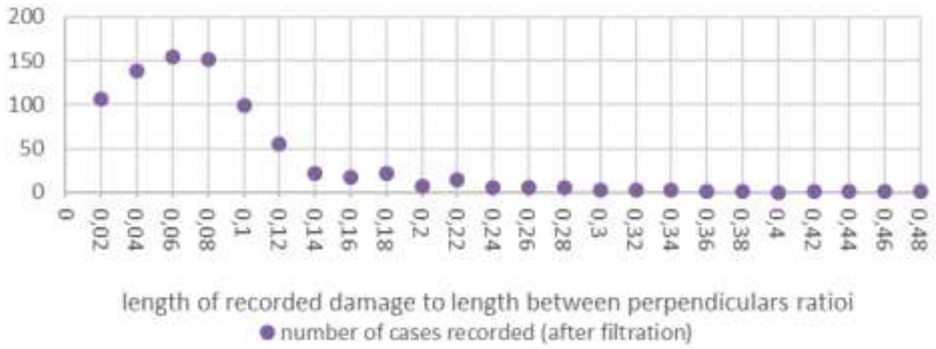


Figure 21. Number of collision incidents (struck ships) as gathered by project HARDER in function of a non-dimensional length of damage to a length between perpendiculars of a ship.

Assuming that the distribution during a ship's life (15 years) remains constant, one may come up with a very preliminary estimation of a ship being in a collision with another ship which would be of 10 (and less) percent of its length between perpendiculars equal to just below 80% (0,8). If this value is then multiplied by the probability of a ship being in a collision during the time of life-cycle (in line with the conditional probability definition), the attained value is almost 0,48% (0,0048) (15).

$$P(A \cap B) = P(A|B)P(B) \cong 0{,}59\% * 80\% \cong 0{,}48\% = 0{,}0048 \qquad (15)$$

To compare this figure with the resulting values from the formula from a method included in SOLAS 2009 a calculation of a "p" factor was made for various lengths of ships. (Note: for this estimation the subdivision length was assumed to be equal to the length between perpendiculars) (Figure 22)

As can be seen in Figure 22, values of "p" factor obtained by calculation presented in SOLAS 2009 are nowhere near the values of probability of a vessel sustaining a damage equal to or smaller than those calculated from the probability formula (Figure 21). Neither are they close to the value of 20% (0.2) obtained from calculation of a random damage being equal or larger than 10% of the vessel's length between perpendiculars. It is so because for the preparation of the p-factor it was assumed that the damage extent and location were quantified by applying the probability density function to available statistical data. Consequently, for the preparation of the p-formula it was assumed that a certain damage may happen anywhere in a length of the vessel, hence the probability of a single damage of length of 10% (or less) of the subdivision length calculated as in Figure 21, must be multiplied by the number of possible instances over the length of the ship (in this case: 10), which will result in a figure that is much closer to the values obtained by the SOLAS 2009 method (0.048 and 0.044, respectively). However, the value of factor ‘p’ significantly increases with the length of the vessel (despite the non-dimensional damage length remaining constant) if the Subdivision Length is greater than 260m. This property was not backed up by statistical evidence, but rather is a result of mathematical recalculation of statistical data (for a too small number of ships of Subdivision Length over 260m) to fit the application to ships of greater lengths (with maintained maximum assumed damage length of 60m). This change of “p” value has a significant impact on the final result of Attained Subdivision Index, especially in view of the sensitivity of the results described in earlier parts of this paper and presented in Figure 18.

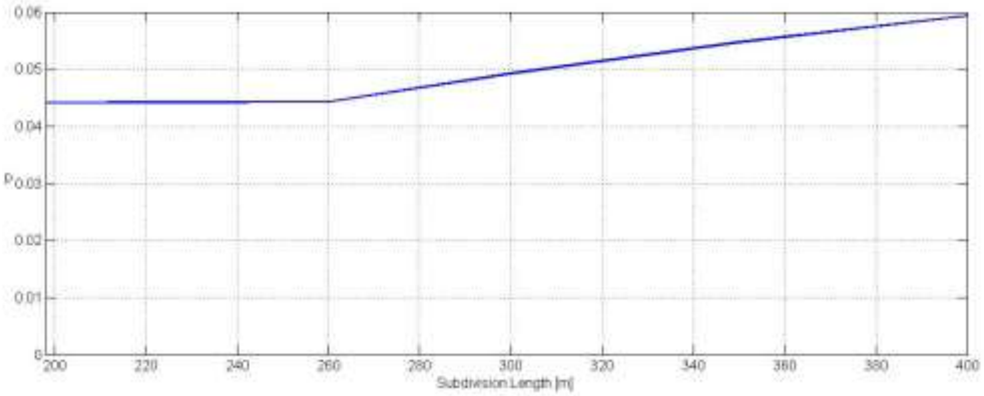


Figure 22. Values of “p” factor for various lengths of a ship at a constant length of damage to subdivision length ratio. (Note: values remain same for overall multiple zones extending over this length)

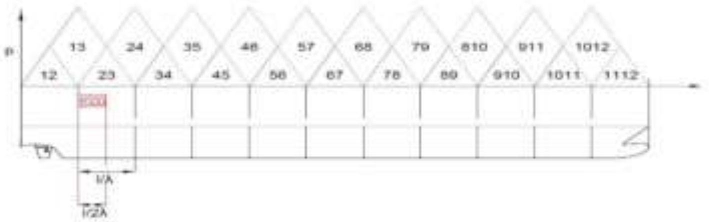
As a result of the analysis of attained values of “p” factor for 2 and 1 zones, it was found that their sum value (with weight over the length of ship applied) becomes bigger than the value of the Required Subdivision index at a length of a single compartment equal of 0.106 of Subdivision Length which at an even zone distribution will equal a damage of length equal of 0.053 of Subdivision Length. (The corresponding analysis was made for the method included in the SOLAS 90 and the result was 0.039 of Subdivision Length.) The overall attained subdivision indexes assuming value of ‘s’ factor 1 for each one and multiple (up to 2 in this case) of an extent corresponding to the survivability to damage indices described above and for a sample Subdivision Length equal 200 m were:

$$\begin{gathered}
A_{SOLAS2009}(l_{DAM} \cong 0{,}053 L_S; zones(1+2); s=1; L_S=200m) = 0.638 \\
R_{L_S=200m} = 0.634 \\
A_{SOLAS90}(l_{DAM} \cong 0{,}039 L_S; zones(1+2); s=1; L_S=200m) = 0.568 \\
A_{SOLAS90}(l_{DAM} \cong 0{,}053 L_S; zones(1+2); s=1; L_S=200m) = 0.830 \qquad (16) \\
R_{L_S=200m} = 0.567
\end{gathered}$$

The calculation results in (16) show that the most probable value of longitudinal extent of damage (for which a vessel meets the criteria) has increased, and that a much higher subdivision index "A" is attained because of the type and structure of the formula.

In order to determine the properties of the probability density function and the fitting polynomial one must determine basic parameters of this curve. This may be done in two different ways. The author decided not to utilize available statistical data for formulation of the equation for "p", but did a simple reverse engineering study instead. A property of the Probability Density Function was used, that its value for 1-zone and 2-zone damage cases must be equal if the length of applied damage instances remains constant. The results are presented in Figures 23 and 24.

The result is a lognormal distribution of a damage length [15,19,20]. The author decided to apply calculations to a certain range of length of damages since the type and nature of a number of very short damages is difficult to be filtered and because there were very few cases in which damages exceeded the non-dimensional length parameter equal 0.3 L_s (Figure 20). As a result a small error in the results presented on Figure 24 comparing to the used statistical data can be observed [7,8].



$$p_{12}+p_{23}+p_{34}+p_{45}+p_{56}+p_{67}+p_{78}+p_{89}+p_{910}+p_{1011}+p_{1112} = P_{1ZONE}$$

$$p_{13}+p_{24}+p_{35}+p_{46}+p_{57}+p_{68}+p_{79}+p_{810}+p_{911}+p_{1012} = P_{2ZONE}$$

$$\frac{P_{2ZONE}}{P_{1ZONE}} - 1 = 0 <=> prob.\left(\frac{l}{2\lambda}\right) = p_{max}$$

Figure 23. Method of deriving the damage distribution from the formula for "p" factor for damages of lengths not more than l/λ.

With the method shown in Figure 23, an approximate damage distribution used for preparation of the formula has been derived (Figure 24).

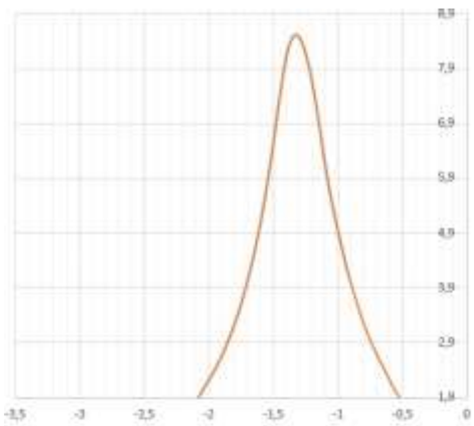
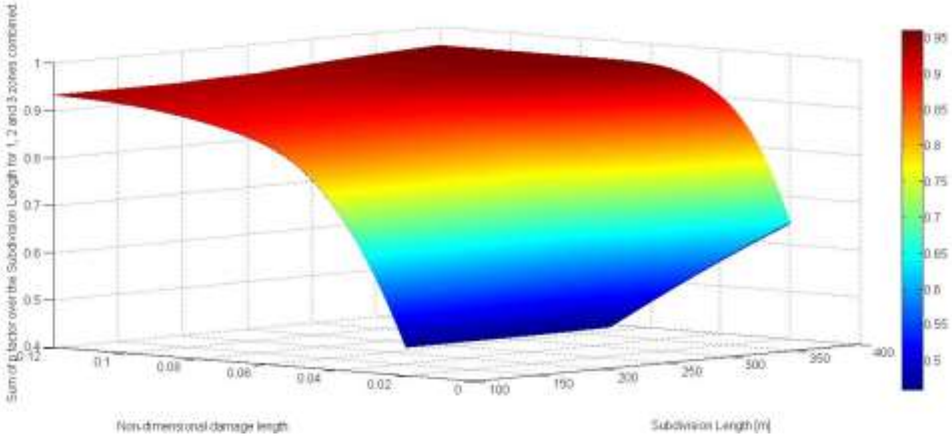


Figure 24) The shape of normal distribution of damages (after application of logarithm function to the function domain in range of 0,009 to 0,3 l/λ)

Calculation of “p” factor is performed to account for the probability that compartment(s) of given size(s) may be flooded. From the results, it seems that the calculation disregards the observation made in the project HARDER [15,19] that the longitudinal size of a damage to the length ratio is independent of the entire length of the vessel (Figures 18,19,20,22). One may only speculate about the reasons for this. This may have been introduced because of the lack of statistical data on certain sizes of ships or other unknown assumptions. The author is of the opinion that lack of this representation in the final method may lead to a gross error very difficult to quantify with the use of mathematical statistics.

Though the method for calculation of “p” factor is formulated correctly from the mathematical perspective, the author is of the opinion that the quality of statistical data is truly unknown (filtered for different reasons and purposes [20]) and that the number of statistical damages and possible causes of accidents have not been either validated or examined for the purpose of accurate probability formulation [17, 19, 21]. As there is no evident statistical or established physical correlation between the non-dimensional size of damage and the size or type of the ship, the author tends to believe that damage cases of a defined size must be represented in calculations in a clear numerical way while cases for which the survivability is known to be impossible to achieve should be numerically eliminated from the investigation to avoid the risk of uncontrollable error.

In order to present the consequences of the assumptions used in the development of “p” factor, another simulation was made. As the formula was found to assign different values to damages of the same non-dimensional damage length to subdivision length ratio for ships of the subdivision length greater than 260 meters (Figure 22), length was also taken as a variable for this simulation (up to 400 meters). The following variables were accounted for: the length of damage and the length of ship. The position of damage was disregarded (forward-most or aft-most), hence no account for the boundary decomposition of “p” factor was given, but because of this assumption, a percentage significance of damages of certain lengths and for Subdivision Lengths, for comparison against the Required Subdivision Index may be derivable. The calculation was made for the range of non-dimensional lengths ratios for each one zone equal 0,02 to 0,12 and for 1, 2 and 3 regular zone length combinations, but with an assumption of an equal non-dimensional length ratio redistributed over the length of each theoretical object [6] (16).



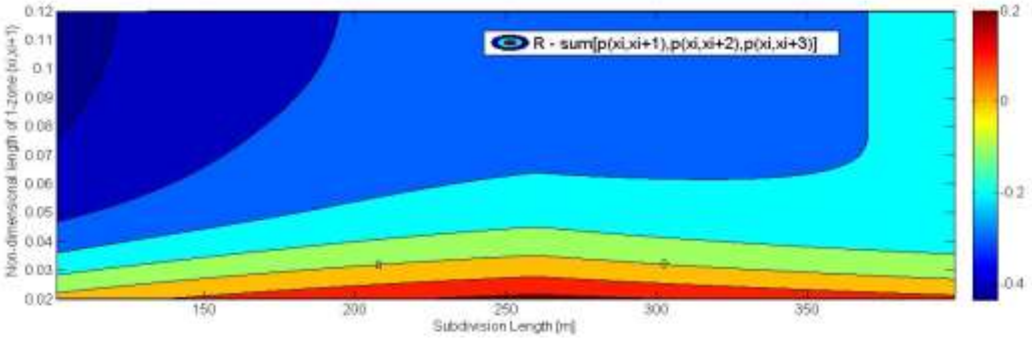


Figure 25. Graphs presenting sums of p-factor for 1 to 3 damage zones in function of Non-dimensional damage length of the 1-zone (upper) and the relationship of this sum to the Required Subdivision Index (below).

As shown in Figure 25, compliance with the criteria (in the shape of function R-A>0) stipulated by the SOLAS 2009 is granted for ships that meet the same stability criteria for hugely different non-dimensional subdivision lengths that correspond to non-dimensional lengths of damage. The situation is similar to that of transverse penetration damage extent factor "r", which to a large extent depends on the same parameters as the function for the "p" factor does.

The same analysis reveals that percentage-wise (as a general rule) a non-dimensional damage length ratio guaranteeing a compliance changes together with the increase in the subdivision length, which does not corroborate the conclusions from project HARDER [2,15,20]. (Figures 24, 25, 26)

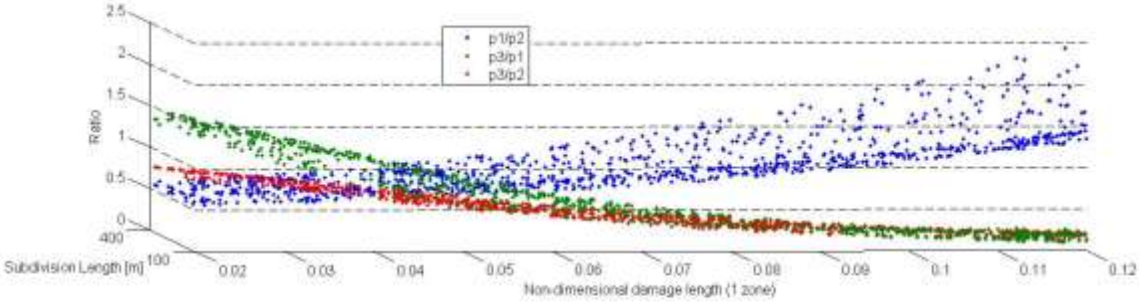
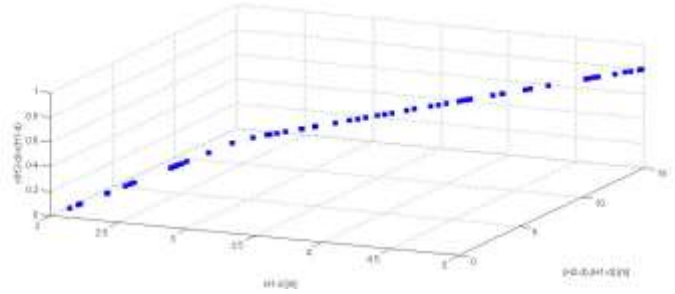


Figure 26) The ratios of p factor for one zone to "p" factor for two zones and for three zones to one zone and for two zones to one zone, in function of the initial non-dimensional one zone damage length and the Subdivision Lengths.

3.3 - "v" factor

The SOLAS 2009 formulae for "v" factor defined in regulations from SOLAS 2009 [6] and responsible for calculation of the vertical damage penetration has been analysed independent of other factors. The method for calculating factor "v" responsible for evaluation of the vertical extent of a damage scenario is as along with "p" and "s" factors defined in a different way than the previous regulations.

As Figure 37 shows the values of v factor are not related to the values of any other coefficients forming the method presented in the SOLAS 2009. The values for certain vertical extent above waterline level are merely a function of a difference of the value for v, as described in Figure 27, calculated at given different heights over the waterline level at given considered draughts (represented by: $H_j - d$). Unlike the formulation for “p” and “s” factors this formulation has not been statistically validated and is merely a result of a theoretical study [19].



$$\mathrm{v(H,d)} = \frac{(H-d)}{7.8}\, if\ (H_m - d) \leq 7.8$$

$$\mathrm{v(H,d)} = 0.8 + 0.2\left[\frac{(H-d)-7.8}{4.7}\right]\ in\ all\ other\ cases$$

$$v_m = \mathrm{v}\left(H_{j,n,m}, \mathrm{d}\right) - \mathrm{v}\left(H_{j,n,m-1}, \mathrm{d}\right)$$

Figure 27. Formula and values of “v” factor in function of the difference between H2-H1 and H1-d

3.4 - “r” factor

The “r” factor (11) has not been defined in a shape of linear equation in any other previous method and by definition it may only allow vessels subjected to evaluation against the SOLAS 2009 criteria to attain additional numerical values of the provided level of safety; as opposed to the previous regulations which were inadequate to accurately consider damages of lesser extent.

Unlike the “v” factor, factor “r” is a function of longitudinal extent of considered damage by link to “p” factor value. Introducing the “r” factor to the evaluation of attained stability after sustaining damage can only lead to obtaining a better score at the cost of possible non-compliance with stability standards introduced for consideration by the “s” factor (13) to the damage scenarios as mandatory in the previously applicable methods.

For the purpose of evaluating the influence of this factor on the final result an assumption was made to consider the practical longitudinal extent of damage between 0,03 and 0,2 of the subdivision length and “p” factors corresponding to these values for both/either single or/and two zone damage and a random practical range of lengths (100 to 400 meters). Using the Monte Carlo simulation technique, the frequency of occurrence of different “r” factor values for randomly distributed transverse extent of damage ($J_b \in (0;0{,}033(3))$ corresponding to 0 to B/2) was determined, and the average value of the “r” was found to be in excess of 0.8 (Figure 28). This proves that the formula for determination of “r” value takes into account a greater probability of less severe damages and assigns larger than average numbers to more than 80% of random damages.

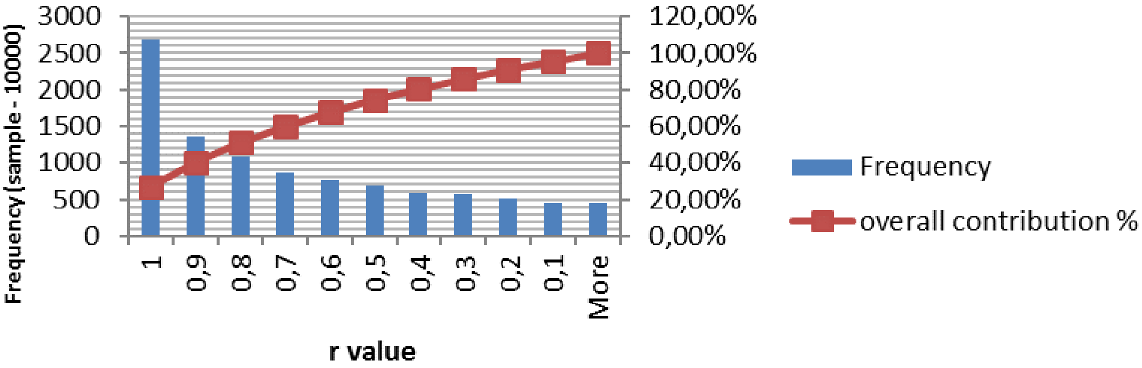


Figure 28. values of "r" factor for random range of transverse extent of damage

3.5 - "s" factor

The additional aspect of ship safety calculation is that As of first of January 2009, the final value of Attained Subdivision Index "A" (Figure 30) is defined as a sum of separate calculations following the same principles for three different initial floating conditions. The three initial conditions are defined as light service draught (representing the lower draught limit of the minimum required GM curve), partial subdivision draught (calculated as 60% of the difference between the light service draught and the deepest subdivision draught), and the deepest subdivision draught (corresponding to the deepest load line of a vessel) (6). In the method from SOLAS 90 (2) the accounting for changeable initial conditions followed a different pattern. The "s" factor was to be calculated for two initial conditions: the deepest subdivision load line and the partial load line defined as 60% of the difference between the light ship draught and deepest subdivision draught. After calculating values for these two initial conditions, the final value of "s" factor for any investigated damage case was to be weighted (17) and resulting value was to be used.

$$s_i = 0.5s_l + 0.5s_p \tag{17}$$

The implications of this change are that for damage cases for which vessels could not have any positive "s" factor value (meaning could not maintain any positive values of righting arm at any range) at the load line draught defined by the rules, vessels now can obtain 0.6 times of the more likely positive "A" value for the lightest possible operation draught (usually corresponding to the lightest ballast draught (arrival)) and the partial subdivision draught. This was impossible according to the rules adopted in the SOLAS 90. It comes from the author's practical experience with using the method from SOLAS 2009 that for some more serious damage cases the discussed here change often results in vessels obtaining "s" factors equal to 1 for the two lighter draughts and the value as low as 0 (zero) for the deepest subdivision draught. This is primarily caused by the fact that the vessels righting arm range decreases more rapidly with the increase of the draught. Attaining such high value (max. 0.6A) of “A” factor without meeting the requirements as stipulated by the “s” factor was impossible in the method from SOLAS 90 (max. 0.5A). This property is further discussed in Chapter 4 of this work.

The “s” factor calculation formulas introduced by different methods are presented in Chapter 2 (Table 2). The net values of the required level of safety obtained by using the method introduced in the SOLAS 2009 Convention were compared with those attained with the help of the rule of ICLL [4] with reference to values coming from SOLAS 90 method. (Figure 40)

In the rules that were set by ICLL 66/88, additional two criteria were formulated. Accordingly, under no circumstances was the final vessel heel angle to be greater than 17 degrees. (20 to 25 degrees are acceptable in both SOLAS methods), and the area below the positive value of righting arm was not to be smaller than a certain value. This requirement has been entirely waived in SOLAS methods.

The method SOLAS 2009 currently in force introduces a stricter method than that in the method ICLL 66/88, within a very narrow range of maximum righting arm values between 0,1m and 0,12m. The three remaining criteria included in ICLL 66/88 are either less strict or absent from the SOLAS 2009 method. As the practical experience of the author seems to indicate the 0,02m difference in GZ value is relatively small and it is unlikely that vessels will obtain such low values while maintaining the mandatory in ICLL 66/88 rule of minimum positive righting arm curve range of 20 degrees.

In addition, the SOLAS 2009 method allows for taking into consideration various damage scenarios which may contribute to the overall positive value of the sum “A” (Figure 24). Assuming that the damage penetration level is such as defined by ICLL 66/88 Convention (B/5), the value of the “r” reduction factor (Figure 28) could go as low as 0,55 and significantly reduce the positive impact on the result from sustaining such damage. However, considering principles of designing cargo ships of nearly all type and size subjected to the SOLAS 2009 regulation, there is (and there has been) no other practical incentive to introduce a watertight perimeter at such large distance from the outer shell. As indicated by the author’s own experience, the result of the lack of this incentive was that for almost all the ships the damage extent as defined by the Convention on Load Lines 66/88 corresponded to the maximum damage extent from the SOLAS 2009 (excluding pipe ducts when fitted). The author therefore, considers it to be reasonable to compare (under the described assumptions) possible theoretical results for different transverse subdivision arrangements and different subdivision lengths of ships only.

In order to allow for this comparison, in view of the “s” factor, the requirements of Reg.27 from the ICLL 66/88 were presented in a corresponding system/convention to the requirements from SOLAS 2009 method. The condition from the Reg.27 was brought to that convention by assigning value 1 to a condition that corresponds to maintaining stability parameters described in this rule criteria (including the under the minimum righting arm curve area criterion not covered by SOLAS) for each considered damage case. In this convention the value 0 corresponds to the attained stability parameters after sustaining the damage multiplied which do not meet at least one of the stipulated by Reg.27 of ICLL 66/88 criteria.

As a result a theoretical model was constructed which allows for such a methods comparison. To avoid impact of hidden dependencies A Monte Carlo simulation technique has been used for a generation of random geometries, which disregards any possible correlation between the variables. In this simulation there was only one fully undependable variable that was taken into consideration: Waterline Length (L). The waterline length was constrained only by minimum and maximum values of 100meters and 400 meters ,and its values were formulated by a pseudorandom numbers generator (from the Software Matlab R2013a).

Other ship parameters were defined as a function of each other with the help of empirical ratio/relationship formulas commonly used in ship design practice; the breadth has been defined as a function of the length so that it maintained within reasonable, and met in practice, values for mono-hulls and then multiplied by a random number generated by Matlab software but within a reasonable, met in practice, range. Again, this value was generated with the help of a pseudorandom numbers generator. The speed of the vessel was approximated from the breadth to length ratio [22] and multiplied by another generated uncertainty coefficient (similarly to quoted above). The corresponding to these above three parameters block coefficient as well as mid-ship coefficient values were calculated by statistically derived formulas [23]. Also, the position of the centre of gravity, the bilge radius for each set of data and the water plane areas were similarly defined as functions of the parameters (See Appendix 1 for assumptions and calculation methodology (see also [24])). Altogether, twenty thousand (20000) hull geometries were generated. Note: The stability calculation method was verified with the use of the NAPA software.

The graph below shows the total positive values of survivability index for the generated as defined above theoretical hulls (Figure 29). Comparison of the criteria is allowed only when exclusively the values for one most conservative draft for both SOLAS 90 and SOLAS 2009 are investigated, and also when the value of the "s" factor is less than one, its value being still added to the sum. The maximum number that the theoretical vessels could therefore achieve, was equal to twenty thousand (20000).

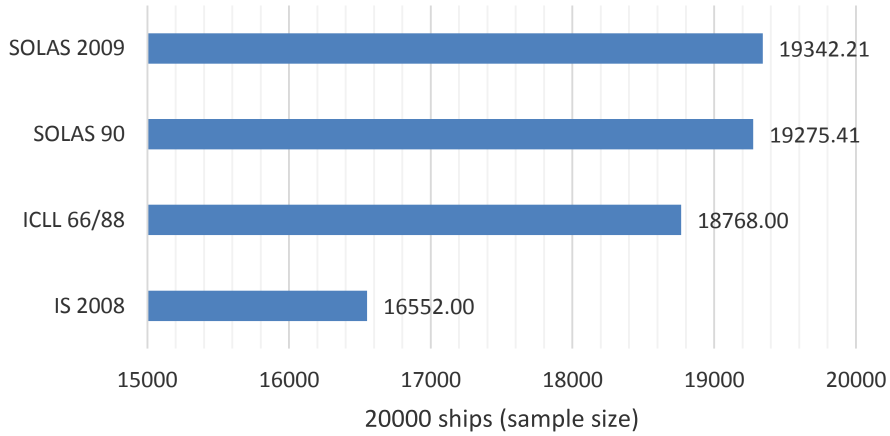


Figure 29. The sum of the survivability indices for the randomly generated hulls (see text for assumptions) from SOLAS 90 and SOLAS 2009 and the sum from the methods from ICLL 66/88 (damaged ships) and the IS 2008 (Intact ships) should this criteria be presented in the same form as the ones included in the SOLAS regulations.

From the Figure 29 the author concludes that out of the three investigated stability criteria for damaged ships it is the oldest one ICLL 66/88 that gives the most conservative results for the largest amount of randomly generated hulls. The method presented in the SOLAS 90 gave less conservative results by more than 500 out of 20000 (>2,5%) and the one from the SOLAS 2009 assigned even higher values to the same sample of ships by more than 50 points (an additional 0,35%).

As easy as these results may seem to interpret, they alone do not mean that the safety standards have been lowered. These results mean only that for a random large sample of hull geometries of different geometrical parameters and center of gravity values, the SOLAS 2009 rule assigns the biggest number of positive points by assigning the largest value of “s” factor. To better understand the problem of these characteristics of ships stipulated by the criteria in regulations they would have to be additionally confronted with the exciting forces acting on a ship. However, these results clearly show that it may be worthwhile to ask the question whether the parameters of the transverse GZ curve are always a sufficient measure of the survivability potential of vessels and whether the control over the value of the survivability index was maintained to a satisfactory (primarily to ship operators) level.

To answer this question it is crucial to investigate the methodology and the method used for the preparation of the s-factor presented in the SOLAS 2009. The s-factor was developed as a measure of probability of ship survival in waves (18) and was derived from multiplication of three different probability components: $f_{(H_s|coll)}(H_s)$ is the probability density distribution function of sea condition (as function of significant height only) expected at the time of collision. Unfortunately, there is no evidence that any statistical correlation exists between the sea condition and the probability that a collision happens. Furthermore, if any attempt is made to correlate the significant wave height at the time of accident with type and nature of the collision of ships, other sea condition parameters, such as wave period and e.g. visibility should be considered as well. Unfortunately, no information about such correlation (if any) nor the details of the calculations were published and could not be obtained by the author.

$$s = \int_0^\infty dH_s * f_{(H_s|coll)}(H_s) * F_{surv}(t_0|d_{j,k}, T_j, H_s) \qquad (18)$$

The $F_{surv}(t_0|d_{j,k}, T_j, H_s)$ function is the calculated probability of survival for a given period of time (30 minutes) when the ship suffers a specific damage case $d_{j,k}$ at draught T_j. From the Harder project [13] an engineering formula was derived (14) that gave similar results. The correlation between this formula and a significant wave height was formulated (Table 3) [8]. This correlation ,however, suggests that survivability of a ship depends solely on the properties of righting arms of vessels and the wave height. This paper makes an attempt to argue that this may not be entirely true (See Chapter 11).

