DANGERS ARISING FROM APPLICATION OF THE PROBABILISTIC METHOD (AS INCLUDED IN SOLAS 2009 Ch.II-1) TO MEASURING LEVEL OF SAFETY OF CARGO SHIPS

(DOI No: 10.3940/rina.ijme.2018.a3.469)

P S Szulczewski, Gdansk University of Technology, Poland

SUMMARY

From application of a probability based methods to evaluating safety of ships arise certain dangers of hazardous conditions omissions and results misinterpretations. In this paper a few areas in which these dangers occur are identified and described. The purpose of this work was to highlight these areas and suggest a way forward for developing methods for evaluation of safety of ships that would address these identified dangers. In this work the Author focuses on mathematical analysis of selected equations provided in the currently used method as included in SOLAS 2009 Convention. The following factors were selected for evaluation: p_i – probability of a selected damage occurring, s_i – probability of surviving a selected damage, A – Attained Subdivision Index and R – Required Subdivision Index. From the performed analysis the conclusions are drawn that there are numerous areas where application of the investigated method may lead to dangers to maintaining controllable level of ship safety.

NOMENCLATURE

A	Attained Subdivision Index)* representing the probability of a vessel surviving damage [-]
R	Required Subdivision Index)* representing a required value of probability A [-]
p_i	represents the probability that only the zone i under consideration will be flooded, disregarding any horizontal subdivision. [-]
s_i	represents the probability of survival after flooding the zone i under consideration. [-]
A_s	Attained Subdivision Index (A) for the deepest subdivision draught)*
A_p	Attained Subdivision Index (A) for the partial subdivision draught)*
A_l	Attained Subdivision Index (A) for light service draught)*

)* as defined in SOLAS 2009 Part B Ch.II-1 Rules

1. INTRODUCTION

Ships are designed to maximize their capacity and efficiency and in the current model of trade economics it would not make much sense to design and build cargo ships for any other reasons. In order to maintain safety standards in these conditions, the rules are imposed on designers to stay in certain boundaries in their pursuit to maximize cost efficiency with less regard to design impact on life and environment.

For the purpose of implementing safety to design process designers must first introduce a knowledge based regime on their designs. Such regime has to include statistical evidence that clearly shows frequency of serious accidents at sea and from this data the significance levels for safety of ships can be derived. As there is no statistical evidence, that different ship types (cargo ships) are subjected to different levels of risks of colliding or grounding (Neil Ellis, 2007), the population of different types of ships is taken into consideration as a whole. In construction of general methods for controlling safety this may lead to risks of omissions of certain factors that may have impact on safety and possible misinterpretations of the results. One of examples of such problem can be found in the currently applicable to various ship types method as included in the SOLAS 2009 convention. This current method of evaluating safety of ships is based on specific rules and regulations that include analysis of an investigated ship stability. For various types of ships general criteria have been developed. These criteria have been developed not only through modifications of required parameters of righting arm curves, but also by changes in damage scenarios used in such analysis.

To certain ship types different rules are applicable, but for some ships of different type this one regulation applies. Not meeting the specified in the regulation requirements for stability and unsinkability classifies ships as dangerous, and causes that 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 theoretical studies (e.g. Gerigk, 2010, Kendrick 2013). Consequently, analysis of safety of most ships in damaged conditions remains prescriptive and is based on a set of criteria which are based on analysis of a righting arm. To a certain extent this is also applicable for selected vessels to which PSA (Probabilistic Safety Assessment) as included in SOLAS 2009 regulations has been implemented. In this work dangers arising from application from the probabilistic method as included in SOLAS 2009 convention are highlighted. This is achieved by applying mathematical analysis of the elements constituting the method, mainly A, R and the probabilities p_i and s_i.

2. WHERE IS THE CATCH?

2.1 PROBABILISTIC APPROACH TO SAFETY – ATTAINED PROBABILITY - A

The attained level of safety (represented by "A") in the currently used method introduced together with SOLAS 2009 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 damage, respectively (1).

$$A = \sum p_i s_i \tag{1}$$

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 (2) of the mean values obtained from calculations from damage cases to both ship sides and for different draughts: namely the subdivision draught (usually corresponding to the deepest operational draught), the partial draught, being calculated by an adequate formula (SOLAS 2009) and the light service draught (usually corresponding to the lightest draught the vessel may operate in e.g. light ballast draught).

$$A = 0.4A_s + 0.4A_p + 0.2A_l \tag{2}$$

The value of attained safety level for cargo ships, calculated for any of the above mentioned draughts, is in no case to be less than the value obtained by multiplying the required level of safety "R" by a factor 0.5. In case of passenger ships this value is not to be less than 0.9.