In 2012, as a part of work for the GOALDS Project, a new formula for safety was developed (19). In Cichowicz, Olufsen work [8], the authors prove that survivability of a ship is not only a function of righting arm curve parameters, but also of (at least) the residual volume and initial metacentric height of the vessel.

s	Hs (m)
0.25	1
0.5	2
0.75	3
1	4

Table 3. Relationship between the factor "s" value and the significant wave height the vessel is to survive if the "s" value is of this figure and above.

$$s = \exp(-\exp\left(0.16 - 1.2 * \frac{A_{GZ}}{\frac{1}{2}GM_f * Range} V_R^{1/3}\right)) \tag{19}$$

4. Advantages and disadvantages of the currently used methods of assessment of safety of ships in damaged conditions. Motivation for the research.

As a result of the investigation and analysis presented in Chapter 3 conclusions might be drawn that there are at least several drawbacks of the currently valid method that can lead to inaccuracy and the lack of transparency of the results. During his career the author has gained some experience in practical implementation of various current methods for evaluation of cargo ship stability listed in Chapter 2 (Table 1). As a result of implementation of any of these methods, the potential improvement of designed objects utility (e.g. cargo capacity) is reduced. Introduction of additional requirements for operational safety necessitates more work on construction of ships and increases their mass. To date, no comprehensive study has been published to show the impact of current regulations on the mass of light ship and the reduction of deadweight and the direct impact on labor costs at the building stage. Also, there is little scientific evidence that this increased effort to avoid potential consequences of the loss of the ship in emergency conditions is fully justified environment and human safety –wise.

To fully present safety regulations vis a vis the other rules for ship construction that are crucial in designing structure and shape of the ship, one must first look into Regulations on other aspects of ship construction.

The current structure of rules on safety of ships is very complex. It is mainly because of a complex relationship between the Flag States, Classification Societies, and the Owners/Operators of ships. This relationship may be summarized (in broad terms) that, in the end, it is the Flag State of the country a ship is flying that is guaranteeing the fulfilment of all mandatory safety requirements by the ship. Therefore, it is in the hands of the Flag to determine whether the ship is seaworthy and adequately equipped. Needless to say, many Flag States do not have the resources to monitor all the vessels flying their flags and so cannot be confident that the ships maintain all standards or are designed within the acceptance condition of this Flag State.

This leads to the appearance of third party bodies and Classification Societies that receive authority to act on behalf of Flags and therefore become responsible for assessing the safety of ships. The leading Classification Societies are now grouped in the IACS

(International Association of Classification Societies) which now consists of 12 members that include the largest members there like: NK, DNV GL and ABS. The IACS merchant fleet constitutes approximately 96% of the worldwide fleet (tonnage-wise) and 75% of worldwide fleet (unit number-wise) [13]. The remaining fleet may be governed by some Flag States directly or other small Classification Societies which are not members of the IACS. It is important to note that in many cases the ships that are not classified by an IACS Classification Society do not meet IACS minimum requirements.

Classification Societies that are members of IACS must maintain certain standards (mainly in terms of Safety of their fleet). These standards are, to a large extent, stipulated by the IMO (International Maritime Organization) yet there are numerous differences between the requirements from each Classification Society. This paper focuses on formulating of a method of identification of safety parameters that may incorporate the derived from other IACS recommendations and requirements properties introduced by either IACS or IMO that are categorized into groups:

- Mooring and Anchoring
- Electrical Systems
- Fire Protection
- Subdivision, Stability and Load Line
- Machinery
- Navigation
- Strength of Vessels
- Materials and Welding

Listing all the requirements related to safety from the Classification Societies (members of IACS) is a difficult task. Because requirements and recommendations are grouped into certain categories and dealt with by different departments and officials within these organizations. This may lead to the lack of correlation between specific requirements and to possible overseeing certain safety aspects of ship’s combined characteristics. The main disadvantage of the rules/requirements is, therefore, their selective structure which incurs a high risk of being in contrast with the holistic approach to safety.

Different rules apply to different types and sizes of ships should the material, structure, load or equipment. In general, e.g. for Container Ships and Bulk Carriers above 150 meters in length the likely main differences may be summarized as in Table 4.

Specific rules inside the Regulations listed in (Table 4) may also differ for the two selected ship types, subject to their design details and/or specific purposes. Other rules may also apply subject to specific parameters of ships, their flag and/or particular classification society requirements.

This general presentation shows, that throughout the design process, vessel parameters possibly of crucial value and impact on the active and/or passive safety, are governed by different rules which are optimized for different reasons to a particular vessel.

It is surprising, therefore, that for two selected ship types identical stability rules may apply. Intact and damage stability rules seem therefore not to be connected to any other requirements for ships and are a function of size, general purpose of freeboard parameters of the ship. (Table 1)

Container Ship (Length>150 m)	Bulk Carrier (+ Cargo on Deck) (Length>150 m)
Mooring and Anchoring: - IACS UR A1,2 Strength of Vessels (and fittings): - IACS UR S1,2,3,4,5,6,7,10,11,14,21, 21A,26,27 - ISO 6954 ed.2000 - ICLL 66/88 as amended - SOLAS 2009 Subdivision, Stability and Load Line: - IACS UR L2 - ICLL - IS Code 2008 - SOLAS 2009 Electrical Systems: - IACS UR E Fire Protection: - IACS UR F Machinery: - IACS UR M - MARPOL 78 Navigation: - IACS UR N - SOLAS 2009 as amended - COLREG Materials and Welding: - IACS UR W	Mooring and Anchoring: - IACS UR A1,2 Strength of Vessels (and fittings): - CSR for Bulk Carriers 2006 as amended - IACS UR S1,1A,2,3,4,5,6,7,10,11, 12,14,19,21,21A,22,23,26,27,28,30 - ISO 6954 ed.2000 - ICLL 66/88 as amended - SOLAS 2009 (+Ch.XII) Subdivision, Stability and Load Line: - IACS UR L2 - ICLL - IS Code 2008 - SOLAS 2009 Electrical Systems: - IACS UR E Fire Protection - IACS UR F Machinery: - IACS UR M + M65 - MARPOL 78 Navigation: - IACS UR N - SOLAS 2009 as amended - COLREG Materials and Welding: - IACS UR W

Table 4. General list of Class and Statutory requirements applicable to selected ship types.

Analysis of the Rules and Regulations governing the stability in damage conditions for various ship types (Table 1) reveals many similarities between them. Such similarities are mainly due to the fact that regulations evolved in the process of addressing certain deficiencies seen in operation of ships of different types rather than in the process of seeking some acceptable level of safety prior to a deficiency being exposed by any emergency situation. Consequently, all the currently available rules seek adequate stability parameters after a collision. Stability parameters in question are limited to the value of metacentric height, maximum value of righting arm, the shape of GZ curve, a theoretical heeling angle and a positive area under this GZ curve. Other limiting factors may include the final equilibrium heeling angle and the point of the deck or the nearest weathertight or unprotected opening flooding together with a theoretical heeling angle calculated after the damage. Such structure of rules has advantages and disadvantages.

The main advantage of the current methods seems to be their practicality in common everyday use by achieving categorization of the governed by them areas. Correctness of the engineering values applied in them which has been verified by years of practical application and multiple studies.. However, with the process of digitalization of the design process, some more accurate and complex methods for assessing safety have already been developed [25 – 31]. Up to now, these methods however did not find their way to common design practice as their application requires a relatively large area of expertise and is time consuming.

Drawbacks of the existing methods can be seen when the methods are presented in a comparison summary. (Figure 30) If the required resistance to hazards defined by selected prescriptive and probabilistic rules (included in, e.g. ICLL 66/88, MARPOL 78, SOLAS 2009) applicable to ships of different sizes were maintained these hazards could be graphically interpreted in the same way. In this paper for this purpose, the transverse extent of damage was neglected and a theoretical possible resistance of ship to transverse damages was presented instead. Marked with green color areas mean full compliance with the minimum stability requirement included in ICLL 66/88 and MARPOL 78 and “s” factor equal to one for SOLAS 2009. Red color corresponds to a ship not meeting the requirements from ICLL 66/88 or MARPOL 78 or having “s” factor equal to zero in case of SOLAS 2009. (Figure 30)

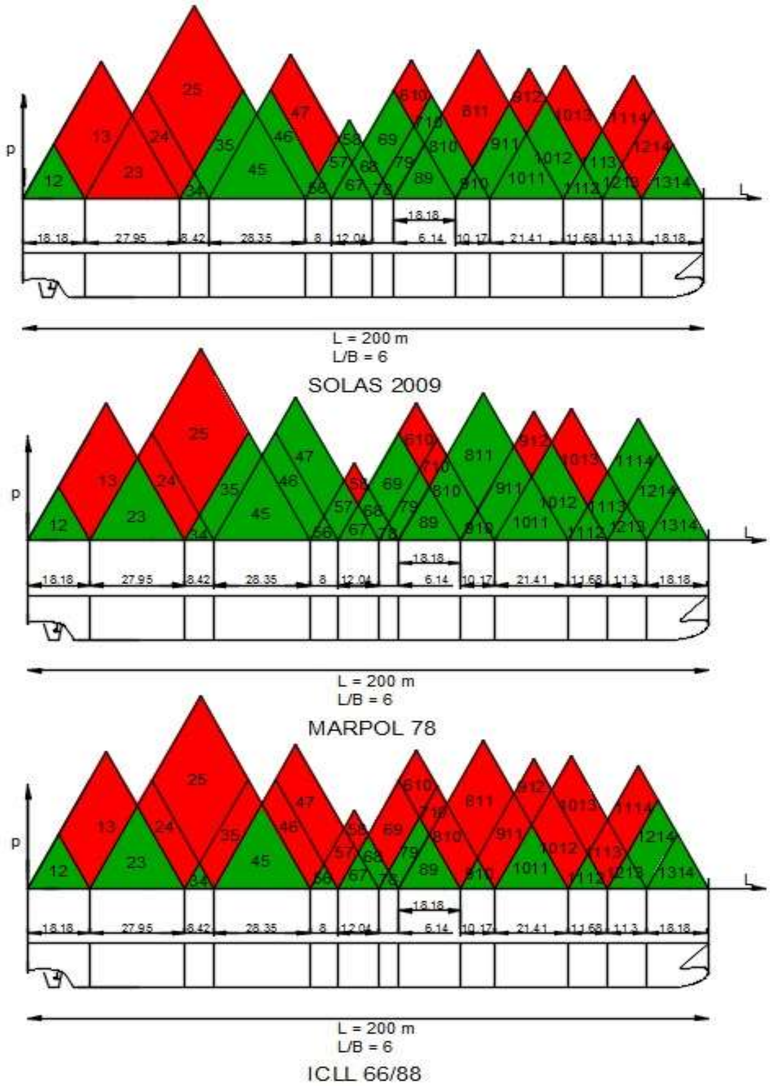
It must be stressed that the minimum stability criteria defined by different rules for safety of ships in damaged conditions differ and deterministic rules (such as MARPOL 78 or ICLL 66/88) do not allow for assigning partial compliance with them. Therefore, for compliance with the deterministic rules, the minimum stability parameters must be maintained. On the other hand, stability requirements included in SOLAS 2009 will allow for some positive contribution from calculated cases in which the requirements are not fully met and only some positive values of stability curve are kept.

Another important difference between the method included in SOLAS 2009 and the deterministic rules is the fact that it allows for additional contribution to the Attained Subdivision Index from Lightest Subdivision Draft and Partial Subdivision Draft (14). This was introduced to account for the fact that a vessel will not operate all the time at its deepest subdivision draft. The author is of the opinion that the routes of cargo vessels are usually economically optimized to maximize the use of their deadweight and even if the vessel operates in its ballast condition, it is seldom the light service draft, but rather a heavy ballast condition (e.g. the cargo hold used for ballasting). Such practices are more related to the comfort and navigation safety rather than to maintaining positive stability parameters after a possible damage. The author has not found any statistics in the literature on the subject that might confirm the factors applied for calculation of factor “A”. (14)

The results and calculation assumptions (Figure 30):

- The loading condition for three rules corresponds to the same deepest subdivision draft.
- The green colour indicates full compliance with “s” requirement (=1) for SOLAS 2009 rules or mandatory stability parameters defined in rules MARPOL 78, ICLL 66/88
- The red colour indicates the lack of compliance with any of requirements described in MARPOL 78 or ICLL 66/88, or the complete lack of positive stability range at an initial angle of less than 20 degrees in the case of SOLAS 2009 method.

The attained results, if SOLAS 2009 “p” factor definition was applied to all three cases in Figure 30, are shown in bottom part of this Figure.



SOLAS 2009:

$$p_{12}+p_{34}+p_{35}+p_{45}+p_{46}+p_{56}+p_{67}+p_{68}+p_{69}+p_{78}+p_{79}+p_{710}+p_{89}+p_{810}+p_{910}+p_{911}+p_{1011}+p_{1012}+p_{1112}+p_{1113}+p_{1213}+p_{1314}= =0{,}66024$$

MARPOL 78:

$$p_{12}+p_{23}+p_{34}+p_{35}+p_{45}+p_{46}+p_{47}+p_{56}+p_{57}+p_{67}+p_{68}+p_{69}+p_{78}+p_{79}+p_{89}+p_{810}+p_{811}+p_{910}+p_{911}+p_{1011}+p_{1012}+p_{1112}+p_{1113}+p_{1114}+p_{1213}+p_{1214}+p_{1314}= =0{,}77570$$

ICLL 66/88:

$$p_{12}+p_{23}+p_{34}+p_{35}+p_{45}+p_{56}+p_{57}+p_{67}+p_{68}+p_{78}+p_{79}+p_{89}+p_{910}+p_{1011}+p_{1112}+p_{1213}+p_{1214}+p_{1314}= =0{,}52761$$

Figure 30) Graphs showing possible damage cases required by the rules (SOLAS 2009, MARPOL 78 and ICLL 66/88) for which a vessel must maintain positive stability parameters.

By comparison, the Required Subdivision Index defined in SOLAS 2009 for cargo ships (assumed Subdivision Length = 200m) (8) is equal to 0,6364.

The ship presented in Figure 30 is a theoretical ship, with an assumed subdivision and of unassigned type. The purpose of introducing such a theoretical model is to show that the vessel may fully comply with the SOLAS 2009 rule by providing a large stability reserve (as defined by “s” factor) in some areas of the ship and none whatsoever in others, whereas by implementation of older deterministic rules this risk is mitigated. At the same time, comparison of the results for SOLAS 2009 and ICLL 66/88 reveals that in order to meet the simplified requirements (in form of Σp>R) the vessel would have to provide a sufficient (as described in the rules) stability reserve in significantly more cases when compared with the requirements from the ICLL 66/88 convention and significantly less to comply with MARPOL 78 convention. (Figure 30)

The simplified theoretical model presented in Figure 30 does not describe the requirements from SOLAS 2009 in full; In particular, the averaging of the “A” value for different drafts as it was described in Chapters 2, 3 and above (14). In order to show how this averaging of the “A” value impacts the final results another Monte Carlo Simulation for a floating object of constant geometry shape, yet of different size and size ratios (similar to the ones described in Chapter 3) was made. This simulation reveals the tendency of increase of both measured for evaluation of “s” factor parameters (i.e. the GZ maximum value and range of the GZ curve) with a decrease in deadweight to Light Service draught equal to 60% of the deepest subdivision load line and partial service draught equal to a sum of light service draught and a 60% of difference between it and the deepest subdivision load line as defined in SOLAS 2009 (Figure 31).

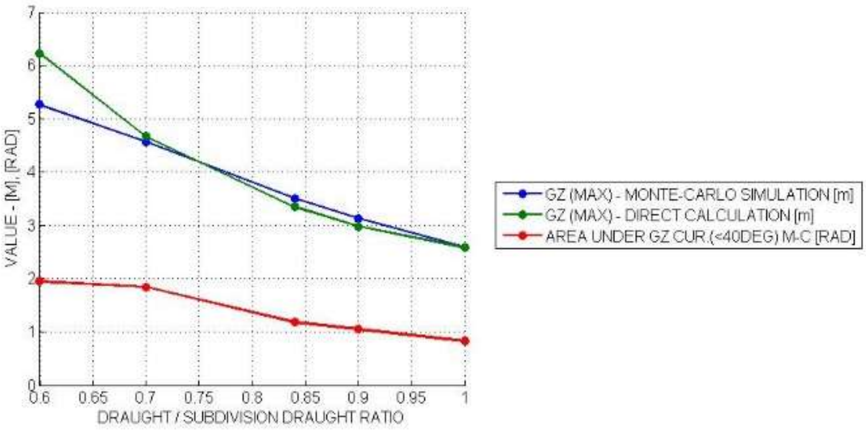


Figure 31. Values of GZ max and area under GZ curve for different ratios of calculated draught to the maximum vessel draught. (Monte Carlo simulation and direct calculation)

The results from this simulation clearly show that the projected value of both parameters: GZ max and the range of positive value under the GZ curve significantly increases with a decrease in draught (Figure 31). This is mainly due to the change in the submerged geometry as may be directly calculated from a formula for GZ. (Note: For this comparison, the results from a direct calculation of GZ for a theoretical vessel of parameters as shown in Figure 30 were also shown in Figure 31.)

The conclusion is that it will be a much easier task to prepare a loading condition for a vessel at 0,6 of deepest subdivision draught that will provide large initial stability parameters (GZ max and Range) and therefore, offer a much greater potential for maintaining sufficient (according to the Rules) stability parameters after damage. Failure to consider even one zone damage case scenario (zone 23 – see Figure 30) for any of the examined theoretical loading conditions is not an obstacle for meeting the required criteria and if for any reason the value of attained subdivision index is lower than the required one for the deepest subdivision draught, this may still be compensated by larger values for the light service draught and partial service draught, for which the vessel is much more likely to offer greater initial stability parameters and a much larger freeboard than in the case of the requirements from ICLL 66/88 or, e.g. MARPOL 78. Another conclusion from the above analysis may be that the method included in the SOLAS 2009 does not provide a clear answer for the ship operators when in emergency situation. The survival of at least 1-zone or at least 2-zone damages requirement is no longer present in the current version of the method and hence, it is possible that the ship operators will have limited knowledge about the ships ability to remain safely afloat after even a very small breach of an outer-shell.

It is of uttermost importance to note that a formula governing the probability of the ship being in a collision (as included in the method from SOLAS 2009) takes into account collisions with other vessels only and does not consider any other hazards to ship hulls integrity such as grounding or structural failure. The author considers this to be a big disadvantage of the probabilistic method presented in the SOLAS 2009 and is of the opinion that the matter will have to be addressed by maritime safety governing institutions in the near future.

The industry standard for measuring stability of the vessels is to measure their geometrical parameters in both intact and damage conditions. As previously mentioned there have been attempts to introduce other properties of ships as governing stability [8, 28, 32], but they have not found their way to common application. However, with digitalization of the design process it can now be seen that, with limited number of simplifications, a direct calculation of vessels dynamical righting moment is not much more complicated than the calculation of the righting arm on its own. With introduction of the dynamical calculations a large error related to confrontation of a changeable with vessel's size and parameters relationship between the heeling moments acting on a ship and righting moments can be greatly reduced.

The currently valid regulation for calculation of "s" factor (13) has been to a large extent based on the formulas included in the ICLL 66/88 and further evaluated by independent studies [8]. The studies that lead to preparation of the SOLAS 2009 formula for the factor "s" were based on statistical analysis of the sea condition during accidents and the stability parameters of the vessels at that time [8]. This also has large impact on the disadvantage of the evaluated approach. Because the method formulation did not take into the account the actual righting ability of vessels represented by the righting moment acting against the external heeling moments it does not provide designers and/or crew with information about survival ability of the vessel in theoretical emergency situation.

With the above advantages and disadvantages of the current methods for evaluation of safety of ships, the author has decided to seek parameters and formulas that would be a compromise between user-friendliness and accuracy. An attempt to present a direct method of evaluation of safety of ships that provides measurable levels of safety of a floating object for any user and at any life stage of this ship is presented in the subsequent Chapters of this paper.

5. The purpose and scope of the Thesis

The hypothesis: It is possible to extract a set of parameters that are readily available in common cargo ship documentation and are of decisive impact on safety of cargo ships because the behavior of ships in waves is primarily a function of static, damping and added mass coefficients easy to approximate accurately using these parameters.

In the history of shipbuilding numerous efforts have been made to assure that transportation by sea is safe to an acceptable level. With the know-how and experience of designers increasing in time and digitalization of the design process with harmonization of navigational rules and requirements, methods of design for safety seem more possible today. This thesis aimed at determining a method of identification of a set of parameters which might comprehensively describe properties of damaged cargo ships and help to use this knowledge in every day engineering practices.

The risk of causing harm to life, environment and the property that during operation of ships is in majority of cases a result of o a possible loss of functionality of certain systems of the ship. Certain systems onboard are responsible for the safe operation of vessels. When the ship environment equilibrium is somehow impaired by, e.g. collision, cargo explosion, or system malfunction, the risk is greatly increased. In the case of cargo ships, the calculation of risks can be greatly simplified when compared with, for example, passenger ships. As mentioned in Chapter 4 one of the main disadvantages of current regulations is that they treat the risk to cargo ships selectively and address it separately for each system instead of comprehensively describing the combination of systems of the ship as the one system for whom risks are not simply a sum of the risks to each individual system (Figure 32).

Safety, at the design stage can be understood in many ways and evaluated using different methods and techniques, hence a selection of a method has to be carefully planned and accurately engineered with mitigation of subjectivity of the process mitigation. (The methodology and methods of selection process are further described in Chapter 6) Accordingly, the purpose of this thesis is therefore to utilize the gathered experience over the years of shipbuilding and couple it with tools and techniques the modern technology provides. Also it is of uttermost importance that the developed method is easy to apply at any stage of the life of ships. Ideally, the method can be further developed to give the crew onboard a ship the green light or the red light when making their decisions in emergency situations.

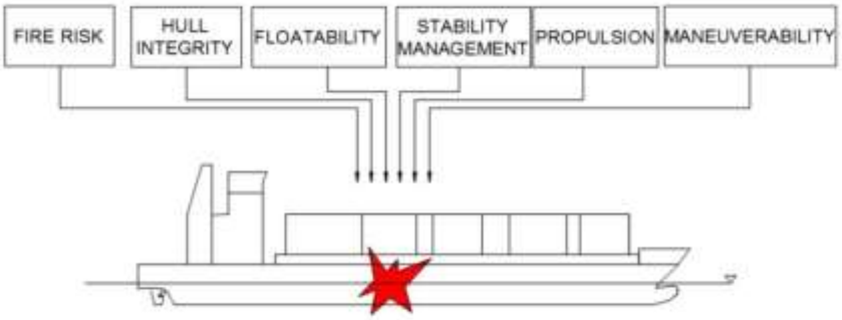


Figure 32. Risks after hazard occurrence during cargo ship system exploitation.(not caring dangerous goods)

The scope of this work, may be divided into two parts:

In the first one deficiencies in the current design methods and rules governing construction of ships are identified.

In the second part, development of the theoretical calculation model is presented against the background of these deficiencies of the current design methods. Assumptions and method range of application, are included and, for further evaluation of the method, structured identification of ship parameters is presented. These identified parameters have a decisive impact on safety of cargo ships. They are further compared with existing methods or practices with the help of a selected ship design. The differences, where appropriate, between the methods described in the first part and second part of the paper are further analyzed.

The decision making process in this new method is explained and possible ways of harmonizing this new method with the existing engineering practices are further described. The possibilities for further improvement and increase of range of application are also discussed. The paper focuses on practical implementation of the method and refers to the current state of knowledge presented in the first part (Chapters 2, 3, and 4 of the paper).

6. Research methodology

Research work for achieving the goal of formulation of the new method was conducted prior to the method formulation and was divided into stages. First, the objective of the work was defined. The objective had to be accurately formulated for the purpose of reaching the desired outcome without a risk of overlooking certain aspects of it. The model structure is presented in Figure 33 and its application further described in Figure 34.

Research methodology is represented by the combination of quantitative and qualitative approach. This was mainly because of difficulties in defining consequences which may be understood in many different ways [31, 33].

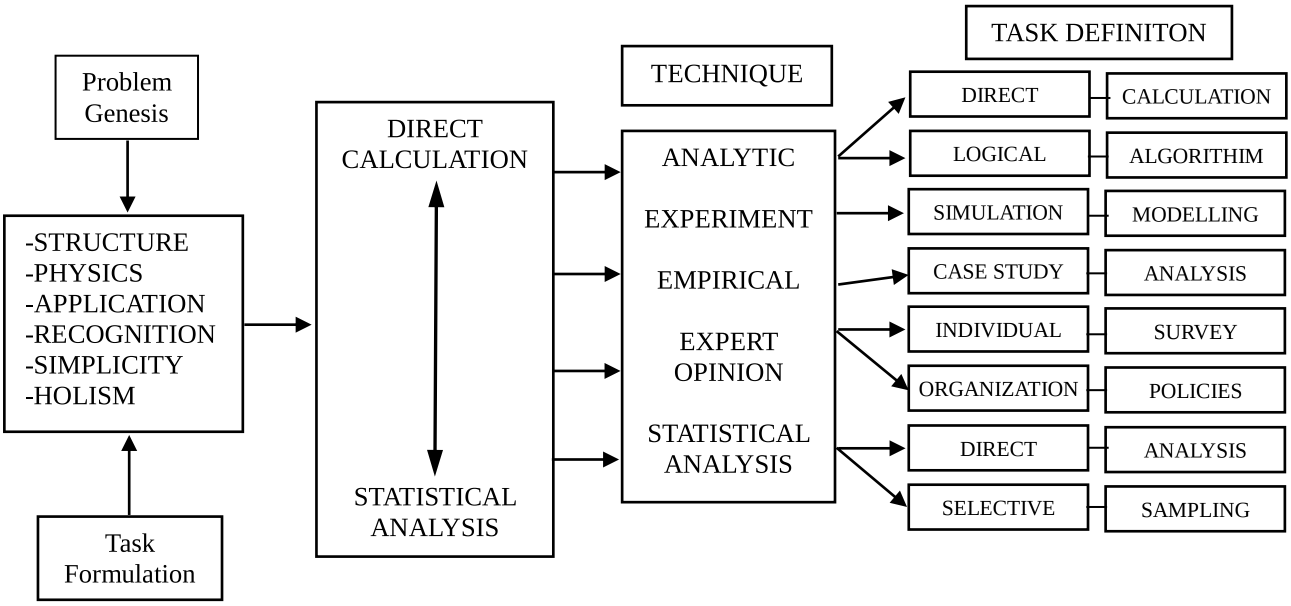


Figure 33. Understanding the problem - The input data gathering and processing methodology

The main characteristic of the approach the author used for this research is connected to the risk calculation and the correlation of quantitative and qualitative characteristics of defined properties of the evaluated object and environment. The approach selected had to be related to the need of separation of variables that can be described in a quantitative and qualitative way. Some properties are strictly quantitative, whereas others cannot be quantified and must be represented by a certain quality in which the quantification of smaller elements/properties is possible in decision making process (0 or 1).

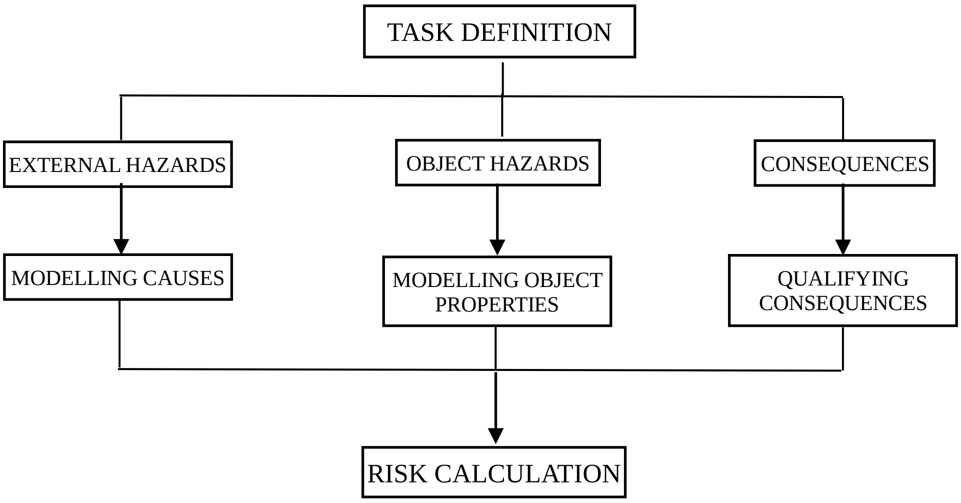


Figure 34. Understanding the problem – methodology of modelling the input variables.

As already indicated, the risk based approach was selected to govern the final structure of the method. The process of selecting this method for assessing the safety of large engineering objects such as ships has already been very well described in the literature on the subject. [25, 31, 34], but for the purpose of this paper a slightly different route was followed. (Figure 35, 36).

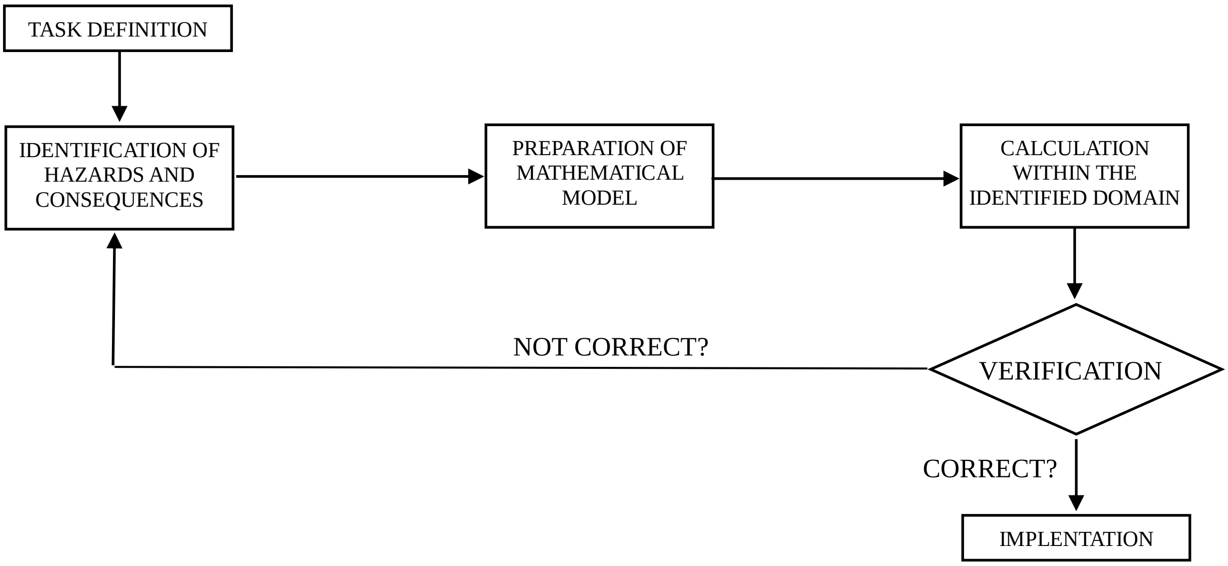


Figure 35. Research methodology – Identification of hazards and consequences quantification and model implementation process.

Figure 36. Research route showing the impact of hazards on designed object and possible consequences arising from the combination of the two in the context of the environment

The basic concept behind the currently valid approach is that a Bayesian probability as governed by Cox's theorem can provide a comprehensive description of Safety (SOLAS 2009), but the recent development of safety analysis has been more focused on alternative methods utilizing risk calculation methods [31, 34] (20).

$$R_i = \sum_{i=1}^{n} P_i * C_i \tag{20}$$

$$P_i = probabiity\ of\ \mathrm{i}\ hazard\ occurance$$
$$C_i = consequences\ from\ \mathrm{i}\ hazard$$

The paper presents verification of the currently valid risk methods for assessing ship safety and presents development of the author's own calculation model.

7. Proposition of a parallel method for assessment of risks for ships in damaged conditions. Introduction of un-survivability risk analysis to the current models.

7.1 Safety – what is it ?

In the last several years, numerous attempts have been made to formulate a method of assessing safety for ships in damaged conditions [25 – 31]. Many of these methods have been presented and summarized at the ICSSOV conferences or in publications on the subject [e.g. 35].

When assessing the safety of a design or a ship in operation it is an imperative that general definition of safety is agreed on. In general it may seem evident that the application of the risk calculation method is the methodology the scientists have agreed on. However, there are still differences of opinion with regard to the final shape of the method.

It may well seem possible that one of the reasons there are differences of opinion is the lack of a clear definition of safety. Also, the way we understand safety of ships may change in the future. Some scientists define Safety in relation to Risk as follows :

"*Safety is the state of acceptable risk*"
- Vassalos, Jasionowski [25]

"Property that reflects acceptable risk in relation to people, property and environment"
- Gerigk [31]

The author has decided to follow the Merriam-Webster Dictionary [37] general definition: safety is (among other definitions):

> "Freedom from harm or danger: the state of being safe" [37]

On the basis of the Merriam-Webster Dictionary definition the author is of the opinion that no subjectivity should be applied to the definition "freedom from (…)". The author is of the opinion that safety cannot be numerically calculated and is inherently related to time and environment in which the object operates (life, natural environment, property). The probability of an error in observations and/or understanding of hazards related to the operation of the analyzed is very high. This error introduces risk to safety (as per definition) and therefore we will not know for sure if it is safe to operate the object until we stop operating it.

Because the likelihood (probability) of any hazard occurrence (on the basis of physics, or/and our experience and knowledge) may be lower in certain conditions or at a certain time and higher in others hazards change. Safety, however, is an absolute.

Another obstacle in quantification of consequences is related to their severity. It may seem sufficient to use a numerical, probability based, model for decision making process when the possible consequences are negligible (for example, if one bets a dollar by tossing a coin). Generally, the risk of applying the above mentioned model to the gambling process is acceptable. However, it may be wrong (or at least inadequate) when the stakes are high. One may easily assume that most people would not bet their lives even when the chance of failing is much smaller (e.g. 0.167).

Safety-wise, it is clear that potential consequences of losing any large ship (cargo or passengers) are disastrous, and the risk level we are willing to accept is very low then.

Consequently, the risks we are facing during the operation of a vessel must be constantly kept in mind. The qualitative risk model allows for a better control of the acceptable risks level. The risk analysis allows us to understand how unsafe the task is that we are going to be involved in, and how much human effort is really needed to lower it. After all, we will not know for sure that the ship is safe until we have successfully completed its scheduled decommission, and we will not know that the ship is unsafe until it sinks, for example.

In other words, the cargo ship is safe if she doesn't cause any harm to life, environment or property during its entire life cycle. Accordingly, the ship safety is not a function of risks the vessel faces, but rather depends on its characteristics and properties that allow it to withstand any of the risk encountered in its operation.

To summarize the above and on the basis of the definition of the word 'safety' from Merriam-Webster Dictionary [37], the author is inclined to believe that safety cannot be evaluated in terms of probability or subjectivity and therefore, cannot be holistically assessed by the quantitative risk calculation, which by definition (20), depends on probability of hazards. Safety is an absolute. No ship can be regarded safe until proven otherwise during its time in/of operation. Therefore, commonly used opinions such as "higher levels of safety" are misleading and relate to semantics. Safety is an absolute freedom from hazards which in real life cannot be fully ensured during operation, and we must accept certain levels of risk involved in the operation of vessels.

7.2 Risk – calculation method

Risk analysis may provide useful information about the environment, design and operation of ships that may cause a ship to become dangerous to life, environment or property during its life. After all, it must be the physical properties of the environment, design and operation of ships that provide ground for decision making process.

The author is of the opinion that risk may be defined as follows:

“Possibility of loss or injury”
- Merriam-Webster [37]

“A chance of loss”
- Jasionowski, Vassalos [25]

The risk can be calculated in terms of probabilities related to the object and not to (its) safety. Therefore, we can make a decision whether the vessel is capable of withstanding all the identified through risk analysis hazards and dangers and not cause harm to people, environment and/or property in certain conditions, and effectively determine the conditions in which the operation of a vessel is safe or not. It is to be stressed that measuring a risk is not the same as the measuring of safety, and it cannot be directly related to it.

The techniques of evaluating risks vary [25 - 31, 38], but are all defined by mathematical formula (20). In general, the differences between the risk models are mainly related to:

- Weight factors applied to statics for probability of hazard occurrence calculation
- Vulnerability calculation methodology
- Consequences categorization

The formula presented by Gerigk [31] is the following

$$R = P_c * P_{c/f} * P_{c/f/ns} * P_{c/f/ns/tts} * C \tag{21}$$

where:
P_c – Probability of collision
$P_{c/f}$ – Conditional probability of flooding
$P_{c/f/ns}$ – Conditional probability of not surviving the flooding
$P_{c/f/ns/tts}$ – Conditional probability of not surviving the flooding at a given time.
C – Consequences

The formula presented by Jasionowski [25] is:

$$f_T(t) = \sum_i^3 \sum_j^{n_{flood}} \sum_k^{n_H} w_i * p_j * e_k * c_{i,j,k}(t) \tag{22}$$

where:

$f_T(t)$ – Unconditional probability that an event of time to capsize t occurs (corresponding to Risk of ship sinking in time t). Commonly named as “ship vulnerability to flooding”.

w_i – Probability mass function of the 3 specific loading conditions.

p_j – Probability mass function of the damage extents and the n_{flood} number of flooding extents calculated according to the harmonized probabilistic rules for ship subdivision [39].

e_k – Probability mass function derived from the statistics of sea states recorded at the instant of collision where n_H is the number of sea states considered.

$c_{i,j,k}(t)$ – Probability mass function of the event of capsizing in the set time.

After careful verification of the above cited models and others [25 - 31, 38], the author proposes a risk model and finance formula for risk well known to the shipping and engineering societies in the following form:

$$\mathbf{R} = \mathbf{P} * \boldsymbol{V}^{\boldsymbol{T}} * \mathbf{C} = \begin{bmatrix} p_1 \\ \cdots \\ p_n \end{bmatrix} * \begin{bmatrix} v_1 & \cdots & v_m \end{bmatrix} * \begin{bmatrix} c_1 \\ \cdots \\ c_m \end{bmatrix} = \begin{bmatrix} p_1 v_1 c_1 + \ldots + p_1 v_m c_m \\ \cdots \\ p_n v_1 c_1 + \ldots + p_n v_m c_m \end{bmatrix} \qquad (23)$$

where:

- **P** - Probability of hazard occurrence in given weather conditions (probability mass function – distribution) <l;…;r>
- $\mathbf{V^T}$ - Vulnerability of the object to the hazard in different terms: (hazard probability, hazard extent, initial condition etc.) <k;…;m>
- **C** - Consequences, in terms of loss of life, harm to environment and cargo or ship loss for given vulnerability object properties <k;…;m>

The main difference between the models above and the proposed model is that the probabilities <1…r> and <k…m> are not dependent on each other and/or do not force the end user (e.g. Master, Approval Engineer, Designer) to use advanced mathematics for verification This means that they are calculated separately and are not conditioned one against the other and that they are governed by equations with predetermined factors releasing the end user from evaluating the cause and effect scenario and as a consequence ,allowing for a final black and white result for each and any hazard. This approach allows for better risk control and increases the possibilities for risk mitigation for selected environmental conditions (in the selected case: weather at sea). Furthermore, it allows for easy transformation of mathematical equations describing risk.

The difficulties arising from the use of any risk model are related to the accurate quantification of probabilities and consequences and to the acceptance criteria. One may argue that they are subjective, but following the general definition of safety from the Webster-Miriam dictionary quoted above, the author has chosen to select a descriptive form for modelling consequences (qualitative). Consequently, a chance of losing a ship or/and dangerous cargo or a loss of life onboard is modelled as a separate cell in the risk matrix that allows control over the evaluated risk levels.

The vulnerability of the object may be calculated on the basis of the ship speed, stability, structural integrity and fire/chemical risk mitigation abilities and operation properties (including location). In recent years a lot of research has been done to move away from statistical approach in describing hazards [40]. The method proposed in this paper utilizes some of the currently available research results [31, 40].

The calculation methodology details are presented in Chapter 8 of the paper and a practical example is shown in Chapter 11.

7.3 Goal to attain

In recent years, and for selected types of ships, the goal based design standards have been realized by the industry in the form of regulations. [8,41,42,43,44]. These rules focus on efficiency and structural integrity. Ship resistance to hazards defined above still remains a limitation there.

The ship design methodology that focuses on safety and efficiency may be implemented if prescriptive nature of regulations governing safety is changed. Example of such methodology for cargo ships is shown in the flow chart on the next page. (Figure 37).

Furthermore, in recent years many publications and a lot of scientific research have been focused on the best way of capturing dynamic effects of ship behavior in motion [8,25,29,31,45-55]. Different approaches presented and applied by different scientists have their specific advantages and drawbacks. It may seem that the most accurate method that takes into account all the governing factors is the direct pressure integration method applied in, e.g. Proteus3 software [56]. Direct pressure integration allows for direct calculation of all the factors from the form and accompanying water motion, but it is very time consuming and difficult to control. In reality, it is so time consuming that the author does not see any possibility of this method being used in practice for quick decision making in the foreseeable future. One of the alternatives was presented and verified in 2009 in the work of F. Kluwe [29]. F. Kluwe’s approach is efficient and at the same time quite accurate in predicting the behavior of the vessel. However, the nature of the equations presented in his work leaves little possibility of controlling (in an accurate way) the error for various hull shapes and mass distributions of the ship. The alternative to the above models and what seems to be a good compromise (for current personal computers) is to apply Ursell-Thasai method and strip theory [57,58]. The applied model and its accurate verification are presented in Chapter 8.

The goal, therefore, is to present a tool/method that can be used at any stage of the life of the ship and will be easy to use and most of all, will be accurate enough to become an industry standard for black-and-white decision making processes.

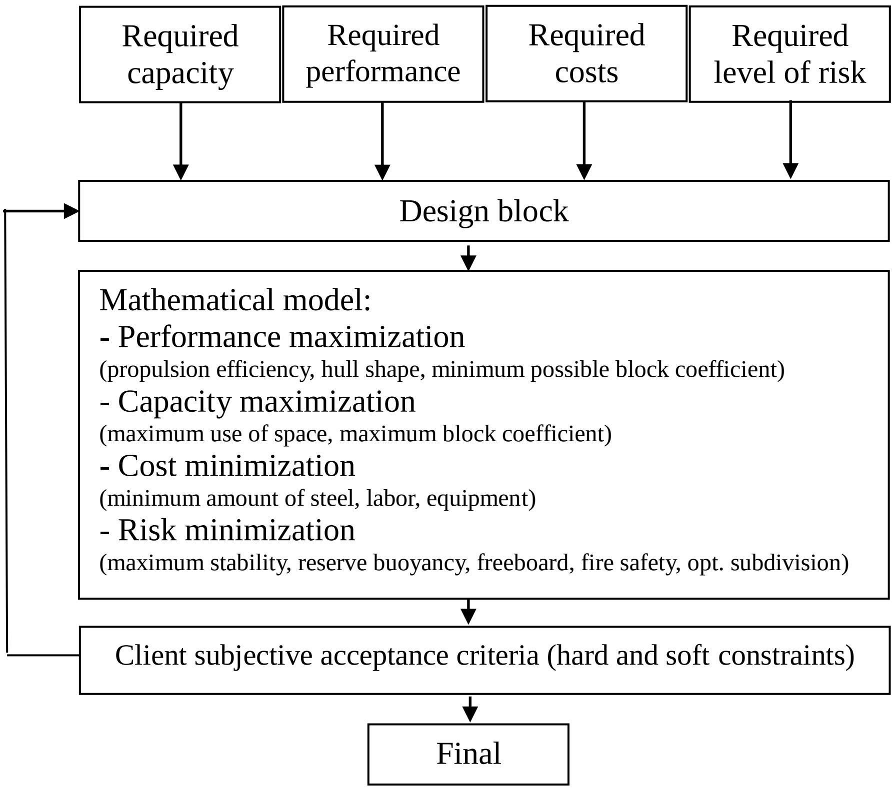


Figure 37. Application of the proposed method to a sample design flow chart [44]

7.4 Probability of hazard occurrence

Probability of hazard occurrence can be expressed in different terms. Up to date, it has been a common practice to investigate statistical data of ship-ship collisions, their size and location. The main drawback of the current approach is that the remaining hazards described in literature and subparagraph “Consequences of hazard occurrence” have not been taken into account and so accurate addressing of these threats has been disallowed. The other drawback is that statistical data have to be filtered. Even after the introduction of a sheet for reporting collision damages for the GOALDS [8] program, the data filtering was still a major task to overcome [8, 59, 60]. In practice, apart from the increased probability of a damage to the most forward area of the ship which seems to be adequately addressed by the ICLL requirement for installation of a collision bulkhead, there is no physical proof that any part of the ship is at a greater risk to be damaged than other parts thereof. [19, 60] (Figure 39). On the basis of this approach, the author has decided to implement sample data of collisions at a different stage and for the risk control associated with an object. For the purpose of calculations of level of risk the author decided to apply a constant factor of significance to any compartment/combination of compartments. Having a constant factor of significance of any damage will provide a statistically unbiased result of risk from flooding a compartment to the vessel, which then may be further evaluated with the help of statistics stipulated in Risk Control Criteria or ALARP methodology [31]. Similarly to the above damage, the risk of caring a dangerous cargo (in terms of pollution, high value, or fire) may also be considered in control options.

Bad weather that is unrelated directly to the object is a hazard taken into equation at this stage. Current methods do not provide any visible assessment of bad weather impact on the safety of ships in serious accident situations. This may easily be changed if an estimation of the behavior of a vessel in certain weather conditions is introduced. Up to date, masters on-board ships have not had any tool to help them estimate the stability of a ship in emergency conditions. Naval Architects know that a vessel subjected to a collision and flooding may be evaluated for safety with the use of s-factor present in the SOLAS 2009; however, in an emergency situation, such assessment becomes almost impossible to perform because it involves going through detailed calculations which often consist of hundreds of pages and as the s-factor was developed on the basis of statistical data, it cannot (ad hoc) provide an answer with sufficient amount of confidence.

As sea going vessels may freely change routes, operators and owners, and may be therefore engaged in worldwide trade in any location almost regardless of ship characteristics; probability of bad weather hazard occurrence may be calculated on the basis of available worldwide statics for ocean states and for a long period of time. In order to meet the sought after in this paper goal, it is important to emphasize that this statistical derivation must not be directly used for decision making process, but the final result must show the response of the vessel to different visible weather characteristics.

This measurement of weather conditions that usually takes place in practice determines the significant wave height and the apparent wind force in Beaufort scale. It is important to note that most trained mariners are familiar with and proficient in recalculating the apparent wind force to the true wind force. In line with the set up goal for this method, vessels characteristics must be confronted with measured by seafarers values.

There is no proven correlation between weather conditions and probability of hazard occurrence, hence for the purpose of this method long term weather statistics for the worldwide sea waters was used. The statistics used in this paper were the statistics first presented and tabularized. [61] (Figure 38).

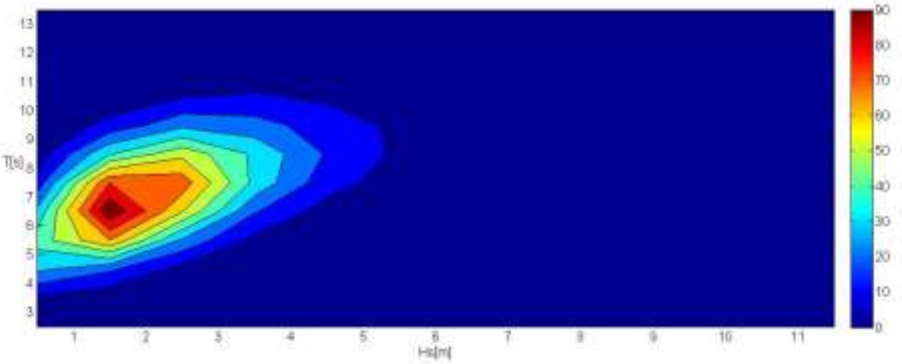


Figure 38) Frequency distribution of sea states in function of wave periods and significant wave height for world-wide trade. (Total number normalized to 1000) [61]

The above approach to environmental conditions is based on the assumption that serious accidents happen regardless of the weather and the vulnerability of the object to this accident must be evaluated. The likelihood (probability) of accident happening may then be introduced into the method at the risk control options [31] (e.g. RCC – Risk Control Criteria) stage.

7.5 Vulnerability of a ship

The vulnerability of a ship to hazards described in the above section is related to many different factors. The response of the vessel to a damage to its original structure is related to the following factors:

- Weight distribution and initial stability of a vessel
- Subdivision and Arrangement:
    1) Position of a damaged compartment (damaged compartments)
    2) Size of a damaged compartment (damaged compartments)
    3) Geometry of a damaged compartment (damaged compartments)
- Initial floating condition of a vessel
- Quantity and type of cargo onboard
- Response of a vessel to damage (in function of damage position)

In order to determine the actual vulnerability of the vessel, all these aspects need to be investigated separately and independent of each other:

7.5.1 Weight distribution and initial stability of vessel:

As described in Chapter 3 of this paper, the current calculation of stability method is based on evaluation of static parameters of ship hull and appendages only: righting arm curve and metacentric height in selected possible damage scenarios being investigated with a weight factor assigned on the basis of statistical evidence of collisions only and a separate deterministic investigation of stability after damage to the bottom of the hull. As a separate requirement for ships over 80 meters in length, a minimum allowable freeboard is governed by the ICLL regulations. As described in the subparagraph “Probability of hazard occurrence” and Chapter 4 of this paper, it is not a holistic approach that addresses the evidenced serious accidents.

The stability of a ship in sea waters is governed by multiple parameters. Furthermore, it is essential to underline that damage stability and intact stability cannot be easily compared. This is mainly related to the fact that the Maritime Law suggests that any ship that is involved in a collision should remain in its location [62]. Consequently, after a collision the movement parameters change, and the forward speed of the vessel is minimized.

The impact of forward speed and the risk of oscillations have been very well described in the literature [29, 63, 64 et al]. The difficulty of assessing safety of the vessel in terms of damage stability may originate because of two aspects of the vessel situation:

- Initial stability and floatability after the collision with another ship or object, or after the introduction of emergency condition for other reasons (such as hull integrity failure, cargo shifting, ballast system malfunction etc.).
- Stability and floatability of the ship after Master’s reaction to the emergency that may include some alteration of the course and speed in order to decrease the roll movement of the ship [31].

After a collision, the initial condition is assessed by officers onboard. If excessive roll angles are observed, a decision is made to change the course so that the vessel goes to head waves or wind and at a low or dead-slow speed. Additional tool that officers onboard a ship may use is to add or remove ballast water in order to change the weight distribution and/or position of center of gravity of a ship. This will have a significant impact on behavior of ships in waves too, but requires plenty of time prior to the effect of it to take place. There is no requirement for the time in which Master must make a decision to change course and the decision is based on Master's judgment only. It is difficult, therefore, to assess the time in which the captain orders a change of the course and in which the course is changed. This would then have to be assumed and for the purpose of this work the author assumes a 100 second- period in which the vessel's unsteady behavior in waves can be addressed.

As the available research clearly shows the risk of oscillations changes with the change of initial conditions, these being:

- Change of natural period of roll of the ship due to flooding
- Change of speed of the vessel

If in the new condition after damage the oscillations appear to be dangerous to safety (and if the situation allows for this), a Master will make a decision to alter the heading. If for stability and/or floatability reasons a Master decides to improve stability by changing course, the new condition must also be assessed, but the criteria for the new condition must be different and must assure safety outside the time domain.

Consequently, there may be two initial vessel's conditions on which officers onboard must have sufficient information to allow for a decision making process:

- Initial condition with 0 speed and worse heading, but with damage applied to vessel.
- Condition with low speed ahead and the heading in which roll angles are minimized.

The proposed calculation method is described in Chapters 8 and 9 of this work.

7.5.2 Subdivision and Arrangement

As highlighted in the foreword to this work, ship construction and operation poses hazards to life, environment and property. It is an often unspoken truth that during the construction of ships there are a large number of casualties and that economic factors often take priority over the efficient use of the Earth's resources. It is difficult to find any reliable statistical data on the number of deaths during shipbuilding, but it is commonly known that it is not unheard that one person dies and a few others are seriously injured during the construction process of an average-size cargo ship. It is to be stressed that the above information is solely based on the author's own experience in working in the shipbuilding industry in the Far East Asia.

When the number of fatalities during the ship construction and dismantling is confronted with the number of casualties during the operation of ships, it visible that every average sized cargo ship may pose a much higher risk to life during construction than during the entire operation cycle of it. Because of lack of access to the confidential statistical data on deaths in shipyards, the author may only speculate on a relationship between the weight of steel used for construction of ships and the number of lives they have taken in shipyards. Since this number may be much greater than the number of casualties among seafarers, it is imperative that the recommendations to ship designers, such as the one presented in this paper, should not involve unnecessary increase in the lightweight of designed ships and optimize the subdivision of ship to provide most efficient allocation of steel watertight boundaries.

Ships are designed to maximize their capacity and efficiency and in the Adam Smith's model of economics it would not make much sense to design and build cargo ships for any other reasons. In order to maintain safety standards, rules are imposed on the designers to stay in certain boundaries in their pursuit to maximize cost efficiency regardless of costs to life and environment. In order to address it, one must first introduce a knowledge based regime on the design. First and foremost, the statistical evidence clearly show the frequency of serious accidents at sea and from this data the significance levels for safety can be derived. As there is no rational reason why different ship types are subjected to different levels of risks of colliding or grounding, the population of different types of ships was taken into consideration.

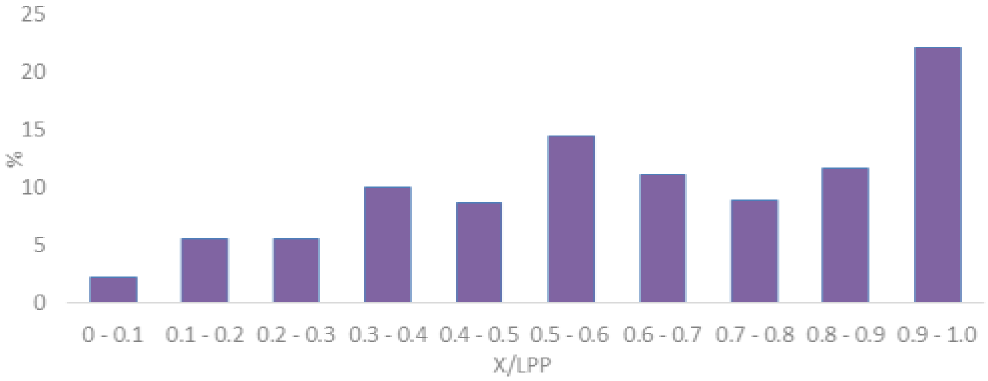


Figure 39. Damage location for collision damages according to GOALDS database [8]

Statistical records show that in the years 1990 – 2012 there were 2271 grounding incidents and 7598 of other different collisions. In that period the total amount of ship-years [65] was 602998 [65]. Assuming an average lifespan of a vessel is 25 years, there is a nearly 10% probability that any given ship will run aground at some point in its life, and a 31.5 % will face a serious accident related to either machinery, collision or hull breach are observed. with the length of the ship divided in ten equal parts and with the assumption that a damage is sustained inside these parts, one may arrive at final figures of probability of flooding in these areas (for details see Point 7.5.9). These probability figures remain relatively high in all areas of the ship. Figure 39 shows that different importance factors towards different area of the ship assigned (as it was made in regulations A.265 and SOLAS 90) cannot be fully justified in the light of this new statistical data. Furthermore, the increased value of probability assigned to the most-aft and most-forward area considered for flooding (as in the current regulation) cannot be justified either.

Further, assessment of energy absorption of a structure subjected to force seems to be an overwhelming task. Numerous attempts have been made to make analysis of a structure response to an impact [16, 41, 66, et al]. All these attempts neglected the fact that the structure of the vessel along with thicknesses of plating varies in different areas of the vessel (e.g. tug area, thicknesses for Ice-Class etc.). Without knowing where the damage was sustained, any investigation of all the possible scenarios of structure response is a very difficult and time consuming task.

The author is of the opinion that because of various possible reasons of collapse of hull integrity, the best way of identifying the vessel safety in such emergency situations is to learn exactly what a ship’s stability and floatability are after a possible (envisaged) hazard takes place. Having sufficient information on behavior of the ship during an emergency, officers onboard can make best decisions possible and so give priority to safety of lives, environment and property.

7.5.3 Position of a damaged compartment

There is no clear statistical evidence (see Chapter 7.5.2) and no analytical proof that there is an increased probability of a collision in any part of the ship in its length (apart from the most-forward compartment - this scenario addressed in the requirements of ICLL 66/88 on installation of collision bulkheads). As a consequence the author proposes to apply an even significance factor to any longitudinal position of a damage and control the risk arising from emergency with use of risk acceptance criteria [e.g. 31].

7.5.4 Size of a damaged compartment

Extensive research on the applied size of a damage has been made in the past as well and currently valid regulations utilize a lot of knowledge and data gathered during this research [2, 6, 9, 20, 67]. In reality, the probability of e.g. flooding any tank adjacent to the outer-shell is always bigger than the probability of flooding tanks away from the outer-shell. As presented in Chapter 3 of this paper, this was reflected in the current regulations. However, in the current regulations this increased probability is not directly related/linked to risk and possible consequences from flooding of these compartments resulting with a possibility of catastrophic consequences from flooding of even a potentially small tank, for which the flooding probability is relatively low and even if the tank is located close to the outer skin of a ship. Furthermore, and as it was discussed in Chapters 3 and 4 of this paper by introducing the Required Subdivision Index, the possibility of catastrophic consequences is not eliminated or controlled by current regulations. To address this issue, the author is of opinion that it is necessary to investigate all the large tanks (e.g. >1% of displaced volume) in terms of their impact on stability regardless of statistically derived probabilities and apply our knowledge about the likelihood of event happening at the risk control stage.

7.5.5 Geometry of a damaged compartment

The geometry of tanks when flooded has a significant influence on their impact on stability. The current industry standard stipulated by regulations is to assess direct reduction of buoyancy and free surface effect from water inside of the flooded tank(s). In order to account for time -dependent process of flooding [6, 9, 20] and changing geometry of tanks in vertical direction, some regulations also require the intermediate stages of flooding to be assessed [6, 9, 20], but again from the two mentioned above factors perspective only.

In reality , the mechanism of flooding is far more complex and it impacts stability of a vessel in the following ways:

- Reduction of buoyancy due to flooding
- Free surface effect
- Sloshing inside of tank(s) effect
- Change of floating position

The time dependency of tank flooding process introduces a risk of mistake in evaluation of condition of it. Flooding of a tank will depend on many different factors which are difficult to assess by crew onboard a ship at a time of incident. Furthermore, mathematical models that govern cushions in tanks and the flow of water through openings at ship position varying with movement would be difficult to apply and use in practice. The author is of the opinion that any given tank should be assessed in terms of risk to stability and floatability it induces.

In the presented method the calculation is therefore based on seeking the largest negative impact that flooding of each tank may have on stability and floatability of the vessel. Consequently, for some tanks it is the reduced buoyancy, for other tanks the free surface effect and for yet another group of tanks it may be the combination of the two. The impact of sloshing for majority of tanks and spaces onboard is relatively small, but for relatively large tanks should still be assessed as to their number and then added to the final result. Different methods may be applied to calculation of sloshing effect. The author has chosen to apply a Monte Carlo analysis for many different shapes and sizes of tanks as well as initial ship stability parameters (see Chapter 10 for details).

7.5.6 Initial floating condition of a vessel

Traditionally, the initial floating condition of a vessel is described by the following factors:

- Righting arm curve (restoring moment)
- Initial metacentric height

In more detail, movement of any ship on water is governed by more properties or properties that influence the two mentioned above factors. A prudent designer will consider the following parameters governing stability and floatability of any vessel.