At the same time, it is crucial to mention that some assumptions have been made to prepare the formulas for calculation of factors "p_i" and "s_i" (Marie Luetzen, 2001).

The formula for the Required level of safety, in case of cargo ships is a function of length of a ship only, and the condition to be met, as stipulated by the current regulations as described in SOLAS 2009, is (3):

$$\boldsymbol{A > R} \tag{3}$$

2.2 REQUIRED LEVEL OF PROBABILITY A - R

The factors 0.4 and 0.2 applied to calculation of A factor have been derived from practical experience in operation of ships and assumption that any vessel will most likely not be in a fully laden condition when an incident leading to hull damage occurs (2). Because these factors were not in the previous version of the method as included in SOLAS 90 and because the value of the required level of probability "R", against which the value A is compared, was prepared under an assumption that selected vessels meeting the previous criteria must meet the new criteria only (Figure 1) the impact of implementation of these factors on the actual level of safety of ships was investigated and the results of this work are presented in the following Chapters.

In accordance with the official publications (e.g. SLF Committee 47/3/3 – 2004), only one criterion for the actual selection of statistical population 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 the equation for Required Level of Safety "R" because their impact on the final result was considered too big (SLF 47/3/3 2004, influential variables – Luetzen 2001). 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 1). The standard error of fitting the formula for R to this data is estimated at 0.035 which in this case may be considered large. At this point it must be emphasized that the probabilistic method found its application to a much larger number of ship types than General Cargo Ships and Container Ships. These other ships (e.g. Ro-Ro ships, Ore Carriers) have very different internal subdivision and the impact on safety arising from applying the same Required Subdivision Index formula to those ships becomes very difficult to control or measure. In the following Chapter simple Monte Carlo analysis of samples of theoretical (barge shaped) hulls were made and possible dangers for the safety of ships are shown.

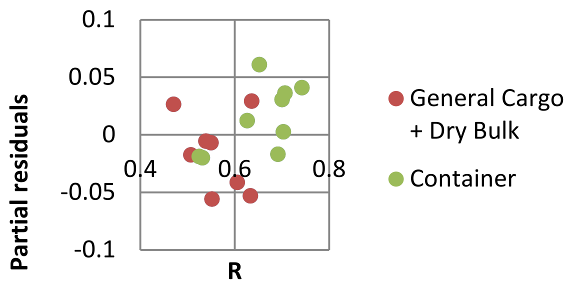


Figure 1. Residual analysis in regression of the population of ships used for preparation of the Required Subdivision Index "R" formula.

3. ANALYSIS OF THE MATHEMATICAL FORMULA SENSITIVITY AND IDENTIFICATION OF DANGERS FROM USING THE PROBABILISTIC METHOD

3.1 PROBABILITY OF A DAMAGE - p

The industry standard for measuring stability of the vessels is to measure their geometrical and basic mass parameters in both intact and damage conditions. There were attempts to introduce other properties of ships as governing stability (e.g. Cichowicz 2012, Kendrick 2013, Szulczewski 2014), but till date they have not found their way to common application.