- Position of center of buoyancy of a ship
- Position of center of gravity of a ship
- Mass/Weight distribution of a ship
- Hull and appendages size and geometry.
- Floating position (draught, trim and heel)

Currently, apart from detailed mass distribution around the longitudinal center of gravity axis and the geometry of hull appendages, all the parameters are examined for the purpose of intact stability and damage stability assessments. The hull appendages (if present) missing parameters may be easily taken from the structural drawings of any ship, the distribution of mass around the longitudinal center of gravity axis is very difficult to determine, but luckily it oscillates within a certain narrow range [68, 69]. In practice, an approximate formula is used to determine this value called Weiss formula (24).

$$T_N = \frac{\sqrt{g*GM}}{2*i}; \qquad i = \sqrt{\frac{I_{xx}}{\Delta}} \cong 0.4B \tag{24}$$

7.5.7 Quantity and type of cargo on-board

Any cargo vessels' vulnerability to flooding depends also on the cargo it carries. Various cargo has a different reaction when in contact with water. Some cargo absorbs water (some grains) some provides additional buoyancy to the vessel (e.g. timber). For example at this very moment guidelines are published how to treat additional timber on deck cargo in terms of stability. However, these guidelines to be used in conjunction with SOLAS 2009 are seldom followed in practice because of computational difficulties. The impact of cargo does not only have direct impact on stability, but also influences vessels' moment of inertia around the center of gravity longitudinal axes. Currently no rule or regulation obligates designers to check or assess this impact as no rule or regulation requires checking the mass moment of inertia around the longitudinal axis going through the center of gravity of a ship in general.

Additional impact of type and cargo is its potential threat not only to stability and hence hazard to life, environment and property, but also to other safety aspects. Some cargoes are highly toxic, radioactive or highly flammable imposing enormous threat to a ship and even more so the environment and must be assessed to determine risks of carrying them onboard.

The author is of opinion that this assessment may be made on the basis of the available Codes (Such as CSS [70]) which describe levels of risk from carrying different types of cargoes. In addition this may further be confronted with cargo risk mitigation systems (such as fire extinguishing systems) available on-board an assessed ship. The calculation process of this aspect is presented in Chapter 11 and may be afterwards controlled with Risk Control Criteria [e.g. 31].

7.5.8 Response of a vessel to damage

Any given vessel will have different responses to identical external hazards. In case of hull breach the governing factor for vulnerability of a vessel is its ability to return to an upright position, minimize the roll angle to a value in which it is still possible to navigate a ship and her weather-tight openings are not submerged and to maintain sufficient floatability. In different rules and requirements different approaches to assessing this response were utilized. In the ICLL 66/88 [4] one selected representative condition is assessed; MARPOL 78 [67] requires all approved intact loading conditions to be checked and SOLAS 2009 [6] obligates the designers to check stability of a vessel in 3 loading conditions as described in Chapters 2 and 3 of this work.

The author selected one condition (as in ICLL) for checking may be a valid solution to a problem of complexity in this aspect of the current regulations. This condition similarly to the ICLL 66/88 is equivalent to a vessel at its minimum allowable freeboard and with the initial stability parameters corresponding to the lowest approved intact GM value. However, when using this approach there is a risk of not taking into account some conditions with different trim or different loading configuration. To address the above an additional concept of a theoretical floating condition with maximum allowable trim aft and maximum allowable trim forward was introduced. Such theoretical condition will have a lowest approved intact GM assigned. With these assumption the risk of omitting an approved condition which may offer less stability/floatability margin than the one selected is greatly reduced and for the met in practice hull shapes adequately addressed.

The response of the ship in the above described condition to a damage will depend on the flooding of compartments. Any given damage will result with flooding of one or multiple compartments. Consequently, any flooded compartment will have a certain impact on behavior of the ship. This impact depends on the following parameters:

- Position of a tank against centers of gravity and buoyancy
- Size of a tank
- Geometry of a tank
- Initial content of a tank (or lack of content)
- Parameters of a ship movement

The impact of flooding of any given tank or combinations of tanks on the behavior of a floating object may then be calculated. The author decided to utilize Computational Fluid Dynamics software OpenFOAM to calculate the interaction between the fluid in tanks and hull in waves. Another Monte Carlo simulation was performed to establish impacts of different parameters of tanks on different parameters of ship. The calculation method is presented in more detail in Chapters 8, 9 and 10.

7.5.9 Consequences of hazard occurrence:

As presented in multiple studies and supported by statics [8, 11, 12, 34, 71], the most common and critical hazards to safety of ships are listed below:

1) Grounding
2) Hull damage
3) Machinery damage
4) Contact/foundering/collision
5) Fire/explosion
6) Pollution

Reasons 1 to 5 constituted 99.3% of all serious accidents between the years 1990 and 2012 (when only the ships built after 1980 are considered) [34]. The percentage contribution of each type of hazard is summarized in Table 5.

Grounding	20.95%
Hull/Machinery Damage	37.12%
Contact/Collision	32.97%
Fire/Explosion	8.26%
sum:	99.30%

Table 5. Percentage breakdown of serious accidents as per the IHS definition [34]

	Total loss	Serious accidents	No. of fatalities	Population in shipyears	Population in shipyears (%)	Serious accidents (%)	Difference (%)
General Cargo	502	4114	1434	174544	43.12%	47.58%	4.46%
Bulk Carriers	99	1951	381	88807	21.94%	22.57%	0.62%
Ro-Ro Cargo	29	230	29	7839	1.94%	2.66%	0.72%
Reefer	20	303	71	17086	4.22%	3.50%	-0.72%
Container Ships	11	1235	65	55814	13.79%	14.28%	0.49%
Car Carriers	10	227	17	8476	2.09%	2.63%	0.53%
LPG/LNG	8	211	26	17586	4.34%	2.44%	-1.90%
Oil Tankers (large)	1	375	58	34596	8.55%	4.34%	-4.21%
Sum:	680	8646	2081	404748			

Table 6. Table showing the apparent relationship between the "ship-years" of each type of ship and number of serious incidents [11,12,34].

It is important to differentiate between serious accidents and ship losses. The definition of serious accidents is determined by the IHS:

"A marine casualty to a ship, as defined, which results in: Structural damage, rendering the ship unseaworthy, such as penetration of hull underwater, immobilization of main engines, extensive damage, etc. /breakdown/ actual total loss/ any other undefined situation resulting in damage or financial loss, which is considered to be serious." - [34 – IHS]

Most recent statistics data [e.g. 34] reveal a correlation between serious accidents and the number of "ship-years" regardless of ship types. This is opposite to the loss of ships and/or number of fatalities which seem to be governed by more complex relationship (Table 6), but also that the LPG/LNG and Large Oil Tankers (over 60000 DWT) show lower numbers than other types of ships of serious accidents in comparison with the "ship-years" number One may speculate about the reasons of a lower percentage of serious accidents to "ship-years" ratio for LNG and Oil Tankers. One of the possible reasons is that these ships are governed by different construction regime (e.g. MARPOL [57]) than other types of ships investigated. Regardless of the reason behind this difference, these types of ships were excluded from the statistical evaluation of a database. Consequently, by introducing a mean average for all remaining ship types it was determined that any ship is subjected to a risk of being in a serious accident equal to 2.29% per year. Assuming the average life of any ship of 25 years the chances of any vessel being in a serious accident during its life increase to 57.15%. The serious accidents taken into equation here were listed in Table 5.

From the above assessment of risk and hence consequences, the author concludes that it is essential to address all the hazards listed in Table 6 and risks of serious accidents that lead to damage to property, environment and loss of life without prioritizing any of them.

7.5.10 Risk control

There is limited statistical data on the length of time that a vessel carries dangerous cargo. For the sake of uniform and unbiased assessment, constant factors may be applied to all types of vessels designed to carry a cargo that is potentially valuable or dangerous to life or property. Such control, with use of constant coefficients may also be made prior to any voyage. Similarly, a threat of cargo fire emerging was quantified. For cargo ships, the risk of cargo fire is substantial [34] and must be addressed by design and careful operation. Current requirements and guidelines, when followed, greatly reduce the risks, but are separate from a general notion of safety and/or stability in intact and emergency conditions. Furthermore, a risk of cargo fire must be evaluated in terms of its potential consequences which are different from the consequences of loss of cargo, or ship damage. The proposed method of calculation is presented in the Chapter 8 of the paper.

The control of risk may also take place by confrontation with the statistical data of accidents at sea. The method may be based on Probability Density Function as introduced by Pawlowski [19] and Luetzen [16] and implemented into SOLAS 2009 [6]. From the latest statistical data gathered and filtered from the GOALDS [7,8] and HARDER [2] programs, a minimum requirement for any vessel and a safety goal was determined. For the method presentation purpose, the minimum requirement was set to provide a vessel with certain positive stability and floatability after damage is sustained at any compartment or compartments of length 14.5 meters, transverse extent of maximum breadth of vessel divided by five and vertical extent from keel to deck (in this case 16.0 m). This goal was set to provide a vessel with sufficient stability after a damage sustained anywhere in vessel's length.

8. Physical model of behavior of damaged ship in ocean environment

In this paper, a model which separates different mechanisms governing roll motion of the ship in waves was introduced. The analytical model presented here has its roots in W.E. Cummins work [72] and is used as one possible way of obtaining necessary parameters.

8.1 Assumptions

The analytical model is chosen for calculations of behavior of hulls and the "strip-theory" was applied. Therefore, standard for "strip-theory" method assumptions apply [73 – 75]. In order to accurately model the behavior of a ship on waves a set of assumptions was made applicable:

1) The pressure under the wave-crest is modelled with the use of hydrostatics
2) The evaluated objects have a large L to B and L to H ratios (more than 4) and are symmetric.
3) Motion amplitude is small so that equations can be linearized [76]. This means that damping coefficients and added mass coefficients are constant in time/frequency and that motions of a ship can be calculated separately with minimum error to the results introduced (quasi-dynamical approach).
   (This assumption will cause an error in calculations, but as evaluated in multiple studies [e.g. 77], the final values are not very far off the actual values and may be considered a good approximation)
4) The motions that have a decisive impact on survivability of a ship in waves are the motions that impact the vertical position of weather-tight openings or deck lowest

point in the weather conditions and are roll, sway, pitch and heave. Consequently, the stability of a ship can be accurately described by determination of the damping and added mass coefficients for the following motions: roll, sway, sway coupled with roll, heave and pitch only.

5) The waves are non-directional and of single periodicity. (This is not the case at sea, however for the purpose of finding parameters of submerged parts of hull the directional nature of waves was neglected)

8.2 Coordinate system

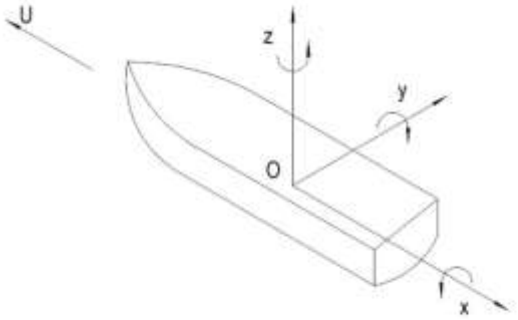


Figure 40. Selected coordinate system [78].

The right-handed system of coordinates [78] is fixed with the center of gravity of the ship and its origin set at a waterline level. Axis Z goes through the center of gravity. Though selection of this model introduces some complexity to the mathematical model, it allows for a good presentation of results.

8.3 Static components in motion equation

In order to account for the motion coupling effects, the proposed method initially considered all six degrees of freedom. It is a commonly used method to split motions into two categories which are treated differently. The first category group contains the heave and pitch, and the second one contains yaw, roll and sway motions. For the first two motions, the method linearizes motions with respect to the wave amplitude. Because the method is used to derive ships' righting ability and floatability parameters and because it utilizes the strip theory for calculations, the coefficients for the two degrees of freedom (surge and yaw motions) were simplified to constants. For the applicable cases, the surge motion is taken into account as an input from the external forces (from waves, wind and sloshing). The roll motion component shows a significantly non-linear behavior with respect to the wave amplitude. The obvious reasons for this behavior are large amplitudes of this motion on the one hand, and quickly changeable parameters governing this motion, on the other. With this in mind, separate assumptions for calculations for the two groups were used and the results were added to each other after recalculation to time domain and with use of the superposition principle. All the motions are computed in frequency domain. The roll motion is calculated at shorter steps to account for the larger amplitudes of motion.

The general equation governing a 6 degree of freedom ship motion can be presented as below, and further simplified and divided into the static and dynamic components (25) [78,79,80].

$$\sum_{k=1}^{6}\left[\left(M_{jk}+A_{jk}\right)\ddot{\eta}_k+B_{jk}\dot{\eta}_k+C_{jk}\eta_k\right]=F_j e^{i\omega t}+F_E \xrightarrow{simplified\ to}$$

$$\left\{\begin{bmatrix} M & 0 \\ 0 & I_y \end{bmatrix}+\begin{bmatrix} A_{33} & A_{35} \\ A_{53} & A_{55} \end{bmatrix}\right\}\ddot{\eta}_u+\begin{bmatrix} B_{33} & B_{35} \\ B_{53} & B_{55} \end{bmatrix}\dot{\eta}_u+\begin{bmatrix} C_{33} & C_{35} \\ C_{53} & C_{55} \end{bmatrix}\eta_u=\begin{bmatrix} F_3 \\ F_5 \end{bmatrix}e^{i\omega t}$$

$$and$$

$$\left\{\begin{bmatrix} M & 0 & -Mz_c \\ 0 & I_x & -I_{xz} \\ -Mz_c & -I_{xz} & I_z \end{bmatrix}+\begin{bmatrix} A_{22} & A_{24} & A_{26} \\ A_{42} & A_{44} & A_{46} \\ A_{62} & A_{64} & A_{66} \end{bmatrix}\right\}\ddot{\eta}_v+\begin{bmatrix} B_{22} & B_{24} & B_{26} \\ B_{42} & B_{44} & B_{46} \\ B_{62} & B_{64} & B_{66} \end{bmatrix}\dot{\eta}_v+$$

$$\begin{bmatrix} C_{22} & C_{24} & C_{26} \\ C_{42} & C_{44} & C_{46} \\ C_{62} & C_{64} & C_{66} \end{bmatrix}\eta_v=\begin{bmatrix} F_2 \\ F_4 \\ F_6 \end{bmatrix}e^{i\omega t}+\begin{bmatrix} F_E \\ M_E/Z \\ M_E/X \end{bmatrix}e^{i\omega t} \quad (25)$$

The dynamic components are represented by M_{jk}, A_{jk} and B_{jk}. The static components of ship motion are described by C_{jk}. In the equation for heave, pitch and yaw motions, the static coefficients are determined by the following equation (26,27,28). (Static components of a simplified ship motion equation for heave and pitch [79,80]:

$$C_{33}=\rho * g * \int b\, dl_s = \rho * g * A_{WP} \quad (26)$$

$$C_{53}=C_{35}=-\rho * g * \int b * l_s\, dl_s = -\rho * g * \left(z_{LM}-z_G\right) * A_{WP} \quad (27)$$

$$C_{55}=\rho * g * \int b * l_s^2\, dl_s = \rho * g * I_{WPy} \quad (28)$$

Static components of a simplified ship motion equation for roll and sway [78]):

$$C_{44}=\rho * g * \nabla * \left(z_M-z_G\right) \quad (29)$$

$$C_{22}=C_{24}=C_{42}=C_{26}=C_{46}=C_{66}=C_{64}=C_{63}=0 \quad (30)$$

The static component of the restoring force for heave (C_{33}) is called Restoring Spring Coefficient, and in the given environment, depends solely on the area at the waterline of the submerged hull (“image” of submerged hull on an imaginary horizontal plane).

The static components of the restoring forces for pitch and coupled motions of pitch and heave are called stiffness coefficients and are functions of longitudinal metacentric height, water plane area and moment of inertia of the water plane area around the y axis. There are no restoring forces for the sway and yaw motions and hence, the remaining coefficients C_{xx} are equal to zero.

8.4 Dynamic components in motion equation

Derivation of dynamic components is a difficult task and numerous attempts have been made in the past to increase the accuracy of the obtained coefficients

Still, the common practice remains to validate analytical/numerical simulations with tests in the ship model basin. For the purpose of this method a derivation technique has been utilized with great focus on eliminating the risk of overestimating these coefficients and limiting the complication of the calculations.

Coefficients M_{jk}, A_{jk} and B_{jk} from equation (25) depend on time and position of the vessel in relation to the sea surface. M_{jk} is called the generalized mass matrix of a ship. The M value is the mass of the ship and remains constant when afloat. Mz_c components (see 25) are related to the acting of mass on the acceleration in a motion in given coordinate system. Given the selected coordinate system at the waterline, the value of z_c is the value of vertical position of the center of ship mass against the origin of the coordinate system. The I_y, $I_{x,}$ $I_{z,}$ I_{xz} are the values of moment of inertia around the respective axis.

The A_{jk} is called added mass coefficients matrix and directly reflects the dynamic force acting on the structure that is caused by the pressure field of the fluid being forced to oscillate by the moving structure. The added mass in the four motions taken into account is governed by the shape of the submerged body, frequency of motion and naturally the size of the submerged body. It is not an easy task to accurately predict the values of added mass coefficients, however alternative methods, such as the close-fit Frank method, which were proven to offer good accuracy [79,81 – 85] may be used. For example, for the derivation of necessary coefficients, a hydrodynamic model may be applied to various range of “mid-ship sections” as well as mass parameters then transferred into a three dimensional model with the use of strip theory. Selected values of the added mass coefficients and damping coefficients for the cross sections in question can then be presented in graphs like the on Figure 41 [79].

The common difficulty in utilizing the close-fit method for calculations of dynamic components is ensuring good correlation for various transverse section shapes. Instead of the usual application of Ursell-Tasai’s [91] method with 10-parameter close-fit conformal mapping (which is very time consuming), the author proposes to use the statistical correlation between the results for various hull geometries and estimate the results for individual shapes on the basis of the length of the cylindrical section and/or block coefficient (at scantling draft) value. Verification of such approach included numerical calculation for various sizes and calculations for cross sections of various shape (see Chapter 10 for summary details). (Note: In addition, because of the symmetry around the X-axis of ship underwater geometry, the transverse and longitudinal motions are decoupled). For practical calculations, a standard recommended by ITTC method for estimation of roll damping was utilized [86] and further evaluated with the method described by Kawahara, Maekawa and Ikeda [87]. Components for movements in other directions come from the generally known formulas [78,79]. The roll movement is more sensitive to the forces that cause it and hence, in order to model it accurately, it was divided into components presented in equation 31.

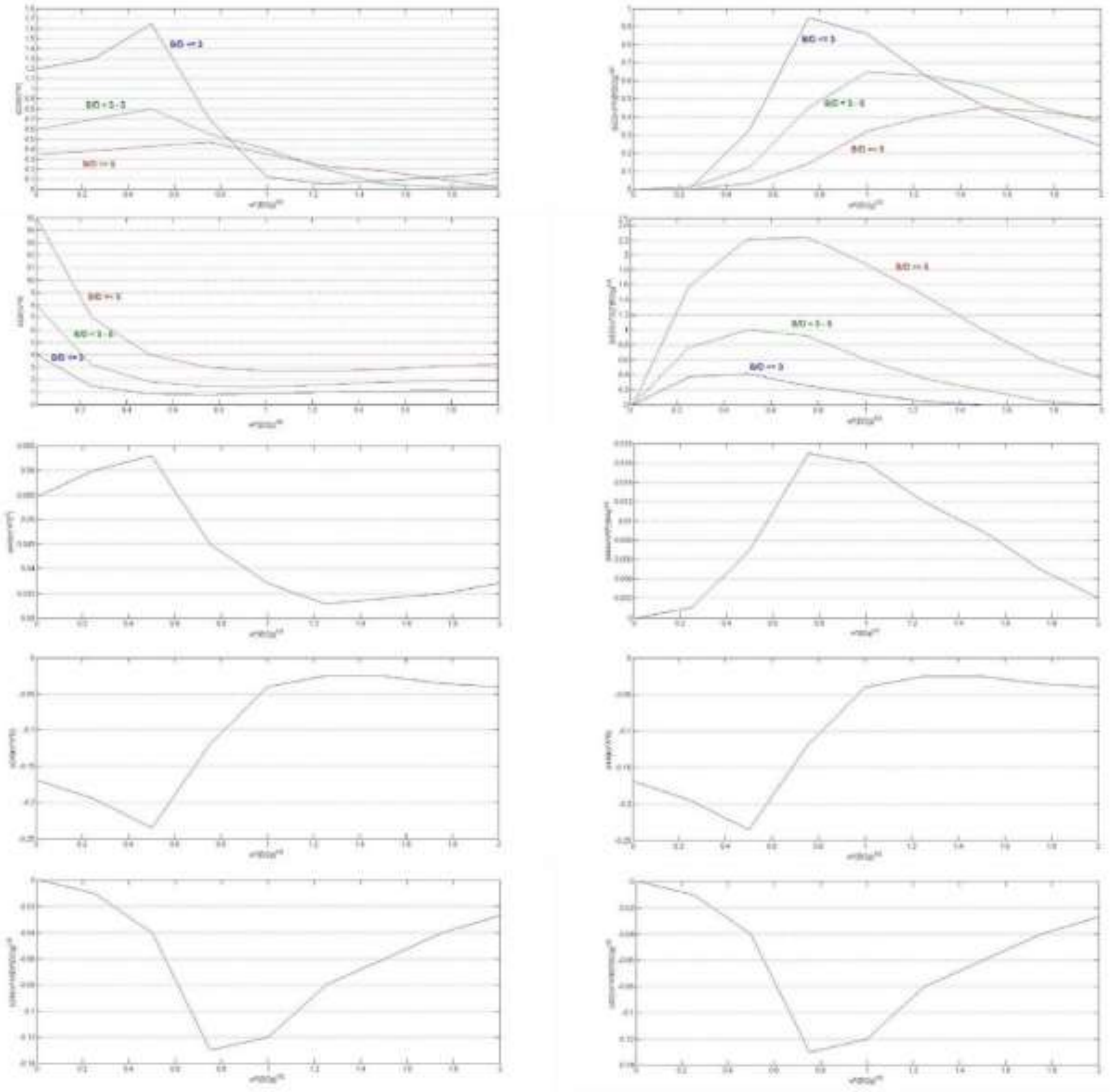


Figure 41. Two dimensional damping and added mass coefficients for the mid-ship cross section of the calculated theoretical hull form and floating condition.[77,79,82]

$$B_{44} = B_{44W} + B_{44L} + B_{44F} + B_{44E} + B_{44APP} \qquad (+ B_x) \tag{31}$$

The B_{44W} is a coefficient described as wave making coefficient. The wave component for a two dimensional cross section is calculated by potential flow theory. A calculation of the damping coefficient in sway motion for a given hull form is needed. Since the longitudinal section of a ship can be quite accurately and relatively easily approximated by analytical formulas, calculation of the wave making component at zero speed may be then performed by multiplication of this coefficient times the roll lever (32) [86].

$$B'_{44W0} = B'_{22} * (l_w - \overline{OG})^2 \tag{32}$$

The ITTC [86] also provides a recalculation method for the wave making component at different speeds. It is important to underline that this component of damping for big ocean-going cargo ships is relatively small in comparison with other components.

The B_{44L} is a lift making component and must be added to ships moving forward and with a sway motion. It is described mainly by speed, size of the vessel and the position of center of gravity of the ship (33) [86].

$$B_{44L} = \frac{\rho}{2} V L d k_N l_0 l_R \left(1 - 1.4\frac{\overline{OG}}{l_R} + \frac{0.7\overline{OG}}{l_0 l_R}\right) \tag{33}$$

The B_{44F} is a frictional component and at zero speed can be derived from the well-known Kato's formula. The Kato's formula describes this coefficient as (among others) a function of area, viscosity and surface friction. ITTC proposes another calculation formula for ships moving at constant speed forward (34) [86].

$$B'_{44F0} = \frac{4}{3\pi}\rho S_f r_f^3 \varphi_a \omega_E C_f \tag{34}$$

The B_{44E} is an eddy making component (35) [86] and comes from the sectional vortices. It's relation to the hull shape was described by half breadth to draught ratio and area coefficients. These were used in this paper as well and are considered industry standard. This coefficient is further recalculated if the vessel is moving at a given speed.

$$B'_{44E0} = \frac{4\rho d^4 \omega_E \varphi_a}{3\pi} C_R \tag{35}$$

The B_{44APP} is additional resistance coming from appendages such as bilge keels and rudders. It is of uttermost importance to underline that in the current methods of evaluation on ship safety the roll damping effect induced by hull appendages is not taken into account in any way. All external hull appendages have some impact on the behavior of a ship. In the method proposed in this paper for identification of physical parameters that have a decisive impact on safety of ships in damaged conditions only the bilge keels are considered. The reason for selecting the bilge keels is that their area is usually the greatest and that they are specifically designed for the purpose of reducing ships roll movement. Their impact must be therefore taken into account. The methodology for calculation of the effect from bilge keels is taken directly from the recommended components by ITTC guidelines. The B_{44APP} coefficient (with respect to bilge keels) can be divided into four components (36) [86].

$$B_{44APP\,(BK)} = B_{44KN0} + B_{44BKH0} + B_{44BKL} + B_{44BKW} \tag{36}$$

It has been found that apart from rather a complex polynomial calculation methodology, the final bilge keel damping coefficients depend solely on the following parameters:

- Breadth of bilge keel
- Position of center of gravity

- Draught of the vessel
- Prismatic coefficient
- Amplitude of motion
- Period of motion
- Angular speed

Furthermore, it has been found that the components B_{44BKL} and B_{44BKW} have a marginal impact on the final value of the sum from equation 36. In the practical range of the parameters listed above, the impact from B_{44BKW} representing the wave making impact is negligible for two reasons. First, as described in Chapter 7, the criterion for acceptance of vessel response in waves is based on the condition of submerging of freeboard. When applying a two dimensional strip method and at fully laden draught, it is clear that for a practical range of vessels submerging of freeboard will appear well in advance of the emerging of bilge keels from water. Furthermore, this component remains small in relation to the B_{44BKN0} and B_{44BKH0} even if the bilge keels emerge from water. In all cases investigated for the purpose of this work this component remained below 1% of any of the B_{44BKN0} and B_{44BKH0} components. Secondly, the lift making component B_{44BKL} is only applicable when the vessel is moving forward. However, and as stated in the guidelines from ITTC [86], the effect of this component is often omitted and starts to play a bigger role for vessels moving at high forward speeds. In the current economic environment, these are very unlikely to be attained for cargo carrying vessels. For this reason, this component was also neglected. The calculation of the damping coefficient for each two dimensional strip does not take place in time domain; it is solely dependent on the input parameters from the calculations without these appendages. In other words the output movement parameters of an investigated shape without bilge keels are treated as input parameters for the equations for calculation of the damping effect from these appendages.

The B_x component of equation 31 is an additional component that is not included in the original ITTC recommended procedure and represents a change in damping parameters arising from flooding of a compartment. This effect has been studied in the past [88, 89, 92] and it was found that though it cannot be easily quantified as it is a result of fluid changing the behavior of the entire object and vice versa, the moment from sloshing on final motion increases almost linearly with an increase of the amplitude of motion and hence, the impact on total roll damping coefficient (percentage-wise) decreases with roll angle and remains relatively small for large roll amplitudes above 5 degrees.

In addition to the damping coefficients, the added mass in roll motion (A_{44}) may be approximated by a function of investigated section area, draught and distance between the center of buoyancy and gravity of moving hull (37) [77,78].

$$A_{44} = \rho A\left(\frac{d^3}{12} + d\overline{BG}^2\right) \tag{37}$$

In the case of a damaged ship, additional mass of water that enters the hull must be considered. This leads to a change of the differential movement equation (38) in such a way that an additional mass is added to the mass of an object. Furthermore, the static coefficient C_{44} must also be amended to reflect the new initial condition of a vessel.

8.5 Excitation forces

It was found that the change of the initial condition of the vessel after tank flooding may be represented by an excitation force added on the right side of the equation (38).

$$F_S = (-M_x - A_x)\ddot{\phi} - B_x\dot{\phi} - C_x\phi \tag{38}$$

$where:$

$$\phi = Ae^{i\omega t}$$
$$\dot{\phi} = i\omega Ae^{i\omega t}$$
$$\ddot{\phi} = -A\omega^2 e^{i\omega t}$$
$$F_S = A_F e^{i(\omega t+\varphi)}$$
$$-(M_x + A_x) = Re\left(\frac{A_F e^{i(\omega t+\varphi)} - C_x A e^{i\omega t}}{\omega^2 A e^{i\omega t}}\right) = Re\left(\frac{A_F e^{i\varphi} - C_x A}{\omega^2 A}\right) = \frac{A_F \cos(\varphi)}{\omega^2 A} - \frac{C_x}{\omega^2}$$
$$B_x = Im\left(\frac{A_F e^{i(\omega t+\varphi)} - C_x A e^{i\omega t}}{\omega A e^{i\omega t}}\right) = Im\left(\frac{A_F e^{i\varphi} - C_x A}{\omega A}\right) = \frac{A_F \sin(\varphi)}{\omega A} - \frac{C_x}{\omega}$$

$where:$

$A_F - Force\ amplitude$
$A - Wave\ amplitude$
$\omega - Wave\ frequency$
$t - Time$
$\varphi - phase\ angle\ (lag)$
$C_x = I^x * \rho^x * g$

The other excitation forces modelled are the forces from waves. Prior to modelling these forces, a goal-based approach is applied to this process. As highlighted in Chapter 5 of this paper, the goal the author wanted to attain while doing this research was to develop a method that provides sufficient information not only for designers, but also for the Masters on board ships. Masters on board do not measure the wave period and also have a limited ability to measure the strength of wind. The well-known and common practice is to measure the significant wave height. The significant wave height ($H_{1/3}$) is by definition “the mean wave height (trough to crest) of the highest third of the waves” [90] and is measured by an experienced crew on-board with the naked eye. The consequence of this is that the crew on board may relatively easily observe the height of waves, but not their period. When evaluating ocean waves’ statistics for the purpose of determining the risks for ocean going ships in shape of a harmonized method, the range of periods of waves must be evaluated.

The purpose of the calculation was to find the factors that are most conservative and hence allow for the evaluation of the forces potentially dangerous to ship survivability, roll movement and floatability. In order to achieve this, the statistical correlation between significant wave heights and the wave periods was brought into a two dimensional shape (Figure 42).