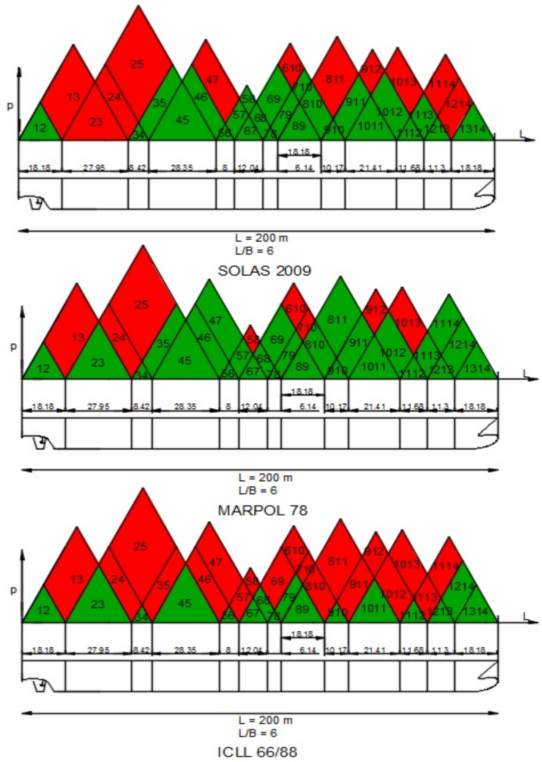
Calculation of "p" factor is performed to account for the probability that compartment(s) of given size(s) may be flooded. In order to present the consequences of the assumptions used in the development of a formula for "p" probability (Luetzen, 2001), a mathematical simulation for the probabilistic method and for older prescriptive methods included in International Convention on Load Lines and MARPOL 78 was made. As the formula for "p" 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, for this simulation length was taken as *constans*, and below this value. 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 value of "p" factor was considered, but because of this assumption, a percentage significance level of damages of certain lengths and for Subdivision Lengths, for comparison against the Required Subdivision Index may be derivable. In order to present the dangers from application of the probabilistic method a calculation was made for the range of non-dimensional lengths ratios for each one zone (i.e. 0,02 to 0,12) and for 2 and 3 regular zones length combinations.

The applied initial conditions and calculation assumptions (Figure 2):

- 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 ship presented in Figure 2 is a theoretical ship, with an assumed subdivision and of an unassigned type. The purpose of introducing such 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. To show this, the values for "p" were calculated for the scenarios when methods included in the regulations ICLL and MARPOL 78 were investigated (Figure 2).

The possible outcome of this is that Master's onboard are not provided with easy to interpret results and must assume an amount of reserve buoyancy of a ship, which may lead to a lack of control over the stability of a vessel in emergency conditions.



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 2. 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 to meet the requirements (as defined by these rules).

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

In addition, it is of uttermost importance to note that a formula governing the probability of the ship being in a collision (represented by “p” - 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. For the purpose of providing more accurate information about safety level offered by vessels such other scenarios would have to be included in the formula for calculation of the probability of damage.

3.2 PROBABILITY OF A VESSEL SURVIVING A DAMAGE - s

The simplified theoretical model presented in Figure 2 does not describe the requirements from SOLAS 2009 in full; In particular, the averaging of the “A” value for different draughts as it was described above (2). In order to show how this averaging of the “A” value may impact the final results another Monte Carlo Simulation for a floating object of constant geometrical shapes, yet of different sizes and size ratios was made. This simulation mathematically confirmed 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 (4)) 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 3).

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

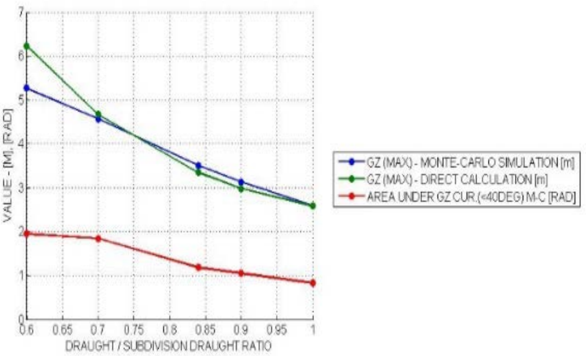


Figure 3. Values of GZ max and area under GZ curve for different ratios of calculated draught to the maximum vessel draught. (Monte Carlo simulation and direct calculation)

The results from this simulation clearly show that when all other parameters (apart from draught) remain unchanged 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 3). This is of course 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 2 were also shown in Figure 3).

The conclusion is that it will be a much easier task to prepare a loading condition for a vessel at less than 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 offer survivability to even one zone damage case scenario (e.g. zone 23 –Figure 2) for any of the examined theoretical loading conditions may then not be 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 is 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 for cargo ships in least favorable initial conditions 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.

One other area where possible dangers of misinterpretations of results from a probabilistic method application occur is in the correlation between formula for the “s” factor and a significant wave height (Table 1) (Cichowicz, 2012). This correlation suggests that survivability of a ship depends solely on the properties of righting arms of vessels and the wave height.