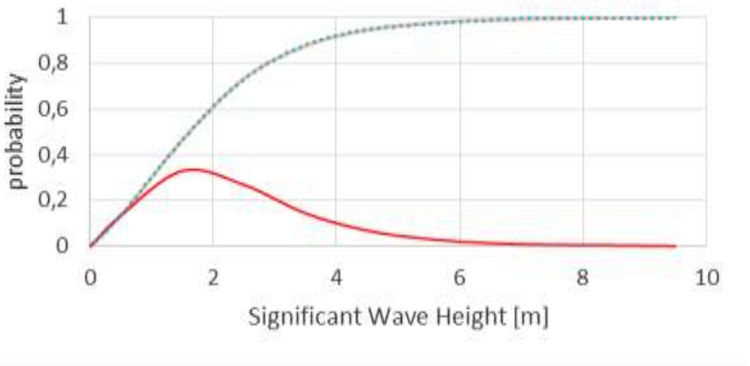


Figure 42) Example probability density function of the significant wave height on the basis of statistical data for the World Wide Trade. [71]

The probability values of wave height may have a very different impact on safety of ships depending on the shape of waves and their period. Therefore, to select just one most probable wave period is considered a very inaccurate approximation. For the purpose of this paper, the author investigated the range of all the periods of waves for waves of significant height up to 4 meters (Probability of which is estimated at more than 0.91).

The forces from waves in the frequency domain calculation model were divided into Froude-Kriloff forces and moments and diffraction forces, and in strip theory, may be presented as integrals for each investigated strip (39, 40).

$$\begin{bmatrix} F_2 \\ F_4 \\ F_6 \end{bmatrix} = \begin{bmatrix} \int f_{2FK}(x) + f_{2D}(x)dx \\ \int f_{4FK}(x) + f_{4D}(x)dx \\ \int (x * (f_{2FK}(x) + f_{2D}(x)) - U * a_{22}(x_{mean})v)dx \end{bmatrix} + \begin{bmatrix} U * a_{22}(x_{mean})w \\ U * a_{42}(x_{mean})v \\ U * a_{22}(x_{mean})v \end{bmatrix} \tag{39}$$

$$\begin{bmatrix} F_3 \\ F_5 \end{bmatrix} = \begin{bmatrix} \int f_{3FK}(x) + f_{3D}(x)dx \\ \int (x * (f_{3FK}(x) + f_{3D}(x)) - U * a_{33}(x_{mean})w)dx \end{bmatrix} - \begin{bmatrix} -U * a_{33}(x_{mean})w \\ U * x_{mean} * a_{33}(x_{mean})w \end{bmatrix}$$

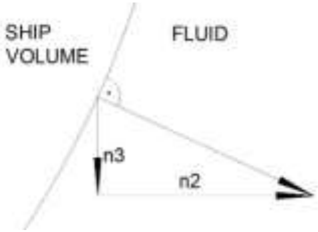
(40)

$where:$

$$f_{2FK}(x) = i\rho g\zeta_a \int n_3 e^{-ik(x\cos\beta + y\sin\beta)} e^{kz} dl$$

$$f_{3FK}(x) = i\rho g\zeta_a \int n_2 e^{-ik(x\cos\beta + y\sin\beta)} e^{kz} dl$$

$$f_{4FK}(x) = i\rho g\zeta_a \int n_4 e^{-ik(x\cos\beta + y\sin\beta)} e^{kz} dl$$



$n_4 = yn_2 - zn_3$

$f_{2D} = a_{22}(x)a_y + b_{22}(x)v$

$f_{3D} = a_{33}(x)a_z + b_{33}(x)w$

$f_{4D} = a_{42}(x)a_y + b_{42}(x)v$

$a_y, a_z, v, w - \mathit{initial\ accelerations\ and\ speeds\ approximated\ as\ per\ Salvesen}$ [77,78]

The accuracy of the model used (39, 40) depends on (among others) the panelization of the cross sections. If the panelization is accurate enough the, vertical and horizontal components of vector 'n' will be accurate; if however the panelization is not accurate or does not follow the geometry that may change rapidly at e.g. knuckles, the error may be large and difficult to control.

Another component that should be taken into account is the wind component. Up to date, it is common that a statistical correlation between the wave height and wind is taken for derivation of the wind speed. The author is of the opinion that confidence in this correlation may be greatly improved if the observation derived parameters of wind speed required for generation of waves of certain height are taken into account. Such parameters for ocean weather conditions may be derived from available literature [92 – 94]. The wind speed is then connected to each investigated "observed" wave condition. The wind force taken into calculations is assumed to be constant and may be applied to the lateral wind area of the vessel at right angle. Because the condition investigated is the one corresponding to a fully laden condition, this area should be with the cargo on deck if the vessel is intended to carry such cargo. In this paper the impact from wind was not directly calculated for the sake of simplification.

For the assumptions used for calculation of impact of flooding water. The investigation revealed that calculation of impact from any tank subjected to flooding provides information on vessels' restoring forces ability in countering this effect. The investigation revealed this impact may be further broken down into the following components:

- Should the size (for example length) of a tank be large, the water in tank will have a noticeable impact on initial stability and the weight of water in tank will have an impact on initial floating condition and center of gravity.
- The sloshing occurring in tank will add to the overall number of heeling moments acting on a ship.
- The shift of the center of gravity in tank will change the righting ability of a vessel (free surface effect).
- Other phenomena (such as air cushions) may be considered rare and at this stage were omitted.

In the case of practical application, the initial condition of a vessel after flooding of a tank may also be easily investigated and determined with the use of popular hydrostatic software or currently existing loading computer software installed on-board ships. Once the initial condition is known and the ship behavior is numerically calculated, the values of sloshing may be added to the right side of the movement equation (excitation forces), or in static terms as additional heeling moment. This, in most cases, will provide the most conservative result as only the constant static righting ability is considered. This may be done by application of the largest possible excitation force to the equation assuming that the direction of this force is always the same as that of the exciting force from waves (the worst possible scenario in terms of roll amplitude). This relationship becomes more complex when the impact on the behavior of the ship from sloshing in the tank is greater. However as practical application of this calculation of impact from sloshing shows (see e.g. Chapter 10), this sloshing force usually has a large impact if the initial heel angles are already large.

In order to accurately and efficiently calculate the discussed coupling effects between the motion of a ship and the fluid in a tank , the transformation can be divided into two stages:

1) Handling mass in tank.

The equation of motion with the mass of the fluid in tank “x” may be presented as below (41):

$$(M + A + M_x)\ddot{\phi} + B\dot{\phi} + C\phi = F_{ext} \qquad (41)$$

In this case only a static impact from the additional mass is taken into account

2) Added Mass and Damping

In order to address this impact and reintroduce it as a complex force acting on the movement of the ship, a force is added to the model on the right side of the equation (42).

$$F_S = F_{Sdynamic} - M_x\ddot{\phi} \qquad (42)$$

The presence of additional mass inside the vessel further influences the added mass and damping properties of the entire floating object. In order to simplify these calculations the model presented in equation (42) was brought to a static form (See Chapter 10 for details).

In order for the process to be efficient, the calculations must take place for all tanks onboard ship. Because this would be impractical a limitation to investigation of large tanks only (e.g. in terms of volume and/or area e.g. Volume > 1% displaced volume) may be introduced.

9. Detailed information on the presented calculation method

The probabilistic method described in Chapters 2, 3, and 4 consists of calculations of probability for collision factors and the conditional probability of survival of any of the investigated collisions. The author proposes to investigate tanks over a certain volume that may impact the righting abilities of the vessel to a noticeable extent. Then, any tank must be investigated as a separate body entailing a certain risk. The diagram showing the proposed calculation method is presented in Figure 43.

In order to present the methodology applied in more detail, the following programs (modules) must be described:

- The program for hull generation. (see Appendix 2)
- Random freeboard numbers range generator
- Applied strip method model for excitation forces calculation

9.1 Identification of parameters responsible for behavior of intact ship on waves

It was found from the investigations presented in Chapters 7 and 8 that for cargo ships of wide range of geometrical and mass parameters the response of the object may be accurately estimated with approximation formulas. The excitation formulas, however, must be calculated directly in the potential (or time) domain. If the strip method is applied, a generation of set of geometries is required that will be subjected to investigated excitation forces. A program was written in Matlab (see Appendix 3 for details) that allows for fitting the basic geometrical parameters to a complex set of geometries with a very limited number of assumptions [86, 87].

Statical and dynamical coefficients	Variables
Friction Damping Coefficient	C_B, d, B, OG, BG, A, (V, ω_e, L_{pp} – at speed)
Wave Damping Coefficient	C_B, d, B, OG, ω_e, $C_M(C_B)$
Lift Damping Coefficient	V, OG, B, d, L
Eddy Making Damping Coefficient	C_B, d, B, OG, ω_e, L_{pp}, $C_M(C_B)$, $\nabla(L_{pp},B,d,C_B)$, φ_a
Bilge Keel (Appendages) Damping Coefficient	C_B, d, B, OG, A, ω_e, φ_a, l_{bk}, b_{bk}
Added Mass Coefficient	$A(B,d,C_M)$, d, BG
Hydrostatical Coefficient	OG, $\nabla(L_{pp},B,d,C_B)$
Excitation forces from flooding coefficient	L_t, B_t, H_t, OG_t, T_p,

Table 7. List of hydro-mechanical coefficients and factors on which they depend.

The response of the hull to excitation forces (roll movement) may be presented as a function of several basic ship parameters (Table 7). From the author’s experience in calculating dynamic motions of different ships an idea arose to generate a series of hulls which would closely fit the parameters of most standard cargo ships. For this work, the program for the hull generation is based on Taylor Hull series 60 with some minor modifications to the original shapes from this series [95, 96]. These modifications took place to more fully describe the geometries and consider more modern geometries with, for example, bulbous bows forward. In this study, only single screw ships were considered. The program was written in Matlab 2014 software (See Appendix 2).

For the purpose of verification, some calculations were made for selected geometries of ships. The geometry included in this paper is that of the vessel of "Szczecin II" type (Figure 44).

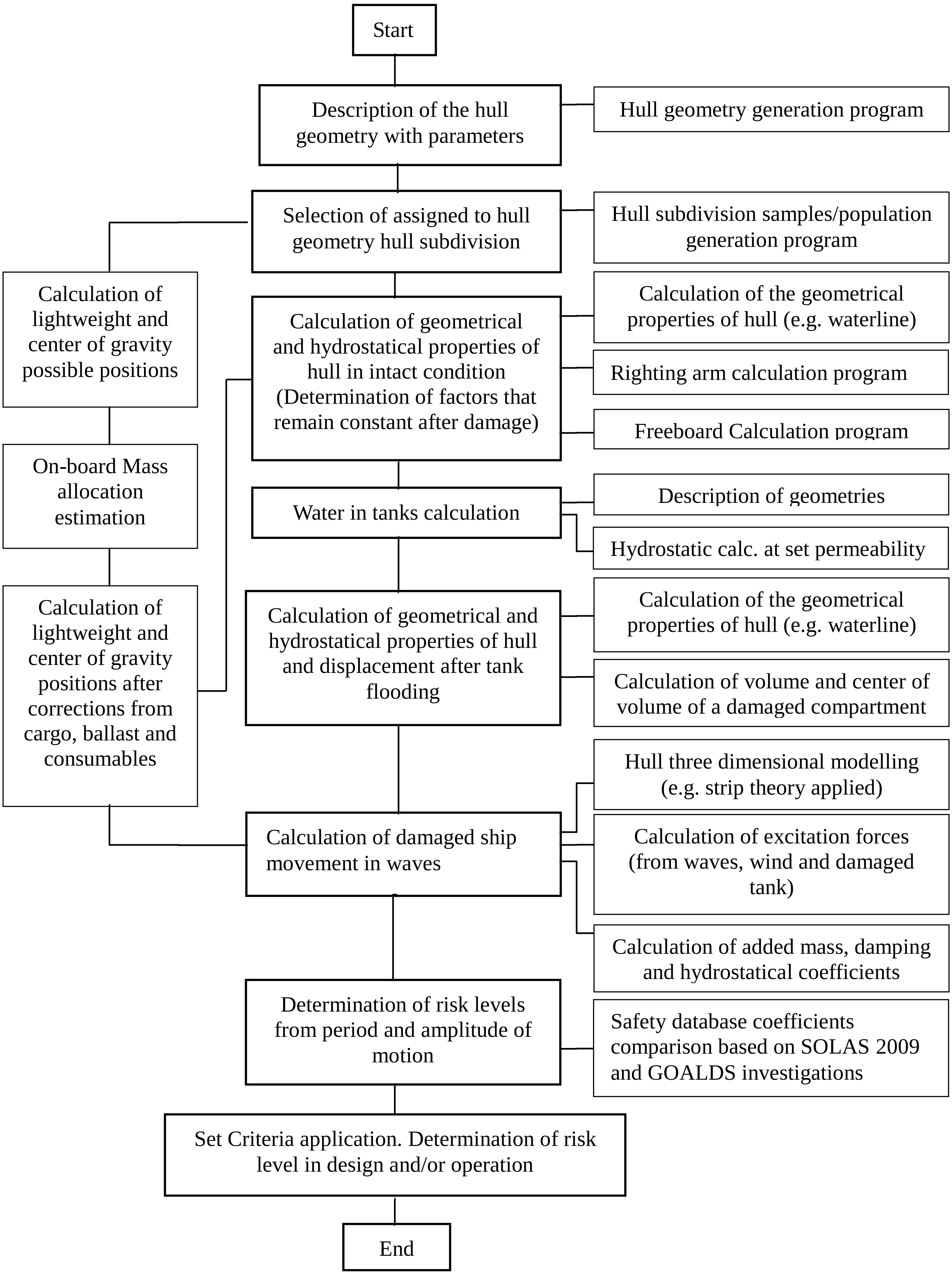


Figure 43. Diagram showing procedure of safety assessment with use of the parameters of decisive impact on safety.

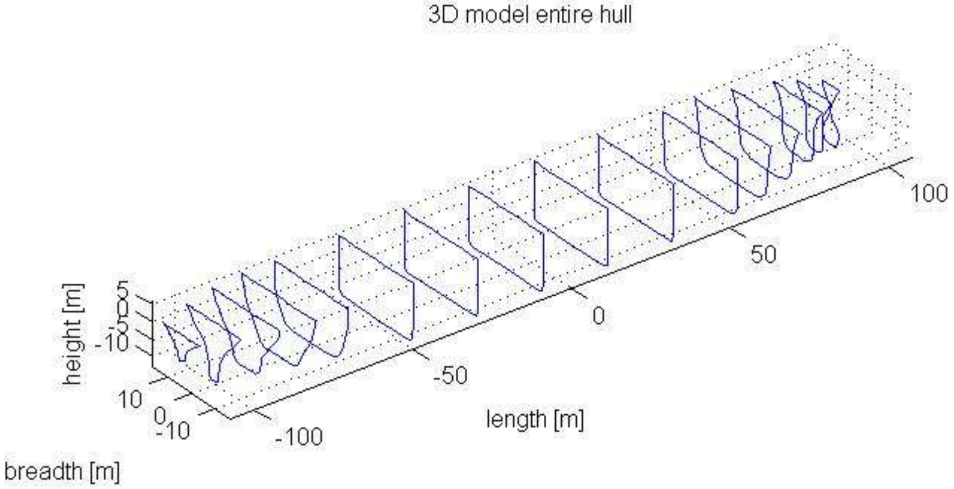


Figure 44. Isometric view of the hull of type Szczecin II

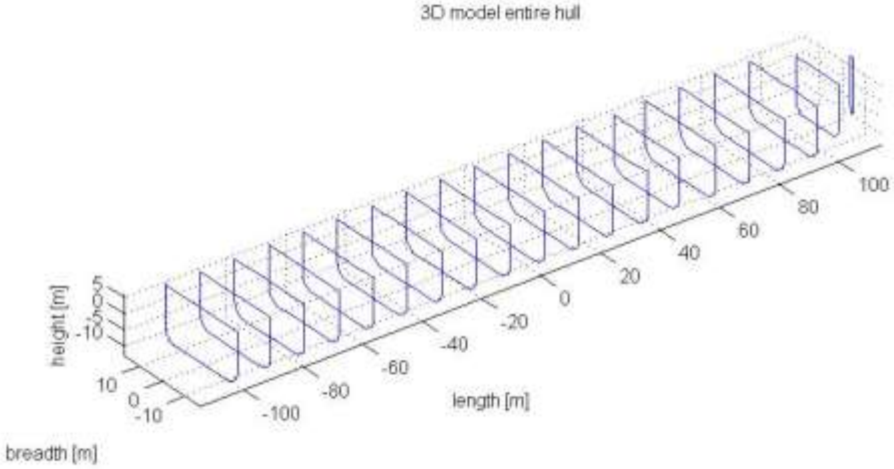


Figure 45. Isometric view of the approximated hull of block coefficient equal to block coefficient of ship type Szczecin II (Based on Taylor 60 hull series).

The mass and geometrical properties of these two hulls are presented in Table 8. As presented in Table 7, all the parameters for the analytical solution of the motion of the vessel in roll, the degree of freedom depends solely on the parameters directly corresponding to the real ship geometry presented in Figure 44 (Table 8). The difference in all these parameters remains small and this suggests that the resulting motion of these two geometries may be similar. For the purpose of verification of the approximation technique, motion calculations with use of calculated as per the assumptions coefficients were performed and the results of the static and dynamic calculations were compared (Figure 46).

As can be seen from direct comparison of dynamic motion results (Figure 46), the difference between the results from the two investigated geometries is rather small and the maximum amplitude difference (within 100 seconds of motion) is 7.25%. As the dynamic components of added mass and damping remain almost exactly the same for the two investigated geometries, the difference may be explained not only by the different shape of the investigated geometry but also by the different position of the center of buoyancy (2.86% - in vertical direction) and the slightly different wetted surface area. The final results however remain within the same order of magnitude.

SHIP PARTICULARS	REAL GEOMETRY:		MODELLED GEOMETRY:		DIFFERENCE:	
Length between perpendiculars, Lpp	205	[m]	205	[m]	0,00	%
Breadth, B	30,48	[m]	30,48	[m]	0,00	%
Mean draught, d	12,09	[m]	12,09	[m]	0,00	%
Block coefficient, Cb	0,81487	[-]	0,81441	[-]	0,06	%
Number of frames	16	[-]	20	[-]		
HYDROSTATICS:						
Vertical centre of buoyancy, KB	6,3491	[m]	6,1678	[m]	2,86	%
Vertical centre of gravity, KG	9,64	[m]	9,64	[m]	0,00	%
Volume displacement, Vol	61558,1	[m^3]	61523	[m^3]	0,06	%
Water plane area, Aw	5483,68	[m^2]	5201,41	[m^2]	5,15	%
DYNAMIC PROPERTIES:						
Ship velocity, U	0	[knots]	0	[knots]	0,00	%
Froude number, Fn	0	[-]	0	[-]	0,00	%
Wave period, T	7	[s]	7	[s]	0,00	%
Wave height, h	2,2	[m]	2,2	[m]	0,00	%
Heading, Betta	90	[-]	90	[-]	0,00	%
Period of encounter, Te	7	[s]	7	[s]	0,00	%
Frequency of encounter, we	0,8976	[rad/s]	0,8976	[rad/s]	0,00	%

Table 8. The mass and geometrical properties of the "Szczecin II" hull and its model compared.

Excitation forces are divided into categories as described in Chapter 8. Although this method of dividing the excitation forces differs from the assumptions used in, e.g. the industry -recognized software Proteus3 [56], it proved that the final results are within a close proximity and so indicate the good accuracy of the assumptions made.

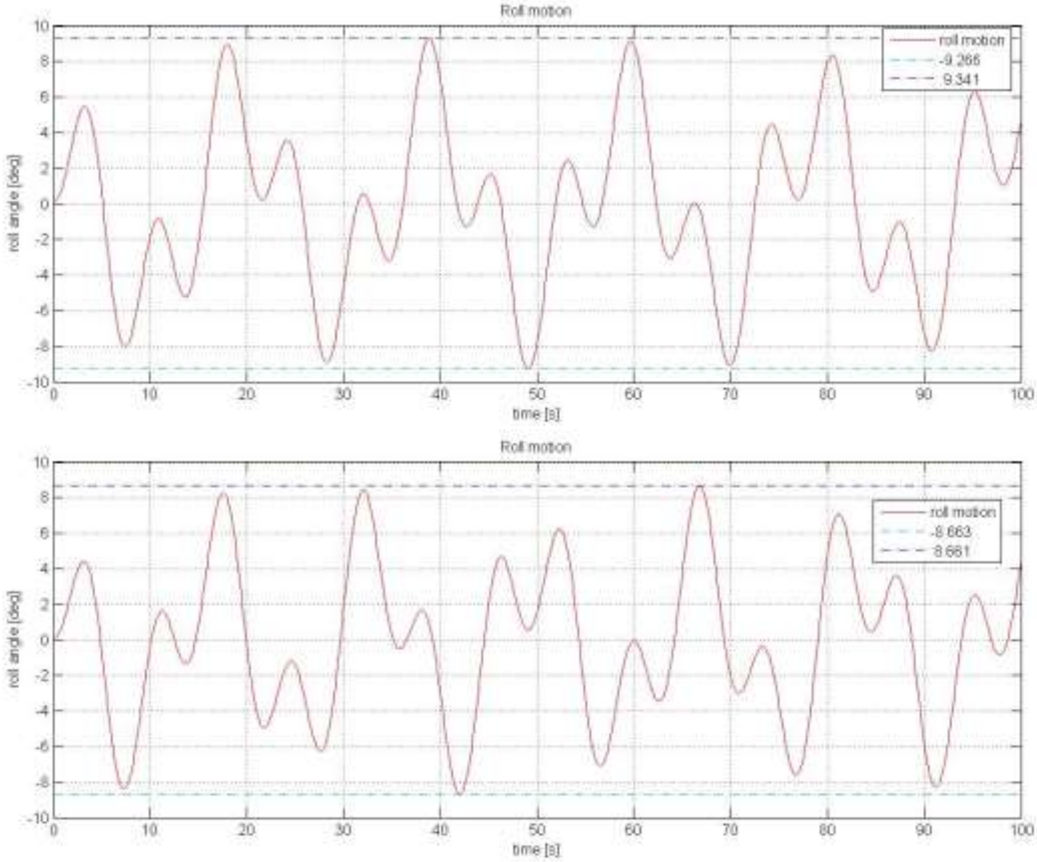


Figure 46. Results of calculations performed for "Szczecin II" oil tanker geometry and the modelled approximated hull. Regular wave significant height 2.2 meters, wave period 7 seconds.

10. Integrated mathematical model of flow and movement of ship in damaged condition.

10.1 Modelling of the object, initial conditions, discretisation of flow equations

As described in the Chapters above, with current knowledge and technological advancement it is impractical to numerically calculate vessels in each and every condition. Approximation methods must be therefore used for calculations. In the strip theory, the ship is divided into a selected number of strips. As the geometry of the vessel changes with the longitudinal position of each strip and changes more rapidly in locations closer to most-aft and most-forward peaks, and such changes are observed to happen at a different rate for different vessels, a simple algorithm for minimization of error was developed (Figure 43). As the designs change with time, it would be illadvised to use the well-known approximation formulas for the estimation of hull shape parameters. The direct input is always preferred, but with sometimes not available data about the geometry of the hull at one's disposal, one can estimate the needed number of strips in a ship by referring to simple geometrical relations instead of engineering formulas. With the investigated vessel's length, breadth and draught known to the designer, the initial volume of a box in which a vessel would fit exactly can be calculated. Compared with other sections for this volume the following properties of panelization of its outer surface apply:

- Added mass coefficient in roll movement is investigated separately for any two dimensional cross sections. Assuming a constant density of water, the value of this coefficient depends solely on the area of the cross section, draught and the distance between the centers of buoyancy and gravity.
- The damping coefficient can be divided into components as described in Chapter 8 of this paper. Under the same assumptions as described in Point 8.1 of this paper the formulas derived from the ITTC official methodology are presented as functions of the following parameters:
  a) Friction component can be calculated with the use of the formula presented in Chapter 8 (34). Parameters r_f and S_f are easily calculated directly from the current industry standard ship models. For the purpose of this research, r_f and S_f values were approximated with the use of formulas proposed by the ITTC (43,44) [86, 97]:

$$r_f = \frac{1}{\pi}\left[(0.887 + 0.145C_B) * (1.7d + C_B) - 2\overline{OG}\right]; \tag{43}$$

$$S_f = L(1.7d + C_B * B); \tag{44}$$

  b) Wave making damping at zero speed component is a function of the moment lever and the sectional sway damping coefficient. Both these values are relatively difficult to obtain analytically and it is usually the strip theory that is used for the initial calculation in calm weather conditions to obtain this component. However, recent research from Kawahara et al. proposes a separate engineering method that, within practical range of application, offers a very good accuracy of the results [87] (See Appendix 3):

$$x_1 = \frac{B}{d}, x_2 = C_b, x_3 = C_m, x_4 = 1 - \frac{OG}{d}, x_5 = \widehat{\omega}, x_6 = x_4 - AA_{32};$$

$$\widehat{B}_w = \frac{A_1}{x_5} * e^{\left(\frac{-A_2 * (LOG(x_5) - A_3)^2}{1.44}\right)}; \tag{45}$$

$$A_1 = (A_1 x_4^2 + A_{12} x_4 + A_{13}) * AA_1;$$
$$A_2 = -1.402x_4^3 + 7.189x_4^2 - 10.993x_4 + 9.45;$$
$$A_3 = A_{31} x_4^6 + A_{32} x_4^5 + A_{33} x_4^4 + A_{34} x_4^3 + A_{35} x_4^2 + A_{36} x_4 + AA_3;$$
$$AA_1 = (AA_{11} x_3 + AA_{12}) * (1 - x_4) + 1; AA_1 = (AA_{11} x_3 + AA_{12}) * (1 - x_4) + 1;$$
$$\begin{aligned} AA_3 = AA_{31}(&-1.05584x_6^9 + 12.688x_6^8 - 63.70534x_6^7 + 172.84571x_6^6 - 274.05701x_6^5 \\ &+ 257.68705x_6^4 - 141.40915x_6^3 + 44.13177x_6^2 - 7.1654x_6^1 - 0.0495x_1^2 \\ &+ 0.4518x_1 - 0.61655); \end{aligned}$$

$$AA_{31} = (-0.3767x_1^3 + 3.39x_1^2 - 10.356x_1 + 11.588) * AA_{311};$$
$$AA_{32} = -0.0727x_1^2 + 0.7x_1 - 1.2818;$$
$$\begin{aligned} AA_{311} = &(-17.102x_2^3 + 41.495x_2^2 - 33.234x_2 + 8.8007) * x_4 + 36.566x_2^3 - 89.203x_2^2 \\ &+ 71.8x_2 - 18.108; \end{aligned}$$
$$\begin{aligned} A_{31} = &-7686.0287x_2^6 + 30131.5678x_2^5 - 49048.9664x_2^4 + 42480.7709x_2^3 \\ &- 20665.147x_2^2 + 5355.2035x_2 - 577.8827; \end{aligned}$$

$$
\begin{aligned}
A_{32} &= 61639.9103x_2^6 - 241201.0598x_2^5 + 392579.5937x_2^4 - 340629.4699x_2^3 \\
&\quad + 166348.6917x_2^2 - 43358.7938x_2 + 4714.7918; \\
A_{33} &= -130677.4903x_2^6 + 507996.2604x_2^5 - 826728.7127x_2^4 + 722677.104x_2^3 \\
&\quad - 358360.7392x_2^2 + 95501.4948x_2 - 10682.8619; \\
A_{34} &= -110034.6584x_2^6 + 446051.22x_2^5 - 724186.4643x_2^4 + 599411.9264x_2^3 \\
&\quad - 264294.7189x_2^2 + 58039.7328x_2 - 4774.6414; \\
A_{35} &= 709672.0656x_2^6 - 2803850.2395x_2^5 + 4553780.5017x_2^4 - 3888378.9905x_2^3 \\
&\quad + 1839829.259x_2^2 - 457313.6939x_2 + 46600.823; \\
A_{36} &= -822735.9289x_2^6 + 3238899.7308x_2^5 - 5256636.5472x_2^4 + 4500543.147x_2^3 \\
&\quad - 2143487.3508x_2^2 + 538548.1194x_2 - 55751.1528;
\end{aligned}
$$

In his work, Kawahara recognized that the wave related component of damping coefficient is related to basic geometrical properties of the ship, i.e. the breadth, draught, block coefficient and mid-ship coefficient. Furthermore, Kawahara recognized that the position of the center of gravity and the frequency of incoming waves do have an impact on the final value of this coefficient. With the application of the known design formulas, this relationship was further modified so that the mid-ship coefficient can be clearly seen to be related to the block coefficient and the design speed of the vessel. Also frequency of incoming waves was linked with corresponding range of significant wave heights.

c) Ikeda [86] has also proposed a method for calculation of the so called eddy-making component of damping. His industry recognized method refers to the Lewis forms and has been verified to offer a good accuracy for practical range of ships. Kawahara has fitted polynomials into this method for range of block coefficient's 0.5 to 0.85, breadth to draught ratios between 2.5 and 4.5 as well as all practical ratios of the center of gravity to draught ratios <-1.5;0.2> and mid-ship coefficients <0.9;0.99>. The calculation method (by Kawahara [87]) is presented below (46):

$$
\begin{aligned}
\hat{B}_E &= \frac{4L_{pp}d^4\hat{\omega}\varphi_a}{3\pi\nabla B^2}C_R \underset{=}{\Rightarrow} \frac{4\hat{\omega}\varphi_a}{3\pi x_2 x_1^3}C_R \\
C_R &= A_E * e^{\left(B_{E1}+B_{E2}x_3^{B_{E3}}\right)}\ where:
\end{aligned}
\tag{46}
$$

$$
A_E = (-0.0182x_2 + 0.0155) * (x_1 - 1.8)^3 - 79.414x_2^4 + 215.695x_2^3 - 215.883x_2^2 + 93.894x_2 - 14.848
$$

$$
\begin{aligned}
B_{E1} &= (-0.2x_1 + 1.6) * (3.98x_2 - 5.1525) * (1 - x_4) \\
&\quad * [(0.9717x_2^2 - 1.55x_2 + 0.723) * (1 - x_4) + (0.04567x_2 + 0.9408)]; \\
B_{E2} &= (-0.25x_4 + 1.95) * (1 - x_4) - 219.2x_2^3 + 443.7x_2^2 - 283.3x_2 + 59.6; \\
B_{E3} &= (46.5 - 15x_1) * x_2 + 11.2x_1 - 28.6;
\end{aligned}
$$

Correction for forward speeds may be taken from the ITTC cited method [86] prepared by Ikeda (47).

$$
B_{44E} = \hat{B}_E * \frac{(0.04K)^2}{1+(0.04K)^2}\,; where\ K = \frac{\omega L}{U} \tag{47}
$$

The eddy making coefficient can be, therefore, accurately approximated for a wide range of hull shapes with the use of the same initial parameters as those used in the wave component instance.

d) The bilge keel component can be relatively easily calculated with the use of the method recommended by the ITTC [86]. Though Kawahara proposed a polynomial fitting method to the Ikeda's methodology [86, 87, 98, 99, 100 – 102], for the purpose of this research it has been proposed that the direct calculation methodology is used. The calculation method described in Chapter 8 of this paper requires additional input parameters of b_{bk} and l_{bk}
e) C – The coefficient responsible for the static change of the vessel righting abilities is directly calculated with use of the general formula (Chapter 8 - 26 - 30).

10.2 Modelling of flooded tank; Method of calculation

The methodology for calculating a change in the above mentioned dynamic and static parameters after flooding is described in Chapters 7 and 8. The main difficulty related to calculating the dynamic components in a time efficient manner is related to superposition of fluid behavior in different motions. Up to date, there have been very few publications covering this problem [e.g. 103], yet some procedures for calculations were already identified a long time ago and applied to calculations and design of free surface roll damping tanks. In order to design an efficient roll damping tank, the sloshing period of the tank must be designed close to the natural roll period of the vessel [104]. The natural period of the vessel depends on its moment of mass that is difficult to calculate at the design stage and even more so in the operation stage when cargo and different ballast configurations change the value of this moment. In consequence, approximation formulas are usually used instead. This may prove to be sufficient for the design of an intact vessel, however for a vessel undergoing flooding, different forces and moments appear and start to play a significant role. Also, in a tank undergoing flooding, the height of water changes. Depending on the height and position of the damaged tank, its natural sloshing period will change as flooding progresses. Both, the value of natural period of the ship in a given loading condition and the sloshing period of a tank that is subjected to flooding are difficult to estimate accurately. Hence, when evaluating the risks related to design and operation of any specific tank one must first make sure that a designed tank will not introduce the risk of oscillations of ship motions and fluid in tank motions and if that is achieved, the most conservative scenario of sloshing impact may be considered. This can be obtained by simply finding the maximum sloshing moment for a given tank for two changeable parameters: the height of water in the tank and the roll movement parameters of the vessel.

Excitation forces from movement of flooding water in the tank described in Chapter 8 are numerically calculated. The variables that were taken into account are shown in Table 9.

The results from numerical calculations of ship behavior after damage on waves provide parameters of motion in a given period of time. This motion may be described by a maximum amplitude and e.g. average frequency. When these initial parameters of ship motion are available a set of initial conditions for calculation of movement of fluid inside of a tank can be made. First, a selection of an investigated shape of the tank is made and simplifications to the geometries are assumed. For the purpose of this work, some simplification is proposed concerning the geometries and position of tanks against the center line (Figure 47).

Variable name	Range investigated
Non-dimensional breadth of tank	0.1 B ~ 1 B
Non-dimensional length of tank	0.01 L ~ 0.2 L
Amplitude of ship motion	2 degrees ~ 30 degrees
Period of roll	5 sec ~ 25 sec
Filling level	10% - 99%
Roll motion damping coefficient	1-2.5

Table 9) Parameters of flooded tank and movement of decisive impact on ship behavior.

The algorithm the author proposed must take into the account the dangers arising from coupling the motions and ought to identify the risks of sloshing as it can have a significant impact on the motion of a ship. In this method, the following values have been selected for investigations when in regular waves environment:

- Initial conditions
  a) Initial roll period
  b) Initial amplitude
  c) Initial center of rotation
  d) Initial damping in roll motion coefficient
- Tank properties
  a) Length, Breadth, Height and geometry of a tank
  b) Filling level in Tank

The position of the tank from the center line will have a significant impact on the behavior of water inside the flooded tank due to the increased vertical movement induced by roll and pitch motions. In the author’s analysis presented in this paper, these effects were added as sinusoidal vertical motions. Furthermore, it was found that for the simplest case the impact on the behavior of fluid inside the tank from the roll motion of the a ship is most significant when the assumed motions of the tank have the most conservative parameters (i.e. the shortest periods and maximum amplitudes of motions). These most critical dynamic forces from the tank are calculated by idealizing the motions of the ship to the sinusoidal motion of largest calculated amplitude and the shortest time period.

The selected initial parameters of the tank (Figure 48) can be taken for the calculations with the following assumptions:

- The tanks of complex geometry can be broken down into simple shapes to allow for selection of a close-fit geometry from a pre-calculated database (Figure 47, Table 9)
- The position of tank with reference to centerline has an impact only on the asymmetry of flooding and the free-surface, but the addition from sloshing is calculated from the roll movement, sway movement and heave movement as if the tank was located at the centerline.

- To calculate the sloshing force (F_S value) in damaged conditions, the filling level in the tank is always assumed to be the one that is most conservative with respect to dynamical sloshing.
- Non-vertical vertical limits of tanks (such as bilge radiuses) are modelled as vertical limits as it largely simplifies the calculation with the certainty that the resulting transversal force is not smaller than the actual one.
- Values of calculated sloshing forces for the different lengths of tanks can be linearly scaled.
- The damping coefficients applied to simulation of movement of the tank can be approximated from ship motions.

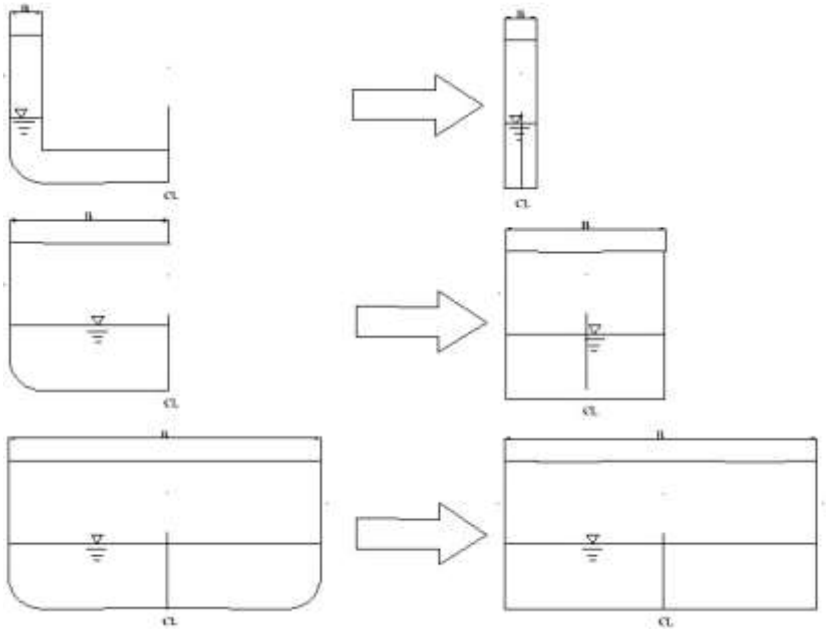


Figure 47) Simplification of tanks geometries for the purpose of sloshing force calculations

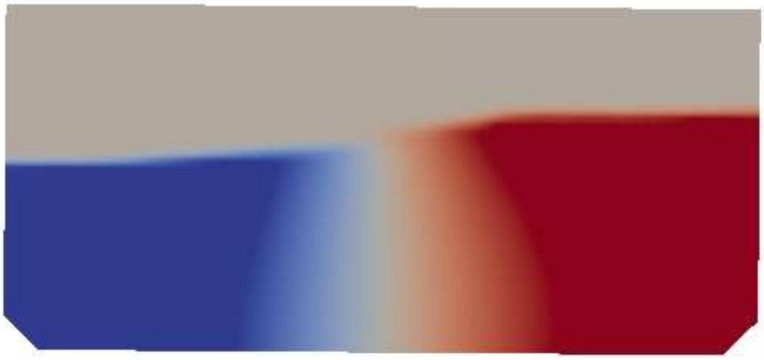


Figure 48) Selected tank investigated. Red color shows area of increased pressure, blue color of decreased pressure.

In the proposed methodology, a pressure distribution on tank's side and bottom is obtained. The forces from fluid in the tank are estimated by a simple integration of pressure on boundaries of the tank. Instead of the usual attempt to couple the forces in any given time step, a procedure presented on Figure 43 was applied. The predicted ship response is a result of a range of possible impacts from the given tank so that the risk for stability and floatability resulting from flooding of any given investigated tank is calculated. This approach allows for calculation of a possible impact of flooding of the tank in any investigated ship and under any initial conditions that is much quicker than the direct numerical integration of pressures in time steps [e.g. 105] (Figure 49).

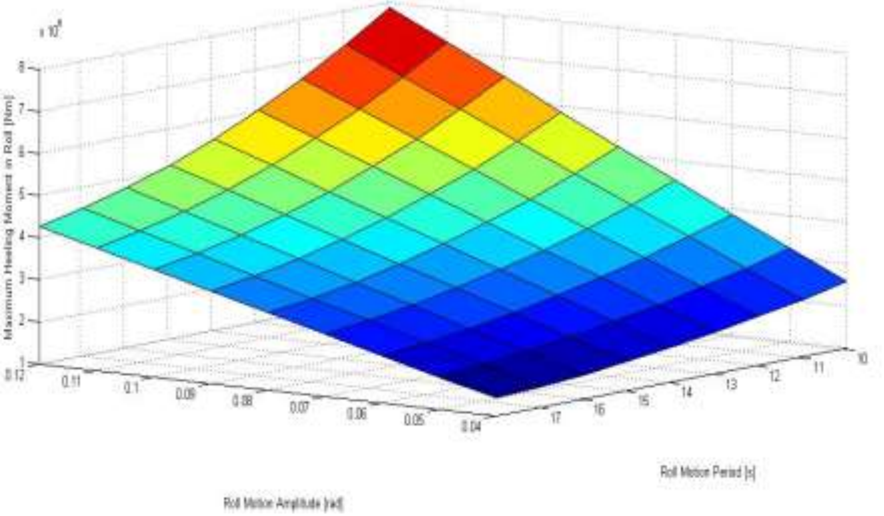


Figure 49. Calculated maximum registered roll moments from sloshing pressure force in a flooded tank (1m length) in function of roll motion amplitude and roll motion period. (The remaining coefficients as listed in Table 9 were fixed for the purpose of this visualization.)

To avoid the coupling of the two almost sinusoidal motions, for any given tank a separate investigation of the relationship between natural roll frequency of the tank and ship roll frequency in waves should be made. In this paper it was achieved with the help of the well-known design formula (48) [55, 89].:

$$\overbrace{2 * n \in N}^{\forall} \omega_{0-TANK} = \sqrt{\frac{\pi * g}{b} * \tanh\left(\frac{\pi * h}{b}\right)} \neq \omega_{roll-SHIP} \tag{48}$$

11. Practical implementation of the proposed method and comparison with results of the method included in SOLAS 2009

11.1 Input Data

For the purpose of presentation of the method, a sample hull shape was selected (Szczecin II) (Figure 50).

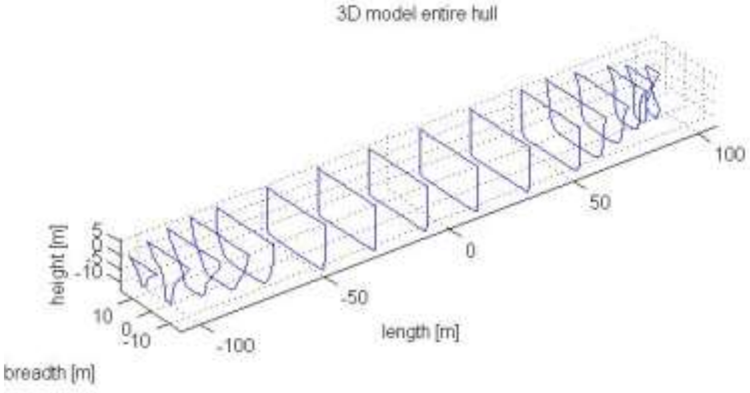


Figure 50. Isometric view of the hull of oil tanker type Szczecin II

In order to reduce time of the, the following assumptions were made:

- One tank only was investigated.
- The vessel was submerged to its deepest subdivision draft and was assumed sailing with the minimum allowable hydrostatic properties as in the existing method (SOLAS 2009).
- The tank was assumed to extent/reach through the entire cross section of the vessel and to be located in such a way that it will not change the initial longitudinal position of the center of gravity and trim of the vessel after flooding.
- The damaged tank was assumed to be 14.5 m. long.

Factor “P” (23) was calculated for waves ranging in height from 1 meter to 4 meters at various wave periods (Table 10).

Wave Height [m]	Wave periods [s]
1	5, 6, 7
2	6, 7, 8
3	7, 8, 9
4	8, 9

Table 10. Range of wave heights and periods investigated for the purpose of method presentation.

The flooded tank volume was calculated to be 5847 m^3. This resulted in an increase in displacement to 61551 m^3 + 5847 m^3 and an increase in draught to 13.23 m. (at a selected permeability equal to 1). The flooding of the tank resulted also in some correction of the center of gravity position arising from the free surface effect. This was calculated to be 0.52 m. upwards and hence, the corrected center of gravity shifted to position VCG = 10.16 m.. Following the calculation diagram (Figure 37), this new initial condition was calculated numerically. For this condition, the vessel’s behavior on waves was examined in selected most probable weather conditions (Figure 38). For the purpose of presentation, the following assumptions were made for the calculations:

- The behavior of vessel was calculated in 100 second time and the initial condition of the vessel was at 0 heel and 0 trim.
- The maximum recorded heeling angle was assumed to be critical and with a big chances of being repeated in the long run.
- Only the heeling angle was recorded.
- Only the beam seas condition was modelled.
- Possibility of submerging of deck at any given heeling angle was assumed to be critical for the survival of ship.
- The impacts from sloshing and wind were not taken into account in potential-based simulation (sloshing was added in static terms).

11.2 Motion calculations results

The initial intact condition was corresponding to a draught of 12.09 meters, trim 0, VCG = 9.64 m. and fully met intact stability criteria set up by the IS 2008 Code regulations.

Values of roll motion amplitude and roll period were identified on the basis of Figures 51 – 61 and further used for evaluating the possible impact of sloshing in the flooded tank.

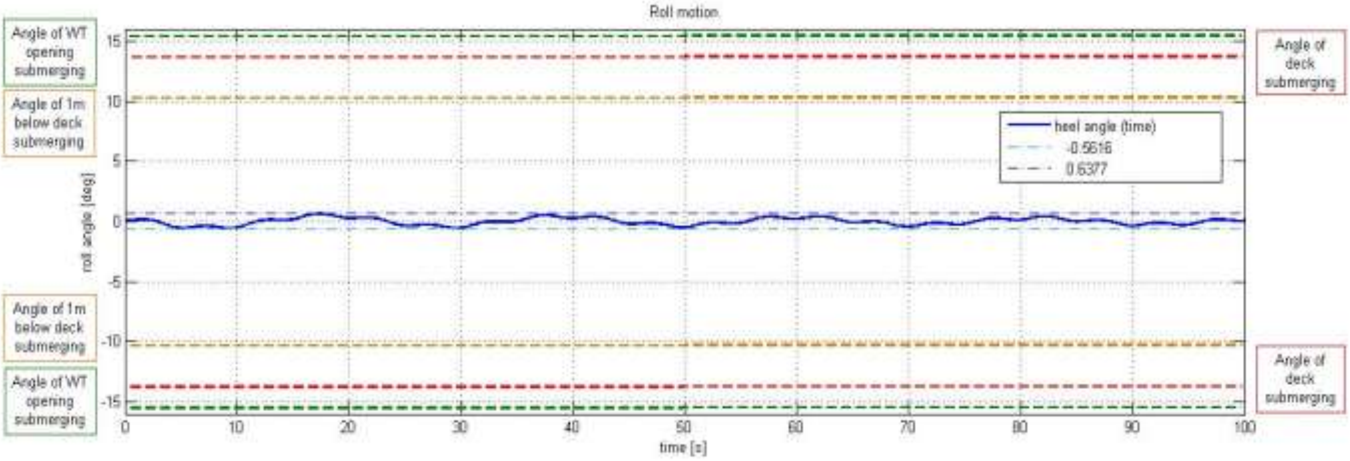


Figure 51. Hs=1m, Tn=5 sec – Roll motion

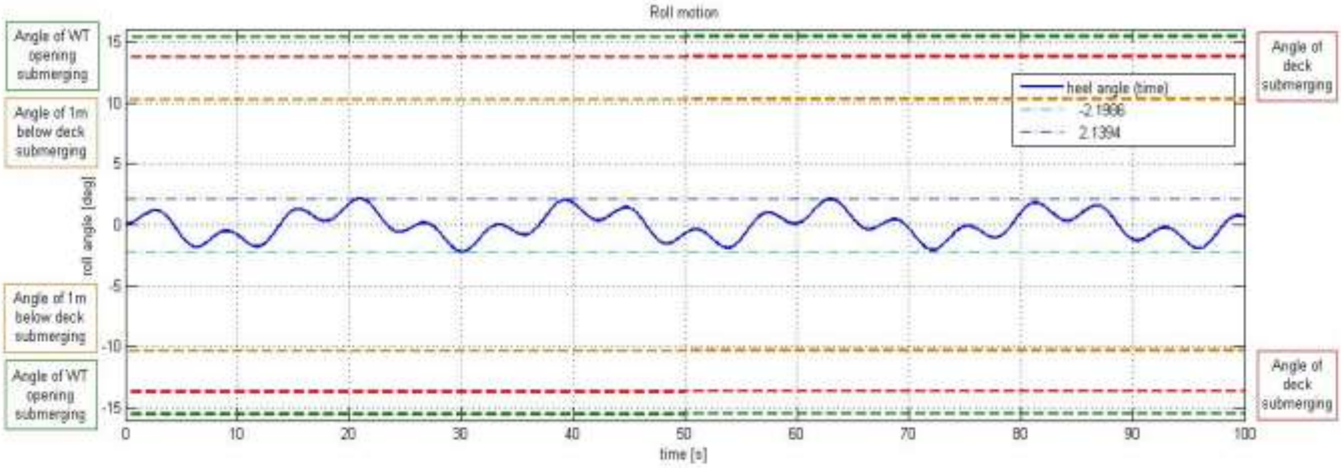


Figure 52. Hs=1m, Tn=6 sec – Roll motion

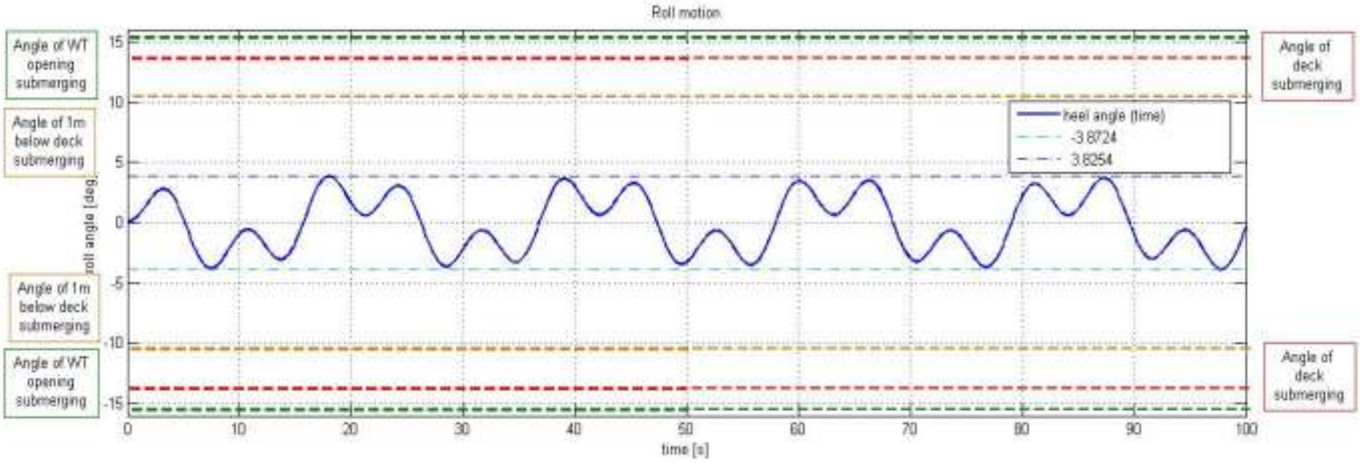


Figure 53. Hs=1m, Tn=7 sec – Roll motion

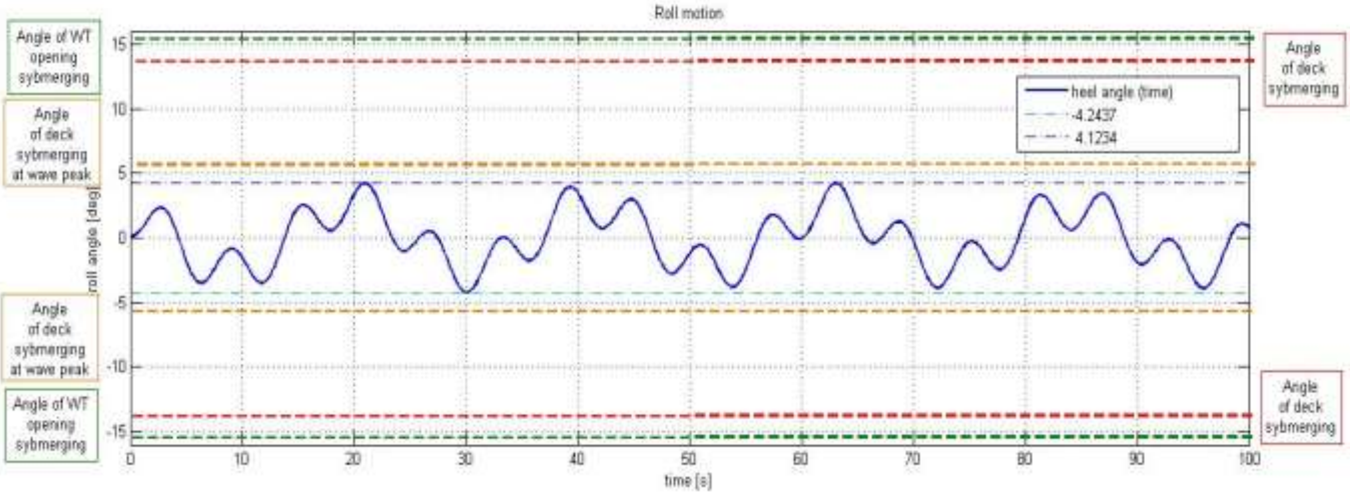


Figure 54. Hs=2m, Tn=6 sec – Roll motion

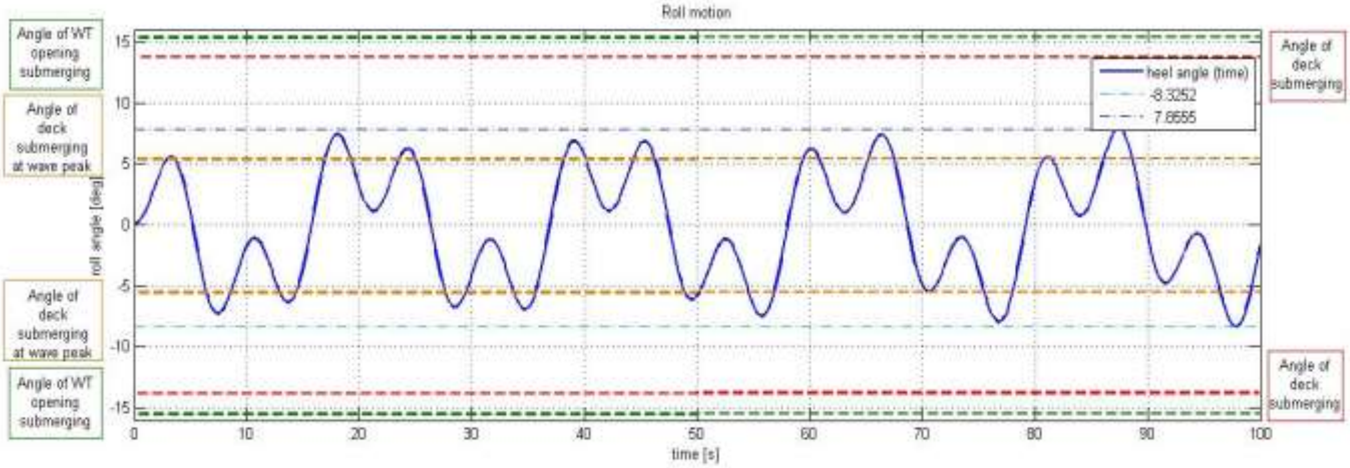


Figure 55. Hs=2m, Tn=7 sec – Roll motion

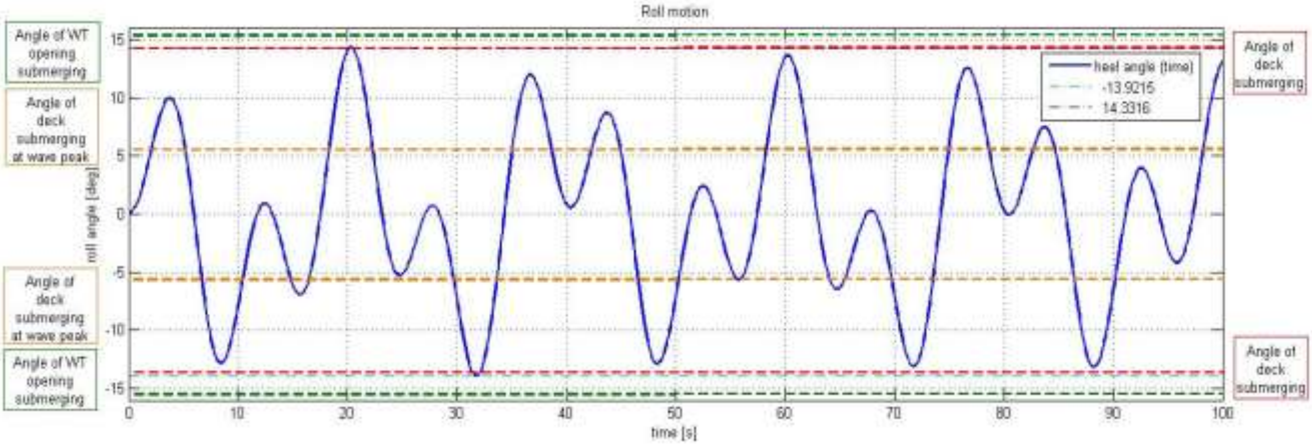


Figure 56. Hs=2m, Tn=8 sec – Roll motion

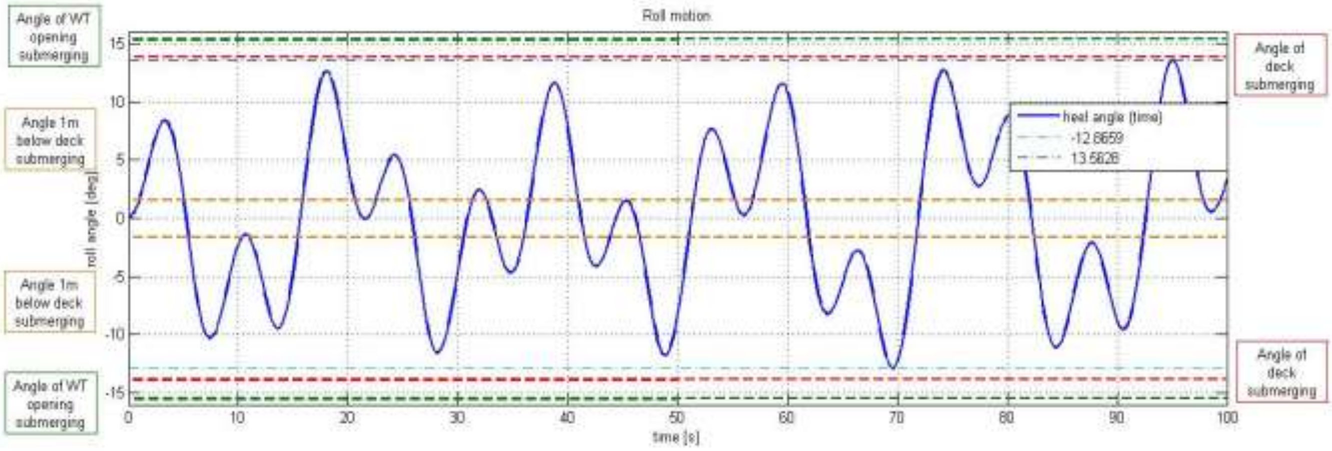


Figure 57. Hs=3m, Tn=7 sec – Roll motion

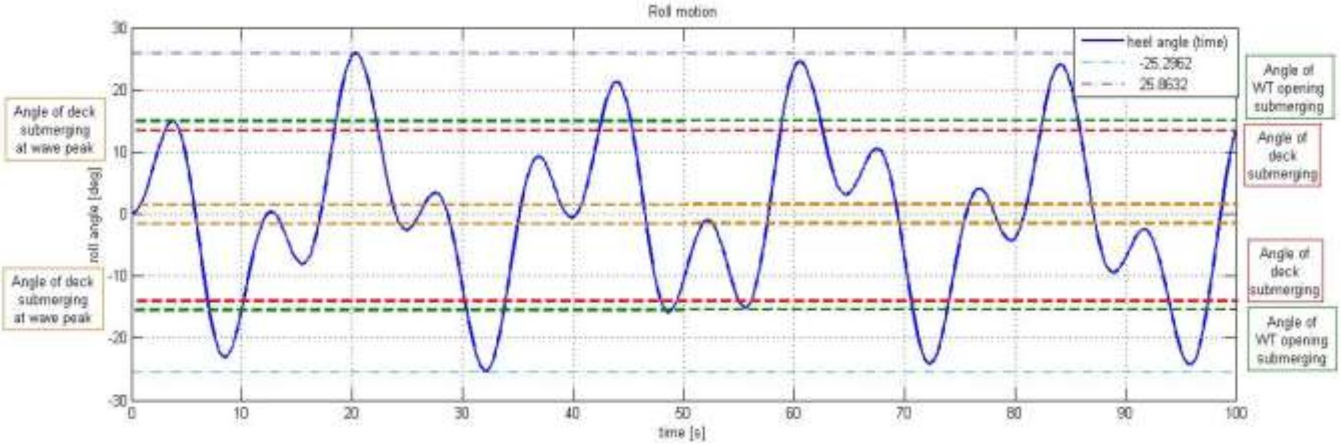


Figure 58. Hs=3m, Tn=8 sec – Roll motion

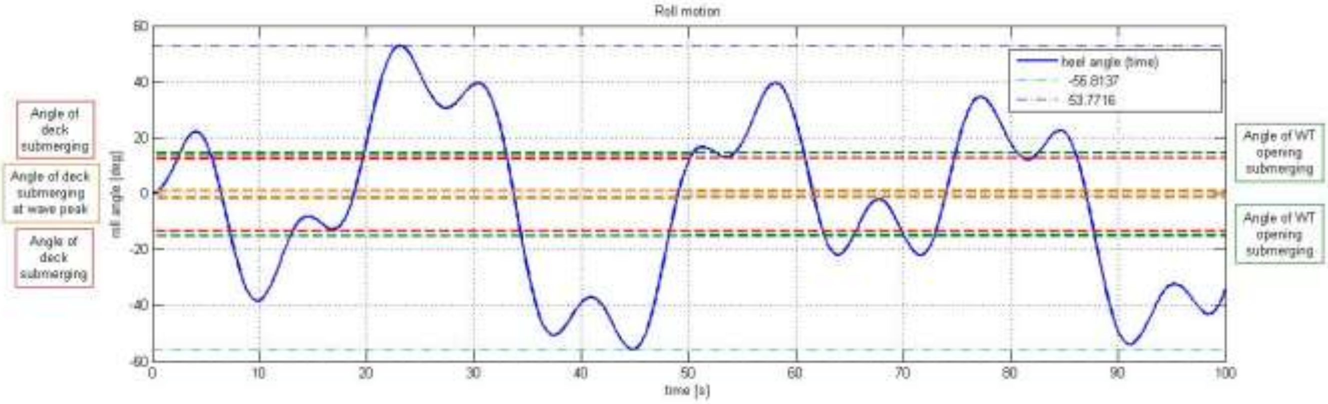


Figure 59. Hs=3m, Tn=9 sec – Roll motion

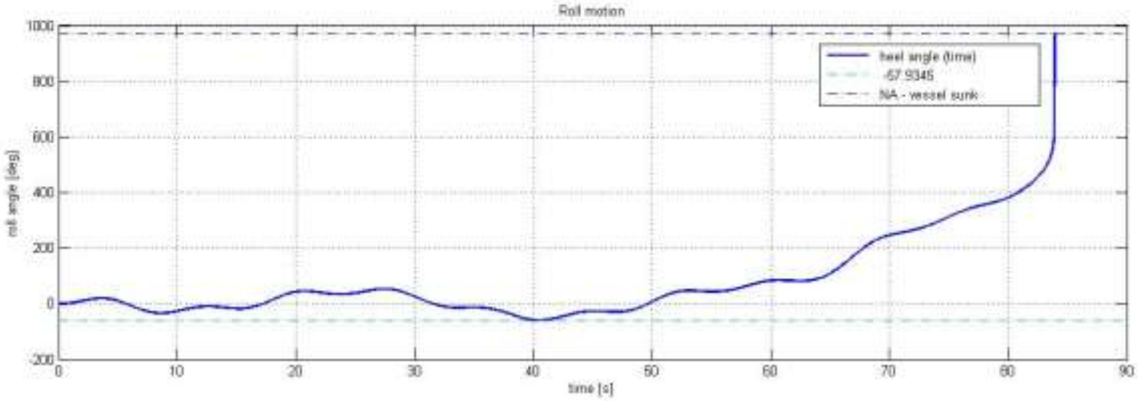


Figure 60. Hs=4m, Tn=8 sec – Roll motion (vessel capsized due to excessive heeling force)