Table 1. Relationship between the factor “s” value and the significant wave height the vessel is to (Cichowicz, 2012).

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

Unfortunately the current formulation of “s” factor does not take into account the probability of a given sea state occurring (Figure 4). There is no proven correlation between weather conditions and probability of hazard occurrence, hence the values of “s” factor, in order to meet the definition of probability of vessel surviving a given damage should be revised in accordance with the available statistical data of sea states.

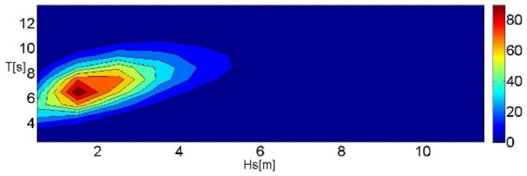


Figure 4. Actual frequency distribution of sea states in function of wave periods and significant wave height for world-wide trade. (Total number normalized to 1000) (Cramer, 1994)

4. COMPARISON OF PROBABILITY CALCULATION RESULTS WITH THE REQUIRED LEVEL OF SAFETY VALUE (R)

In Chapter 3 of this work danger areas arising from calculation of “p” and “s” probabilities are shown. However, the complexity of the investigated method is much larger and there are other areas where dangers to actual safety may occur. As mentioned before, the standards for the new method have been set in such a way 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 method included in the SOLAS 90. 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.

Mathematical comparison between the results obtained by the methods of SOLAS 2009 and previously applicable 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 5).

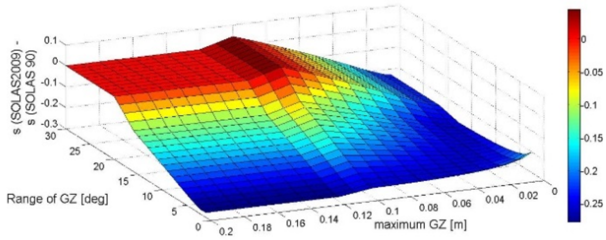


Figure 5. Values of “Δs” function between attained values from SOLAS 2009 and SOLAS 90 for 2 changeable variables (Righting arm range 0,12m to 0,2m is const), Range of positive righting arm curve up to 30 deg).

Comparison between the two methods of SOLAS 2009 and SOLAS 90 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 (Figure 5 and Figure 6). This may raise doubts to controlling, and perhaps even maintaining, a desired level of safety for ships checked with one of this method and not the other.

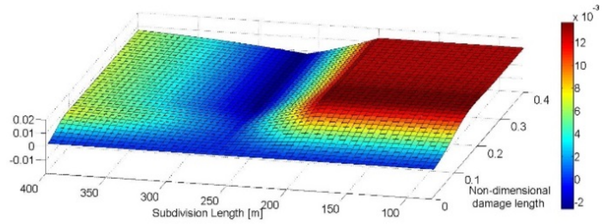


Figure 6. Values of “Δp” function between attained values from SOLAS 2009 and SOLAS 90 for 2 changeable variables (l/λ up to 0,40); Range of length 80 – 400 m.

In order to present the consequences of the assumptions used in the development of “p” factor, another simulation was made. In this simulation 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 obtained. 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.

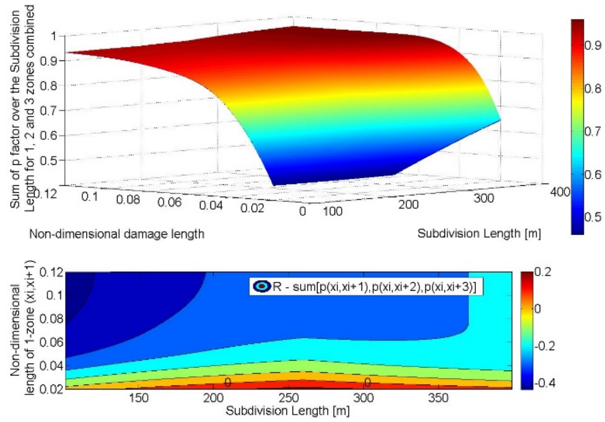


Figure 7. Graphs presenting sums of p-factor for 1 to 3 damage zones in function of Non-dimensional damage length of the 1-zone (upper) and the relationship of this sum to the Required Subdivision Index (below).

The shown in Figure 7 results, present compliance with the criteria (in the shape of function R-A>0) as included in the SOLAS 2009 is granted for ships that meet the same stability criteria for hugely different non-dimensional damage lengths.

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 (Figure 7), which does not corroborate the conclusions from project HARDER (SLF \47/3/3 2004, SLF 45/3/3 2001, SLF 44 Inf.11 2001) and makes it very difficult to control the obtained level of safety.

5. CONCLUSIONS

In this work results from 3 thorough mathematical analysis of formulas from the currently valid methods for assessment of safety of ships are shown.

The results from investigation of the formula for "p" probability primarily indicate dangers of lack of compliance with the "one-zone" damage survivability standard. The results from "s" probability investigation show risks of obtaining large values from lesser draughts when no survivability may be offered at fully laden draught and, further, lack of correlation of the probability value to the probability of an actual sea state occurring at sea (e.g. Cichowicz 2012).

The results from investigation of final "A" and "R" values relationship show risks to maintaining a controllable and uniform level of safety of ships of different types and different subdivisions and revealed that the investigated method may be leading to situation when vessels of different size offer a different level of safety.

As a result of the investigation and analysis presented in the above Chapters 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 and that there is room for improvement in the area of safety of ships.

As previously mentioned, the current industry standard for measuring stability of the vessels is to measure their geometrical and basic mass parameters in both intact and damage conditions. There have been attempts to introduce other properties of ships as governing stability (e.g. Cichowicz 2012, Kendrick 2013, Gerigk 2010), but they have not found their way to common application. However, with digitalization of the design process it starts to be evident that, with limited number of simplifications, a direct calculation of damage cases and dynamical righting moment of vessels is not much more complicated than the calculation of the righting arm on its own, and that its implementation to harmonization of safety of ships could be possible. 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. With this in mind, it would seem feasible to develop more direct rules governing safety of ships in which the danger of misinterpretation of results, or omissions of certain aspects, is mitigated.

6. ACKNOWLEDGEMENTS

The author would like to thank Gdansk University of Technology for their support during preparation of this work.

7. REFERENCES

1. ELLIS, N., "Accident and Incident Data" – 2007
2. GERIGK, M., "Kompleksowa Metoda Oceny Bezpieczenstwa Statku w Stanie USzkodzonym z Uwzglednieniem Analizy Ryzyka" – 2010
3. SOLAS 2009 – Save Our Lives at Sea 2009 Convention – 2009
4. "Report of the Intersessional Correspondence Group (Part 2B) Sample Ship Recalculation Results – SLF Committee 47/3/3 – 2004
5. LUETZEN, M., "Ship Collision Damage" – PhD thesis – 2001
6. CICHOWICZ, J., OLUFSEN, O., "Goal Based Damaged Stability - Project Report "– 2012
7. KENDRICK, A., "Damage Stability Standards – Rational Design or Gratuitous Complexity" – 2013
8. SZULCZEWSKI, P., GERIGK, M., "Application of Quantitative Risk Assessment to Ships in Emergency Conditions" – Journal Pof Polish CIMAC – 2014
9. "Development of Revised SOLAS Ch.II-1 Parts A,B and B-1" – Report from Project HARDER – SLF 45/3/3 – 2001
10. "Development of Revised SOLAS Ch.II-1 Parts A,B and B-1 - Updated Statistics for Extent of Damage" – SLF 44 Inf.11 – 2001
11. GERIGK, M., "Modelling of Hazards, Consequences and Risk for Safety Assessment of Ships in Damaged Conditions in Operation" – SRA-Europe – Pages 3303-3310
12. PAPANIKOLAOU, A., BITHA, K., ELIOPOULOU, E., VENTIKOS, N. P., "Statistical Analysis of Ships Accidents that Occurred in the Period 1990-2012 and Assessment of Safety Level of Ships"– 2015
13. JASIONOWSKI, A., VASSALOS, D., "SOLAS 2009 – Raising the Alarm" – 2008
14. PAWLOWSKI, M., "Probability of Flooding a Compartment (the p_i Factor) – a Critique and a Proposal" – 2006
15. CRAMER, E., LOSETH, R., OLAISEN, K., "Fatigue Assessment of Ship Structures" – 1994