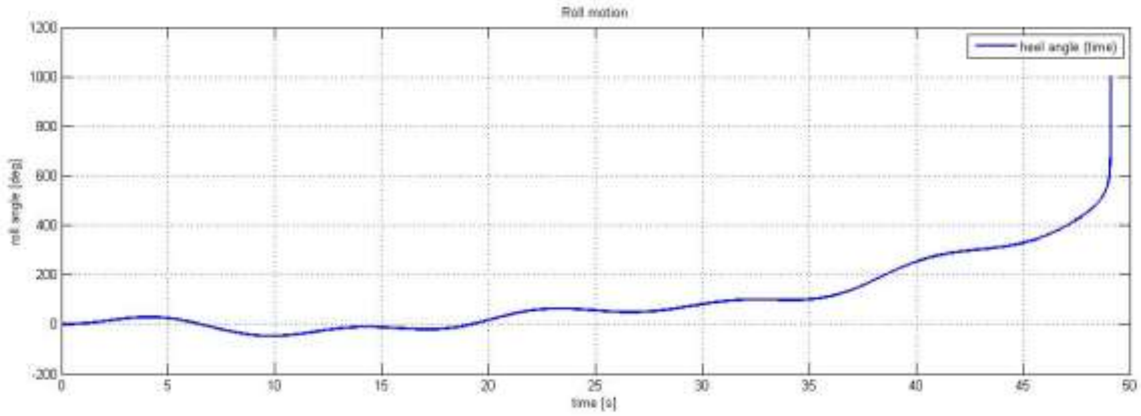


Figure 61. Hs=4m, Tn=9 sec – Roll motion (vessel capsized due to excessive heeling force)

Prior to calculations for sloshing, investigations were made to find out whether the flooded tank's natural frequency and the ship motion do not overlap in such a way as to constitute a risk of oscillations (48). These calculations revealed that the risk of oscillations appeared only during the flooding and not in the final stage thereof. This may be potentially dangerous to the vessel, however given that in an emergency situation the flooding often progresses rapidly this hazard was not further investigated here.

Tn\Hs	1m	2m	3m	4m
5s	21			
6s	72.4	268.9		
7s	244.8	1052.8	2745.3	
8s		2901.2	10932.7	-
9s			-	-

*Table 11. Range of possible values maximum values of sloshing in different weather conditions (in T*m).*

Yet another crucial factor to consider is the impact of wind on the behavior of the vessel. However, in most emergency cases, it is likely that ship Captains will try to position vessel windward so that the heeling moments are minimized. Consequently, in this paper the impact of the wind on the vessel's heel angle does not merit consideration

The vessel's positive static righting arm after flooding was calculated to be disappearing at 67 degrees. The area under uncorrected righting arm which was found to be sufficient before taking into account the sloshing is then compared with the area necessary to counter the impact after the sloshing (Figure 62).

For the purpose of risk analysis, three critical angles of heel were identified. The angle at which the wave peak reaches the deck [106,107] is the angle of static submerging of the deck and static submerging of weather-tight opening on deck (In this case it is assumed to be located at mid-ship and 15.24 m off centerline and 0.7 m above deck). Analysis was made of all these angles in different weather conditions and after flooding and the values arrived at are presented in Table 12.

Tn\Hs	1m	2m	3m	4m
5s	10.3			
6s	10.3	5.5		
7s	10.3	5.5	1.3	
8s		5.5	1.3	0
9s			1.3	0

Tn\Hs	1m	2m	3m	4m
5s	13.8			
6s	13.8	13.8		
7s	13.8	13.8	13.8	
8s		13.8	13.8	13.8
9s			13.8	13.8

Tn\Hs	1m	2m	3m	4m
5s	15.5			
6s	15.5	15.5		
7s	15.5	15.5	15.5	
8s		15.5	15.5	15.5
9s			15.5	15.5

Table 12. Critical values of heel angles top to bottom

- *Angle of submerging the deck at wave peak*
- *Angle of submerging the deck at calm sea*
- *Angle of submerging the nearest weather-tight opening at calm sea*

Tn\Hs	1m	2m	3m	4m
5s	0.64			
6s	2.20	4.24		
7s	3.87	8.32	13.56	
8s		14.33	25.86	ship sinks
9s			ship sinks	ship sinks

Table 13. Recorded angles of heel prior of taking sloshing in flooded tank into account
Green – no risk to survival of ship
Yellow – some risk to survival
Red – inevitability of loss of ship

Tn\Hs	1m	2m	3m	4m
5s	0.64			
6s	2.20	4.24		
7s	3.87	8.90	14.90	
8s		15.25	41.00	ship sinks
9s			ship sinks	ship sinks

Table 14. Calculated maximum angles of heel after applying theoretical maximum impact from sloshing in a flooded tank

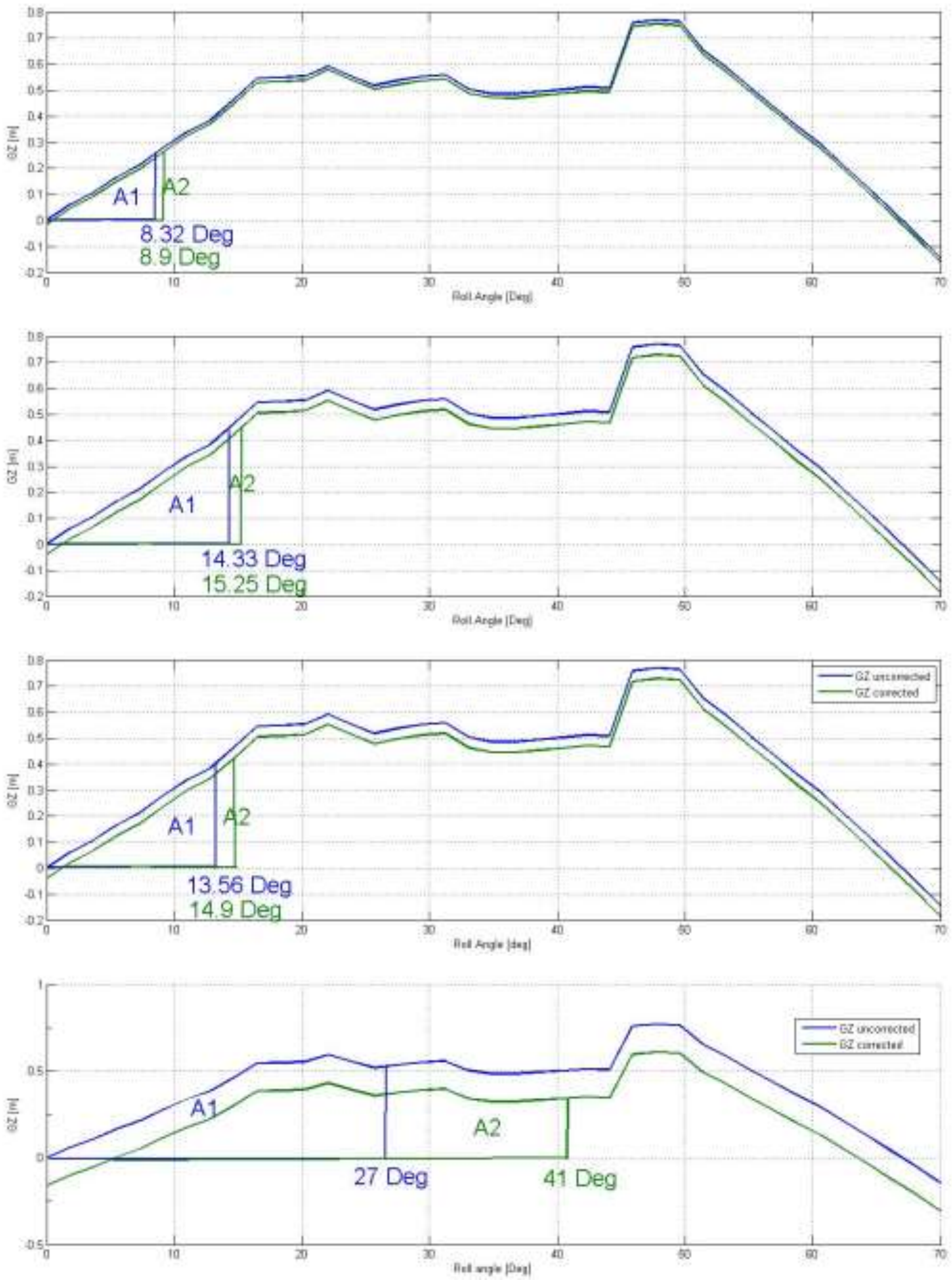


Figure 62. Correction of righting arm curve due to maximum possible impact from sloshing force in investigated flooded compartment

As described in Chapter 7 of this work, the calculations for the maximum roll after the Master reacted to a threat of capsizing took place as well. If the vessel’s heading angle is 90 degrees and no perpendicular wind is considered, the final values from calculations are within the safe margin (Table 15).

Tn\Hs	1m	2m	3m	4m
5s	**0.13**			
6s	**0.14**	**0.81**		
7s	**0.15**	**0.83**	**1.32**	
8s		**0.84**	**1.42**	**2.46**
9s			**1.65**	**2.48**

Table 15. Calculated maximum angles of heel after corrections of course made by the Master.

11.3 Risk Calculation

Probability (as defined in Chapter 6) is calculated in accordance with the probability density function presented in Figure 42. In order to fit a certain probability value to the sea state statistical data, discretization was made in such a way that the value of probability of waves between the discrete values were summed up. The final values formed a vector of probability “P” (Table 16) (49).

Tn\Hs	1	2	3	4
5	0.140571			
6	0.08296	0.127449		
7	0.053002	0.079489	0.051745	
8		0.052845	0.054954	0.063692
9			0.053349	0.036671

Table 16. Values of probability for selected sea states (not greater than) (sum equal to 0.797) Remaining sea states were outside of the investigated domain.

As discussed in previous Chapters of this work, a corresponding model of risk to life, property and environment is utilized. Assuming that the damaged tank was empty before the collision, the risk matrix may look as below (49).:

$$\mathbf{R} = \mathbf{P} * V^{T} * \mathbf{C} = \begin{bmatrix} 0.140571 \\ 0.08296 \\ 0.053002 \\ 0.127449 \\ 0.079489 \\ 0.052845 \\ 0.051745 \\ 0.054954 \\ 0.053349 \\ 0.063692 \\ 0.036671 \end{bmatrix} * \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} * \begin{bmatrix} LIFE \\ ENVIRONMENT \\ PROPERTY - CARGO \\ PROPERTY - SHIP \end{bmatrix} = \begin{bmatrix} 0.3927 * LIFE \\ 0.3927 * ENVIRONMENT \\ 0.3927 * PROPERTY - CARGO \\ 0.3927 * PROPERTY - SHIP \end{bmatrix} \qquad (49)$$

Where:

- **P** - Probability of hazard occurrence in given weather conditions (probability mass function – distribution) <l;…;r>
- $\mathbf{V}^{\mathbf{T}}$ - Vulnerability of the object to the hazard in different terms: (e.g. hazard probability) <k;…;m>
- **C** - Consequences, in terms of loss of life, harm to environment and cargo or ship loss for given vulnerability object properties <k;…;m>

At this stage the risk calculations were set up in such a way that the target was the lack of risk of ship capsizing and/or sinking. Accordingly, the equivalent of the point of no return (PNR - [108,109,110]) was defined as the point of water reaching deck in static position of the ship.

As indicated in Chapter 7 of this work [and e.g. 31,111,112,113)], the risks for the vessel may be understood in different terms and hence, can also be countered and controlled by different means. Additionally, in this case the risk of losing the vessel was strictly compared with weather conditions and the most unfavorable position the ship may be in within the first 100 seconds after the incident. Should the large roll motion amplitude and/or sinking/capsizing of a vessel occur in that time frame, the vulnerability value will be assigned as 1 and in all other cases as 0. For the reasons described in more detail in Chapter 7, the risks to property, cargo and a ship were not prioritized in any way.

The other aspect of risk was related to the vessel's behavior on waves after measures were taken to counter a possible dangerous floating condition (Table 15). It is to be stressed that for the final risk evaluation it is always the highest value of risk that is to be used when applying such model.

$$\mathbf{R} = \mathbf{P} * \boldsymbol{V}^{\boldsymbol{T}} * \mathbf{C} = \begin{bmatrix} 0.140571 \\ 0.08296 \\ 0.053002 \\ 0.127449 \\ 0.079489 \\ 0.052845 \\ 0.051745 \\ 0.054954 \\ 0.053349 \\ 0.063692 \\ 0.036671 \end{bmatrix} * \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} LIFE \\ ENVIRONMENT \\ PROPERTY - CARGO \\ PROPERTY - SHIP \end{bmatrix} = \begin{bmatrix} 0 * LIFE \\ 0 * ENVIRONMENT \\ 0 * PROPERTY - CARGO \\ 0 * PROPERTY - SHIP \end{bmatrix} \qquad (50)$$

11.4 Risk Control Options

The risk calculated in Point 11.3 is expressed in different terms and is a mixture of qualitative and quantitative ways of describing risk [31]. The possibilities for risk control have been well described in the available literature [e.g. 31]). As the risk of sinking (in terms of probability) for the selected scenario of damage was calculated to be 0.3927, it is of the utmost importance to find an acceptable (by designers, insurers and operators) method for evaluating this risk. The value of risk can be divided into a few categories. Different researchers propose different division methods [31, 36]. For the purpose of this work, the author selected basic three levels of risk:

- Tolerable
- Intolerable
- Catastrophic

The difficulty arising from such division has been described in the literature [e.g. 31, 36], but in the author's opinion it is most important that, for selected levels of risk, procedures that are clear and easy to understand for the cargo ship's crew are prepared. These may be the following:

- Risk level: Tolerable – proceed with the journey and seek help in the port of arrival.
- Intolerable – Alter course and/or reconfigure ballast, select route with caution to the weather conditions and seek help in the nearest port.
- Catastrophic – Abandon ship.

These procedures can be presented in a graph showing acceptable levels of risk [e.g. Table 14]. In order to determine the acceptable levels of risk, one must first agree on the likelihood of hazard happening. This is not an easy task, and many researchers have proposed different methods to solve the problem [19, 25, 31, 28]. For the purpose of risk control and very much in line with the content of Chapter 7, the author proposed a formula not very different from the approach included in the available publications. However, in order to avoid relaying on questionable accident statistical data, the likelihood can be quantified with the use of the formula for direct conditional probability (51).

$$p_w * p_e * p_{l/e} = R_o \tag{51}$$

As there is no unbiased (in confidence level terms) statistical correlation between the likelihood of hazard occurrence and a sea condition, this calculation is a multiplication of uncorrelated probabilities. Furthermore, there is no evidence that there is any correlation between the location of a hazard (assigned to any tank) and its position along the length of a ship (see also Chapter 7) [7, 8 et al]. The value of p_w for the selected tank can, therefore, be presented as a vector (52) [61]:

$$\begin{bmatrix} p_1 = Hs_{confidence=0.9} < 1m \\ p_2 = Hs_{confidence=0.9}(> 1m) < 2m \\ p_3 = Hs_{confidence=0.75}(> 2m) < 3m \\ p_4 = Hs_{confidence=0.9}(> 3m) < 4m \end{bmatrix} = \begin{bmatrix} 0.276533 \\ 0.259783 \\ 0.160048 \\ 0.100364 \end{bmatrix} \tag{52}$$

Probability of emergency situations that lead to flooding, can be derived from statistics. Unlike the existing method, the author's proposal is not to go into the details of damage extent, but simply to calculate the probability of an emergency situation in the vessel's lifespan. In this case, it was assumed (for a theoretical study) that for the vessel which has no double bottom where the investigated tank is located and for the tank that was initially empty, the risk arising from flooding of the tank comes from damages only. These may be for example calculated from Table 6. Table 6 also shows that values of probabilities of serious accidents are not dependent on the type of the ship and the cargo it carries (except for tankers and LNG/LPG carriers). Consequently, if the vessel was assumed to be general cargo ship type or any other type of ship listed in Table 6, the probability of a serious accident can be calculated as a constant number p_e. Also, because the investigated tank was empty prior to the emergency and was not a machinery space, the risk of serious accidents described in Chapter 7 (Table 5) may be reduced so that only groundings and collisions are investigated. A sample of such a calculation is presented below (53).

$$p_e = p_c + p_g = 0.5715 * 0.3297 + 0.5715 * 0.2095 = 0.3082 \qquad (53)$$

Finally, in order to determine the probability of an emergency situation happening at the exact location, the author proposes a simple formula based tank volume (or length) percentage when compared with the total vessel displacement (or length). Since the tank extents to its outer shell, this value does not need to be reduced/amended by the probability value for another tank extending to the outer shell. Consequently, for the purpose of this work, the final value can be given by a formula for conditional probability as presented below (54).

$$p_{l/e} = \frac{14.5}{205} = 0.070732 \qquad (54)$$

The final value of the R_0 can be therefore presented as below (55):

$$R_0 = \begin{bmatrix} 0.276533 \\ 0.259783 \\ 0.160048 \\ 0.100364 \end{bmatrix} * 0.3082 * 0.070732 = \begin{bmatrix} 0.0060 \\ 0.0057 \\ 0.0035 \\ 0.0022 \end{bmatrix} \qquad (55)$$

For designers and insurers it is important to establish the level of risk arising from a designed compartment. Acceptable criteria can be based on the cost of building and/or the insurance of ships. As seen in equation 55, the value of R_0 is a vector and hence subject to acceptance criteria that designers and insurance offices may use. This means that if the goal is arbitrary set to tolerate the risk below 1% of the ship loss at any point of its life the R_0 value presented in (55) and the R value in (49) must be confronted (56). If the vessel is unable to survive the emergency situation related to such flooding of a tank in any weather condition, the R_0 value exceeds the allowable level. However, if the vessel (as in the presented case) maintains sufficient stability after an emergency situation for a significant wave heights below 1 meter and in one third of all emergency situations, this risk can be calculated and controlled by equation (56).

$$\sum_{i=1}^{4} R_0 = 0.0174 > 0.01$$
$$\sum_{i=1}^{4} R_{0c} = 0 * (0.0060) + \frac{2}{3} * 0.0057 + 1 * 0.0035 + 1 * 0.0022 = 0.0095 \leq 0.01 \qquad (56)$$

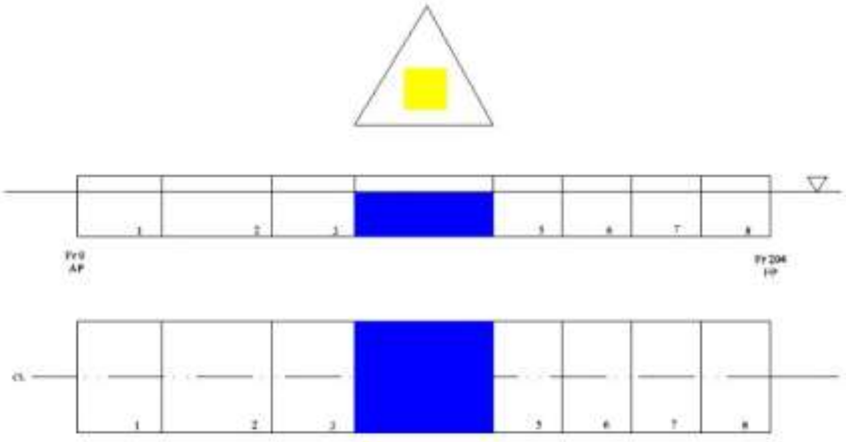
From equation (56) it is evident that the vessel’s ability to counter the hazards related to emergency situations can be quantified and controlled with the use of the risk evaluation. Furthermore, it must be emphasized that any vessel/s ability to counter these hazards be calculated as a function of factors that have a decisive impact on safety of ships in emergency conditions (Table 17) and not only on the basis of parameters of a righting arm curve which is a common practice followed by currently valid rules and regulations [e.g. 1,4,6).

Static and dynamical coefficients	Variables
Friction Damping Coefficient	C_B, d, B, OG, BG, A, (V, ω_e, L_{pp} – at speed)
Wave Damping Coefficient	C_B, d, B, OG, ω_e, $C_M(C_B)$
Lift Damping Coefficient	V, OG, B, d, L
Eddy Making Damping Coefficient	C_B, d, B, OG, ω_e, L_{pp}, $C_M(C_B)$, $\nabla(L_{pp},B,d,C_B)$, φ_a
Bilge Keel (Appendages) Damping Coefficient	C_B, d, B, OG, A, ω_e, φ_a, l_{bk}, b_{bk}
Added Mass Coefficient	$A(B,d,C_M)$, d, BG
Hydrostatical Coefficient	OG, $\nabla(L_{pp},B,d,C_B)$
Excitation forces from tank flooding coefficient	L_t, B_t, H_t, OG_t, T_p,
Additional Investigated tank parameters	V_T – tank volume

Table 17. Parameters of decisive impact on safety of ships in emergency conditions

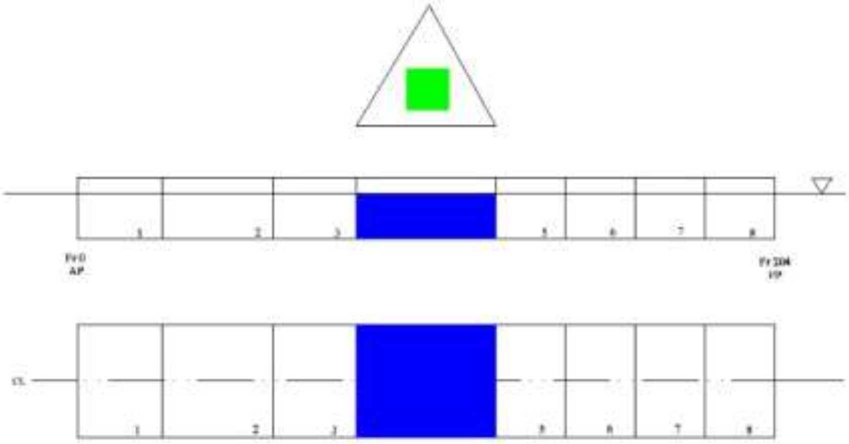
11.5 Comparison of results of risk analysis with the method included in SOLAS 2009

Deepest subdivision draft (defined as per [6])



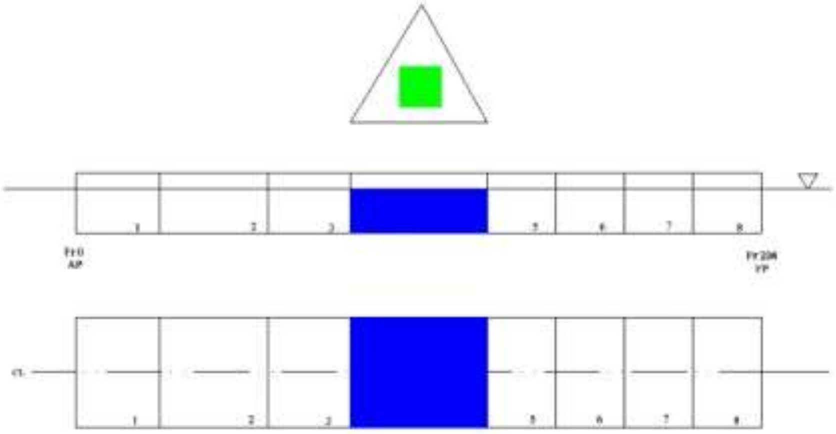
$$p_{1d} \approx 0.024$$
$$s_{1d} \approx 0.992$$

Partial subdivision draft (with assumptions in line with observations from Figure 54):



$$p_{1p} \approx 0.024$$
$$s_{1p} \approx 1$$

Light service draft (with assumptions in line with observations from Figure 54):



$$p_{1l} \approx 0.024$$
$$s_{1l} \approx 1$$

$$A_1 = 0.4 * p_{1d}s_{1d} + 0.4 * p_{1p}s_{1p} + 0.2 * p_{1l}s_{1l} \approx 0.0239; A_{1max} = 0.024 \underset{\Delta}{\Rightarrow} \Delta A = 0.0001$$

Figure 63. Calculation overall contribution from the investigated compartment in SOLAS2009.

12. Discussion and way forward

From analysis and calculations presented in this work it is evident that there are numerous factors that significantly impact risks associated with a design and operation of ships that have not been taken into account in the methods used today (Figure 58). The paper presents the main drawbacks of these methods of assessing the safety of cargo ships that are inherently present in the currently valid rules and regulations and can be briefly summarized as follows:

- Selective structure of the rules, that deal with a selected hazard only. For example, SOLAS 2009 Part B Ch.II-1, evaluates ship stability in damaged conditions only and disregards division of possible consequences in terms of life, environment and property.
- The minimum requirements guaranteeing sufficient stability and floatability parameters after flooding of 1 longitudinal zone or 2 adjacent longitudinal zones are no longer present in the current version of the probabilistic method for cargo ships. This leads to the lack of easy and manageable control over risks vessel may face.
- Establishing the righting ability of vessels does not take place by comparing the righting moments against the external heeling moments and therefore designers and/or crew have no clear information on the survival ability of the vessel from such theoretically analyzed emergency situations or during the emergency situations.

The author believes there is a need for formulating a more accurate and useful method that would address the problems of the current regulations listed above. With that in mind the author formulated a hypothesis:

"It is possible to extract a set of parameters that are readily available in common cargo ship documentation and are of decisive impact on safety of cargo ships because the behavior of ships in waves is primarily a function of static, damping and added mass coefficients easy to approximate accurately using these parameters."

An attempt was made in the paper to identify a method to extract parameters of decisive impact and to formulate methods of assessing safety at design, verification, and operation stages.

The formulated hypothesis was checked to be true subject to conditions which mainly arise from assumptions necessary for the general calculation method selected in this paper. With the help of existing risk evaluating methods, the author also presented examples of risk calculations for ships in emergency situations with the help of a flooding example of one sample tank.

The paper presents methods of obtaining decisive impact parameters and methods of assessing safety for a wide range of cargo ship designs.

Although the method is based on direct physics of motions, it is to be remembered that many simplifications took place during the process. Analytical method of solving differential equations of motion is relatively fast and accurate, however with large changes in ship geometry (e.g. twin screw hulls), the formulations of e.g. damping coefficients must be revisited. Furthermore, in the existing designs, it is not always possible to avoid oscillations between motions of the ship and fluid inside the flooded tank. When the risk of oscillations is large, amended procedures would have to be applied. Hence, at this stage of the method formulation, when applying this method to various cargo ship designs it is imperative that assumptions used in this paper are validated with different numerical and (whenever possible) physical model tests.

On the other hand, it was shown that a computationally efficient quasi-dynamic method that addresses the main drawbacks of current regulations can be formulated and used for evaluating the exact risk levels at any stage of vessel’s life. The author is of the opinion that, with further development, the method presented in this work can become a useful tool for ship designers, insurers and operators.

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Appendix 1

Assumptions used for calculation of range of characteristics (Matlab Code)

```
assignin('base','Leng2',random('unif',100,400,[20000 1]));
assignin('base','Bread2',Leng2.*random('unif',0.12,0.25,[20000 1]));
assignin('base','speed2',((7-(7/0.13)*(Bread2./Leng2-0.12)+17-5*(Bread2./Leng2-0.12)/0.↙
13)).*random('unif',0.9,1.1,[20000 1]));
assignin('base','Height2',Bread2./(-1/24*speed2+2.5));
assignin('base','freeboard2',random('unif',-0.00003*Leng2.*Leng2+0.0226*Leng2-0.078,↙
-0.00004*Leng2.*Leng2+0.0394*Leng2-1.651,[20000 1]));
assignin('base','cb2',(1.06-1.68*(1852/3600)*speed2./((9.81*Leng2).^(0.54))));
assignin('base','cm2',(1+((1-cb2).^(3.5))).^(-1));
assignin('base','cwl2',(1+2*cb2).*(cm2.^(-0.5))/3);
assignin('base','vcg',(Height2/2).*random('unif',0.8,1.4,[20000 1]));
assignin('base','Awl2',Bread2.*Leng2.*cwl2);
assignin('base','BilgeR2',(((1-cm2)/2).*Bread2.*(Height2-freeboard2)./(cm2.*(1-3.14↙
/4))).^(0.5));
assignin('base','cp2',(cb2.*((Leng2.*Bread2).*(Height2-freeboard2)))./(cm2.*((Leng2.↙
*Bread2).*(Height2-freeboard2))));
    Awl = dataset(Awl2);
    Leng = dataset(Leng2);
    Bred = dataset(Bread2);
    cwl1 = dataset(cwl2);
    vcg1 = dataset(vcg);
    freeboard = dataset(freeboard2);
    Height = dataset(Height2);
    speed = dataset(speed2);
    cb1 = dataset(cb2);
    cm1 = dataset(cm2);
    BilgeR = dataset(BilgeR2);
    cp = dataset(cp2);
```

Appendix 2

Based on Taylor Hull Series Hull generation program (Matlab Code)

```
% Sample geometry - 205 m LBP

function [inp] = ReadInput()
% This function reads the input file containing the offset points
inp = struct;

clear all;
clc %Clear the screen
tic
set(0,'RecursionLimit',1500)

I=1;
cp2=0.793;
Leng2(I)=205;
Bread2(I)=30.48;
Height2(I)=17;
BilgeR2(I)=1.935;
freeboard2(I)=4.92;
inp.nFr=20;

% section areas curve

for I=1 %:100
    for x1=1:6
    Q(x1)=-30*(x1/10)^2+100*(x1/10)^3-105*(x1/10)^4+36*(x1/10)^5;
    P(x1)=60*(x1/10)^2-180*(x1/10)^3+180*(x1/10)^4-60*(x1/10)^5;
    T(x1)=(x1/10)-6*(x1/10)^2+12*(x1/10)^3-10*(x1/10)^4+3*(x1/10)^5;
    N(x1)=-0.5*(x1/10)^2+2*(x1/10)^3-2.5*(x1/10)^4+(x1/10)^5;
    F(x1)=-26.562*(x1/10)^6+105.74*(x1/10)^5-
162.71*(x1/10)^4+116.58*(x1/10)^3-34.532*(x1/10)^2+0.6998*(x1/10)+0.7923;
    f(x1) = 0.15;
    if (cp2(I)<0.73)
    t(x1) = -3969.7*cp2(I).^6+16664.6*cp2(I).^5-
28230*cp2(I).^4+24951*cp2(I).^3-12205*cp2(I).^2+3147.7*cp2(I)-335.67;
    else
    t(x1) = 113.64*cp2(I)^2-149.68*cp2(I)+50.221;
    end
    if (cp2(I)<0.74)
    n(x1) = 5.7035*cp2(I)^3-30.16*cp2(I)^2+33.471*cp2(I)-10.606 ;
    else
    n(x1) = -10.417*cp2(I)^2+13.458*cp2(I)-4.305;
    end
    y(x1)=Q(x1)+cp2(I)*P(x1)+t(x1)*T(x1)+n(x1)*N(x1)+f(x1)*F(x1);
    end
    for x1=7:10
    Q(x1)=-30*(x1/10)^2+100*(x1/10)^3-105*(x1/10)^4+36*(x1/10)^5;
    P(x1)=60*(x1/10)^2-180*(x1/10)^3+180*(x1/10)^4-60*(x1/10)^5;
    T(x1)=(x1/10)-6*(x1/10)^2+12*(x1/10)^3-10*(x1/10)^4+3*(x1/10)^5;
    N(x1)=-0.5*(x1/10)^2+2*(x1/10)^3-2.5*(x1/10)^4+(x1/10)^5;
    F(x1)=-26.562*(x1/10)^6+105.74*(x1/10)^5-
162.71*(x1/10)^4+116.58*(x1/10)^3-34.532*(x1/10)^2+0.6998*(x1/10)+0.7923;
    f(x1)=0.05;
    t(x1) = 113.64*cp2(I)^2-149.68*cp2(I)+50.221;
    n(x1) = 5.7035*cp2(I)^3-30.16*cp2(I)^2+33.471*cp2(I)-10.606;
    y(x1)=Q(x1)+cp2(I)*P(x1)+t(x1)*T(x1)+n(x1)*N(x1)+f(x1)*F(x1);
    end
```

```
    for x1=11:16
    Q(x1)=-30*(x1/10-11/10)^2+100*(x1/10-11/10)^3-105*(x1/10-
11/10)^4+36*(x1/10-11/10)^5;
    P(x1)=60*(x1/10-11/10)^2-180*(x1/10-11/10)^3+180*(x1/10-11/10)^4-
60*(x1/10-11/10)^5;
    T(x1)=(x1/10-11/10)-6*(x1/10-11/10)^2+12*(x1/10-11/10)^3-10*(x1/10-
11/10)^4+3*(x1/10-11/10)^5;
    N(x1)=-0.5*(x1/10-11/10)^2+2*(x1/10-11/10)^3-2.5*(x1/10-
11/10)^4+(x1/10-11/10)^5;
    F(x1)=-26.562*(x1/10-11/10)^6+105.74*(x1/10-11/10)^5-162.71*(x1/10-
11/10)^4+116.58*(x1/10-11/10)^3-34.532*(x1/10-11/10)^2+0.6998*(x1/10-
11/10)+0.7923;
    f(x1)=0.05;
    if cp2(I)<0.72
    t(x1) = 96.339*cp2(I)^5-173.59*cp2(I)^4+159.75*cp2(I)^3-
113.4*cp2(I)^2+54.123*cp2(I)-10.686;
    else
    t(x1) = 41.667*cp2(I)^2-49.167*cp2(I)+14.9;
    end
    if cp2(I)<0.73
    n(x1) = -1664.6*cp2(I)^5+5596.7*cp2(I)^4-
7413.2*cp2(I)^3+4815.6*cp2(I)^2-1525.3*cp2(I)+186.79;
    else
    n(x1) = 0.625*cp2(I)+0.4312;
    end
    y(x1)=Q(x1)+cp2(I)*P(x1)+t(x1)*T(x1)+n(x1)*N(x1)+f(x1)*F(x1);
    end

    for x1=17:20
    Q(x1)=-30*(x1/10-11/10)^2+100*(x1/10-11/10)^3-105*(x1/10-
11/10)^4+36*(x1/10-11/10)^5;
    P(x1)=60*(x1/10-11/10)^2-180*(x1/10-11/10)^3+180*(x1/10-11/10)^4-
60*(x1/10-11/10)^5;
    T(x1)=(x1/10-11/10)-6*(x1/10-11/10)^2+12*(x1/10-11/10)^3-10*(x1/10-
11/10)^4+3*(x1/10-11/10)^5;
    N(x1)=-0.5*(x1/10-11/10)^2+2*(x1/10-11/10)^3-2.5*(x1/10-
11/10)^4+(x1/10-11/10)^5;
    F(x1)=-26.562*(x1/10-11/10)^6+105.74*(x1/10-11/10)^5-162.71*(x1/10-
11/10)^4+116.58*(x1/10-11/10)^3-34.532*(x1/10-11/10)^2+0.6998*(x1/10-
11/10)+0.7923;
    f(x1)=0.05;
    t(x1) = 113.64*cp2(I)^2-149.68*cp2(I)+50.221;
    n(x1) = 5.7035*cp2(I)^3-30.16*cp2(I)^2+33.471*cp2(I)-10.606;
    y(x1)=Q(x1)+cp2(I)*P(x1)+t(x1)*T(x1)+n(x1)*N(x1)+f(x1)*F(x1);
    end

%% prismatic coefficients matrix

y2=[y(1),y(2),y(3),y(4),y(5),y(6),y(7),y(8),y(9),y(10),y(20),y(19),y(18),y(
17),y(16),y(15),y(14),y(13),y(12),y(11)];

%% Assumptions for hull geometry construction
%% Lm - Length of cylindric section
%% Lr - Length of aft section

%% Body Plan

%% station 1
```

```
%% slope station - assumed

slopestation1a=5*pi()/180;

%% Y parameters

Ystation1 = [0,y2(1)-BilgeR2(I)/Bread2(I),y2(1)-0.01,y2(1)];

%% Z parameters

Zstation1=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 2

%% slope station - assumed

%% slopestation1a=5*pi()/180;

%% Y parameters

if y2(2)>1
   y2(2)=1;
else
    y2(2)=y2(2);
end

Ystation2 = [0,y2(2)-BilgeR2(I)/Bread2(I),y2(2)-0.01,y2(2)];

%% Z parameters

Zstation2=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 3

%% slope station - assumed

%% Y parameters

if y2(3)>1
   y2(3)=1;
else if y2(3)<y2(2)
        y2(3)=y2(2);
    else
        y2(3)=y2(3);
end
end

Ystation3 = [0,y2(3)-BilgeR2(I)/Bread2(I),y2(3)-0.01,y2(3)];

%% Z parameters

Zstation3=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 4

%% slope station - assumed
```

```
%% Y parameters

if y2(4)>1
   y2(4)=1;
else if y2(4)<y2(3)
        y2(4)=y2(3);
    else
        y2(4)=y2(4);
end
end

Ystation4 = [0,y2(4)-BilgeR2(I)/Bread2(I),y2(4)-0.01,y2(4)];

%% Z parameters

Zstation4=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 5

%% slope station - assumed

%% Y parameters

if y2(5)>1
   y2(5)=1;
else if y2(5)<y2(4)
        y2(5)=y2(4);
    else
        y2(5)=y2(5);
end
end

Ystation5 = [0,y2(5)-BilgeR2(I)/Bread2(I),y2(5)-0.01,y2(5)];

%% Z parameters

Zstation5=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 6

%% slope station - assumed

%% Y parameters

if y2(6)>1
   y2(6)=1;
else if y2(6)<y2(5)
        y2(6)=y2(5);
    else
        y2(6)=y2(6);
end
end

Ystation6 = [0,y2(6)-BilgeR2(I)/Bread2(I),y2(6)-0.01,y2(6)];

%% Z parameters

Zstation6=[0,0,BilgeR2(I)/Bread2(I),1];
```

```
%% station 7

%% slope station - assumed

%% Y parameters

if y2(7)>1
   y2(7)=1;
else if y2(7)<y2(6)
        y2(7)=y2(6);
    else
        y2(7)=y2(7);
end
end

Ystation7 = [0,y2(7)-BilgeR2(I)/Bread2(I),y2(7)-0.01,y2(7)];

%% Z parameters

Zstation7=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 8

%% slope station - assumed

%% Y parameters

if y2(8)>1
   y2(8)=1;
else if y2(8)<y2(7)
        y2(8)=y2(7);
    else
        y2(8)=y2(8);
end
end

Ystation8 = [0,y2(8)-BilgeR2(I)/Bread2(I),y2(8)-0.01,y2(8)];

%% Z parameters

Zstation8=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 9

%% slope station - assumed

%% Y parameters

if y2(9)>1
   y2(9)=1;
else if y2(9)<y2(8)
        y2(9)=y2(8);
    else
        y2(9)=y2(9);
end
end
```

```
Ystation9 = [0,y2(9)-BilgeR2(I)/Bread2(I),y2(9)-0.01,y2(9)];

%% Z parameters

Zstation9=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 10

%% slope station - assumed

%% Y parameters

if y2(10)>1
   y2(10)=1;
else if y2(10)<y2(9)
        y2(10)=y2(9);
    else
        y2(10)=y2(10);
end
end

Ystation10 = [0,y2(10)-BilgeR2(I)/Bread2(I),y2(10)-0.01,y2(10)];

%% Z parameters

Zstation10=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 11

%% slope station - assumed

%% Y parameters

if y2(11)>1
   y2(11)=1;
else if y2(11)<y2(10)
        y2(11)=y2(10);
    else
        y2(11)=y2(11);
end
end

Ystation11 = [0,y2(11)-BilgeR2(I)/Bread2(I),y2(11)-0.01,y2(11)];

%% Z parameters

Zstation11=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 12

%% slope station - assumed

%% Y parameters

if y2(12)>1
   y2(12)=1;
else if y2(12)<y2(11)
```

```
        y2(12)=y2(11);
    else
        y2(12)=y2(12);
end
end

Ystation12 = [0,y2(12)-BilgeR2(I)/Bread2(I),y2(12)-0.01,y2(12)];

%% Z parameters

Zstation12=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 13

%% slope station - assumed

%% Y parameters

if y2(13)>1
   y2(13)=1;
else if y2(13)<y2(12)
        y2(13)=y2(12);
    else
        y2(13)=y2(13);
end
end

Ystation13 = [0,y2(13)-BilgeR2(I)/Bread2(I),(y2(13)-0.01),y2(13)];

%% Z parameters

Zstation13=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 14

%% slope station - assumed

%% Y parameters

if y2(14)>1
   y2(14)=1;
end

Ystation14 = [0,y2(14)-BilgeR2(I)/Bread2(I),y2(14)-0.01,y2(14)];

%% Z parameters

Zstation14=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 15

%% slope station - assumed

%% Y parameters

if y2(15)>1
   y2(15)=1;
```

```
end

Ystation15 = [0,y2(15)-BilgeR2(I)/Bread2(I),y2(15)-0.01,y2(15)];

%% Z parameters

Zstation15=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 16

%% slope station - assumed

%% Y parameters

if y2(16)>1
   y2(16)=1;
end

Ystation16 = [0,y2(16)-BilgeR2(I)/Bread2(I),y2(16)-0.01,y2(16)];

%% Z parameters

Zstation16=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 17

%% slope station - assumed

%% Y parameters

if y2(17)>1
   y2(17)=1;
end

Ystation17 = [0,y2(17)-BilgeR2(I)/Bread2(I),y2(17)-0.01,y2(17)];

%% Z parameters

Zstation17=[0,0,BilgeR2(I)/Bread2(I),1];

%% station 18

%% slope station - assumed

%% Y parameters

if y2(18)>1
   y2(18)=1;
end

Ystation18 = [0,y2(18)-BilgeR2(I)/Bread2(I),y2(18)-0.01,y2(18)];

%% Z parameters

Zstation18=[0,0,BilgeR2(I)/Bread2(I),1];
```

```
    %% station 19

    %% slope station - assumed

    %% Y parameters

    if y2(19)>1
       y2(19)=1;
    end

    Ystation19 = [0,y2(19)-BilgeR2(I)/Bread2(I),y2(19)-0.01,y2(19)];

    %% Z parameters

    Zstation19=[0,0,BilgeR2(I)/Bread2(I),1];

    %% station 20

    %% slope station - assumed

    %% Y parameters

    if y2(20)>1
       y2(20)=1;
    end

    Ystation20 = [0,y2(20)-BilgeR2(I)/Bread2(I),y2(20)-0.01,y2(20)];

    %% Z parameters

    Zstation20=[0,0,BilgeR2(I)/Bread2(I),1];

%% Preparation of file for import

inp.Lpp = Leng2(I); % Length of vessel

inp.xFr = zeros(20,1); % Vector with x-positions of each frame
inp.nPktSp = zeros(20,1); % Vector with number of points per frame
inp.Offsets = cell(20,1); % Cell array with offset points

inp.xFr = [-Leng2(I)/2,-Leng2(I)/2+Leng2(I)/19,-Leng2(I)/2+2*Leng2(I)/19,-
Leng2(I)/2+3*Leng2(I)/19,-Leng2(I)/2+4*Leng2(I)/19,-
Leng2(I)/2+5*Leng2(I)/19,...
                 -Leng2(I)/2+6*Leng2(I)/19,-Leng2(I)/2+7*Leng2(I)/19,-
Leng2(I)/2+8*Leng2(I)/19,-Leng2(I)/2+9*Leng2(I)/19,...

Leng2(I)/38,1.5*Leng2(I)/19,2.5*Leng2(I)/19,3.5*Leng2(I)/19,4.5*Leng2(I)/19
,...

5.5*Leng2(I)/19,6.5*Leng2(I)/19,7.5*Leng2(I)/19,8.5*Leng2(I)/19,Leng2(I)/2]
';

inp.nPktSp =
[26,26,26,26,26,26,26,26,26,26,26,26,26,26,26,26,26,26,26,26]'; % Content
of line 3

% Reading the offset points
for aa=1:20
```

```
 c = cell(inp.nPktSp(aa),1); % Reading the offset points

    %% Z parameters

 Ystation = zeros(5);
 Zstation = zeros(5);
 if y2(aa) > BilgeR2(I)/Bread2(I)+0.01
 Ystation =
[0.01,Bread2(I)*y2(aa)/10,Bread2(I)*2*y2(aa)/10,Bread2(I)*3*y2(aa)/10,Bread
2(I)*4*y2(aa)/10,Bread2(I)*5*y2(aa)/10,Bread2(I)*6*y2(aa)/10,Bread2(I)*7*y2
(aa)/10,Bread2(I)*8*y2(aa)/10,(y2(aa)-BilgeR2(I)/(Bread2(I))-
0.01)*Bread2(I),...
            (y2(aa)-BilgeR2(I)/(Bread2(I))-
0.01)*Bread2(I)+BilgeR2(I)*(2^(1/2)/2),(y2(aa)-
0.01)*Bread2(I),y2(aa)*Bread2(I)-0.001,y2(aa)*Bread2(I),...

y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*
Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),...

y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*
Bread2(I)];
 Zstation =
[0,0,0,0,0,0,0,0,0,BilgeR2(I)*(2^(1/2)/2),BilgeR2(I),BilgeR2(I)+1,BilgeR2(I
)+2,BilgeR2(I)+3,BilgeR2(I)+4,BilgeR2(I)+5,...
            BilgeR2(I)+6,BilgeR2(I)+7,BilgeR2(I)+8,(Height2(I)-
freeboard2(I)),(Height2(I)-freeboard2(I)+1),(Height2(I)-
freeboard2(I)+2),(Height2(I)-freeboard2(I)+3),(Height2(I)-
freeboard2(I)+4),Height2(I)-0.01,Height2(I)];

 else
 Ystation =
[0.01,Bread2(I)*y2(aa)/10,Bread2(I)*2*y2(aa)/10,Bread2(I)*3*y2(aa)/10,Bread
2(I)*4*y2(aa)/10,Bread2(I)*5*y2(aa)/10,Bread2(I)*6*y2(aa)/10,Bread2(I)*7*y2
(aa)/10,Bread2(I)*8*y2(aa)/10,(y2(aa)-0.01)*Bread2(I),...

(y2(aa)*Bread2(I)),(y2(aa))*Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(
aa)*Bread2(I),...

y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*
Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),...

y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*Bread2(I),y2(aa)*
Bread2(I)];
 Zstation =
[0,0,0,0,0,0,0,0,0,BilgeR2(I)*(2^(1/2)/2),BilgeR2(I),BilgeR2(I)+1,BilgeR2(I
)+2,BilgeR2(I)+3,BilgeR2(I)+4,BilgeR2(I)+5,...
            BilgeR2(I)+6,BilgeR2(I)+7,BilgeR2(I)+8,(Height2(I)-
freeboard2(I)),(Height2(I)-freeboard2(I)+1),(Height2(I)-
freeboard2(I)+2),(Height2(I)-freeboard2(I)+3),(Height2(I)-
freeboard2(I)+4),Height2(I)-0.01,Height2(I)];
 end

c={[Ystation(1,26)/2 Ystation(1,25)/2 Ystation(1,24)/2 Ystation(1,23)/2
Ystation(1,22)/2 Ystation(1,21)/2 Ystation(1,20)/2,...
    Ystation(1,19)/2 Ystation(1,18)/2 Ystation(1,17)/2 Ystation(1,16)/2
Ystation(1,15)/2 Ystation(1,14)/2 Ystation(1,13)/2,...
    Ystation(1,12)/2 Ystation(1,11)/2 Ystation(1,10)/2 Ystation(1,9)/2
Ystation(1,8)/2 Ystation(1,7)/2 Ystation(1,6)/2,...
    Ystation(1,5)/2 Ystation(1,4)/2 Ystation(1,3)/2 Ystation(1,2)/2
Ystation(1,1)/2]',...
    [Zstation(1,26) Zstation(1,25) Zstation(1,24) Zstation(1,23)
```

```
Zstation(1,22) Zstation(1,21) ,...
    Zstation(1,20) Zstation(1,19) Zstation(1,18) Zstation(1,17)
Zstation(1,16) Zstation(1,15) ,...
    Zstation(1,14) Zstation(1,13) Zstation(1,12) Zstation(1,11)
Zstation(1,10) Zstation(1,9) ,...
    Zstation(1,8) Zstation(1,7) Zstation(1,6) Zstation(1,5) Zstation(1,4)
Zstation(1,3) Zstation(1,2) Zstation(1,1)]'}
```

Appendix 3

Estimation of Damping Coefficient based on Kawahara / Ikeda (87) method (Matlab code)

```
Tnat = 0.45*dim.Beam;
zg = -2.45;
d = dim.maxDraught;

CB = dim.Vol/(dim.Beam*d*inp.Lpp);

RF = ((0.887+0.145*CB)*(1.7*d+CB*dim.Beam)-2.0*(-1*zg))/3.14;

SF = inp.Lpp*(1.75*d+CB*dim.Beam);

PHI = 5;

KVC = 1.063*10^(-6);

CF=1.328*((3.22*RF^2*(PHI*3.14/180)^2)/(Tnat*KVC))^(-0.5);

BF=4.0/(3.0*3.14)*1.025*SF*RF^3*(PHI*3.14/180)*((2*3.14)/Tnat)*CF;

BFHAT=BF/(1.025*inp.Lpp*dim.Beam^3*d*CB)*(dim.Beam/(2.0*9.81))^(1/2);

%% wave component

X1=dim.Beam/d;
X2=CB;
X3=1/(1+(1-CB)^(3.5));  %% HSVA design formula
X5=2*3.14/const.T;
X5=const.we;
X4=1-(-1*zg)/d;

      A111=-0.002222*X1^3+0.040871*X1^2-0.286866*X1+0.599424;

      A112=0.010185*X1^3-0.161176*X1^2+0.904989*X1-1.641389;

      A113=-0.015422*X1^3+0.220371*X1^2-1.084987*X1+1.834167;

      A121=-0.0628667*X1^4+0.4989259*X1^3+0.52735*X1^2-
10.7918672*X1+16.616327;

      A122=0.1140667*X1^4-0.8108963*X1^3-2.2186833*X1^2+25.1269741*X1-
37.7729778;

      A123=-0.0589333*X1^4+0.2639704*X1^3+3.1949667*X1^2-
21.8126569*X1+31.4113508;

      A124=0.0107667*X1^4+0.0018704*X1^3-1.2494083*X1^2+6.9427931*X1-
10.2018992;

      A131=0.192207*X1^3-2.787462*X1^2+12.507855*X1-14.764856;

      A132=-0.350563*X1^3+5.222348*X1^2-23.974852*X1+29.007851;

      A133=0.237096*X1^3-3.535062*X1^2+16.368376*X1-20.539908;
```

```
    A134=-0.067119*X1^3+0.966362*X1^2-4.407535*X1+5.894703;

    A11=A111*X2^2+A112*X2+A113;
    A12=A121*X2^3+A122*X2^2+A123*X2+A124;
    A13=A131*X2^3+A132*X2^2+A133*X2+A134;

    AA111=17.945*X1^3-166.294*X1^2+489.799*X1-493.142;
    AA112=-25.507*X1^3+236.275*X1^2-698.683*X1+701.494;
    AA113=9.077*X1^3-84.332*X1^2+249.983*X1-250.787;
    AA121=-16.872*X1^3+156.399*X1^2-460.689*X1+463.848;
    AA122=24.015*X1^3-222.507*X1^2+658.027*X1-660.665;
    AA123=-8.56*X1^3+79.549*X1^2-235.827*X1+236.579;

    AA11=AA111*X2^2+AA112*X2+AA113;
    AA12=AA121*X2^2+AA122*X2+AA123;

    AA1=(AA11*X3+AA12)*(1-X4)+1.0;

    A1=(A11*X4^2+A12*X4+A13)*AA1;
    A2=-1.402*X4^3+7.189*X4^2-10.993*X4+9.45;

    A31=-7686.0287*X2^6+30131.5678*X2^5-49048.9664*X2^4+42480.7709*X2^3-
20665.147*X2^2+5355.2035*X2-577.8827;
    A32=61639.9103*X2^6-241201.0598*X2^5+392579.5937*X2^4-
340629.4699*X2^3+166348.6917*X2^2-43358.7938*X2+4714.7918;
    A33=-130677.4903*X2^6+507996.2604*X2^5-
826728.7127*X2^4+722677.104*X2^3-358360.7392*X2^2+95501.4948*X2-10682.8619;
    A34=-110034.6584*X2^6+446051.22*X2^5-
724186.4643*X2^4+599411.9264*X2^3-264294.7189*X2^2+58039.7328*X2-4774.6414;
    A35=709672.0656*X2^6-2803850.2395*X2^5+4553780.5017*X2^4-
3888378.9905*X2^3+1839829.259*X2^2-457313.6939*X2+46600.823;
    A36=-822735.9289*X2^6+3238899.7308*X2^5-
5256636.5472*X2^4+4500543.147*X2^3-2143487.3508*X2^2+538548.1194*X2-
55751.1528;
    A37=299122.8727*X2^6-1175773.1606*X2^5+1907356.1357*X2^4-
1634256.8172*X2^3+780020.9393*X2^2-196679.7143*X2+20467.0904;

    AA311=(-17.102*X2^3+41.495*X2^2-33.234*X2+8.8007)*X4+36.566*X2^3-
89.203*X2^2+71.8*X2-18.108;

    AA31=(-0.3767*X1^3+3.39*X1^2-10.356*X1+11.588)*AA311;
    AA32=-0.0727*X1^2+0.7*X1-1.2818;

    XX4=X4-AA32;

    AA3=AA31*(-1.05584*XX4^9+12.688*XX4^8-63.70534*XX4^7+172.84571*XX4^6-
274.05701*XX4^5+257.68705*XX4^4-141.40915*XX4^3+44.13177*XX4^2-7.1654*XX4-
0.0495*X1^2+0.4518*X1-0.61655);

    A3=A31*X4^6+A32*X4^5+A33*X4^4+A34*X4^3+A35*X4^2+A36*X4+A37+AA3;

    BWHAT=@(we) A1/we*exp(-A2*(log(we)-A3)^2/1.44);

%% Eddy making component

    FE1=(-0.0182*X2+0.0155)*(X1-1.8)^3;
    FE2=-79.414*X2^4+215.695*X2^3-215.883*X2^2+93.894*X2-14.848;
    AE=FE1+FE2;
    BE1=(3.98*X2-5.1525)*(-0.2*X1+1.6)*X4*((0.9717*X2^2-
```

```
1.55*X2+0.723)*X4+0.04567*X2+0.9408);
      BE2=(0.25*X4+0.95)*X4-219.2*X2^3+443.7*X2^2-283.3*X2+59.6;
      BE3=-15*X2*X1+46.5*X2+11.2*X1-28.6;
      CR=AE*exp(BE1+BE2*X3^BE3);
      BEHAT=@(we) 4.0*we*PHI*3.14/180/(3.0*3.14*X2*X1^3.0)*CR;

%% Bilge keel component

bk = 0.3; %% breadth of Bilge keel
BBKB = bk/dim.Beam;

lk = 40; %% length of Bilge keel
LBKL=lk/inp.Lpp;

    FBK1=(-0.3651*X2+0.3907)*(X1-2.83)^2-2.21*X2+2.632;
    FBK2=0.00255*PHI^2+0.122*PHI+0.4794;
    FBK3=(-0.8913*BBKB^2-0.0733*BBKB)*LBKL^2+(5.2857*BBKB^2-
0.01185*BBKB+0.00189)*LBKL;

    ABK=FBK1*FBK2*FBK3;
    BBK1=(5.0*BBKB+0.3*X1-0.2*LBKL+0.00125*PHI^2-0.0425*PHI-1.86)*X4;
    BBK2=-15.0*BBKB+1.2*X2-0.1*X1-0.0657*X4^2+0.0586*X4+1.6164;
    BBK3=2.5*X4+15.75;

    BBKHAT=@(we) ABK*exp(BBK1+BBK2*X3^BBK3)*we;

    B44= @(we)
(BWHAT(we)+BEHAT(we))*dim.Vol*dim.Beam^2*1.025/((dim.Beam/19.62)^(1/2));
%+BBKHAT; if keel effect
```