EVALUATION OF SURVIVABILITY OF A SHIP AFTER DAMAGE WITH APPLICATION OF A RISK CALCULATION METHOD

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SUMMARY

This paper contains calculations of risk for a selected damage case scenario. The calculations took place with use of a risk model designed for evaluating the safety of ships and were compared with the available and published industry standard (as included in SOLAS 2009) as well. The comparison of results is presented in the form of a discussion and concludes that exact risk levels can be obtained at any stage of the vessel's life. The currently valid method as included in SOLAS 2009 regulation provides limited information about the actual survivability of a vessel in emergency conditions. It is hence very difficult to compare the current probabilistic model with risk based survivability calculations to evaluate the actual safety provided by an investigated vessel should it subsequently be severely damaged.

NOMENCLATURE

A_{xx}	total added mass coefficient
A_{WP}	water-plane area
B_{xx}	total roll damping coefficient
C_{xx}	stiffness matrix
Fk	force component, where k = 1, 2, ..., 6
I	total moment of inertia
M_{xx}	Mass matrix
η	ship motion potential
ρ	water density

1. INTRODUCTION

Evaluation of ship safety is a complex problem. There are numerous factors influencing a level of safety from ships to passengers, crew, cargo and the environment in which a floating structure operates.

The safety of ships can be measured in various ways. Till now the industry standard is to measure stability of the vessels by identifying their geometrical and mass parameters in shape of a GZ curve only in both intact and damage conditions. There have been attempts to introduce other properties of ships as governing stability (Cichowicz 2012, Kendrick 2013, Papanikolau 2009), but they have not found their way to common application as yet. The static calculations are based on simplifications and assumptions which does not seem to be entirely necessary as 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 static righting arm on its own. The static calculations, as currently valid, do not show the relation between the changeable with size of vessel relationship between the heeling moments and righting moments. With introduction of dynamical calculations this large error can be greatly reduced.

In the last several years, numerous attempts have been made to formulate a method of assessing safety for ships (Jasionowski 2009, Brown 2002, Kluwe 2009, Wortley 2013, Gerigk 2010 etc.).

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 seems 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.

Currently used 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 floatability 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 theoretical studies. 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.

There are numerous alternative risk calculation models available for calculation of the safety of ships in damaged conditions. One of the models is based on the industry standard formula for risk. This formula is a simple multiplication of probability of a hazard occurring, vulnerability of an object to this hazard and consequences from the response of the investigated object to such hazard. The dangers to ship survivability in form of collision may occur in various weather conditions significantly altering the ship's response to the damage. Therefore for any investigated damage scenario it would seem prudent to calculate the response of the vessel in various weather conditions. The consequences of a vessel surviving or not surviving such damage can then be presented in form of qualitative matrix based on the type of these consequences. In this case the consequences have been divided into terms of life loss, damage to property and harm to environment. The current model for evaluating safety of ships (as included in SOLAS 2009 Convention) does not provide evident information on how the vessel will respond to damage in various weather conditions and what will be the risks from not surviving the damage to these various aspects.

In this paper, there is a presentation of a model for evaluating safety of a vessel after damage in waves. At the same time, an evaluation of a result from currently valid regulation for the identical scenario is presented and included for comparison.

2. CALCULATION INPUT PARAMETERS

For the purpose of presentation of the method, a sample hull shape was selected (Szczecin II) (Figure 1).

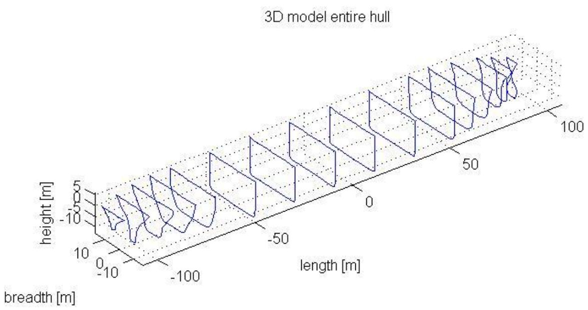


Figure 1. Isometric view of the hull of oil tanker type Szczecin II

The following assumptions were made for the calculations:

- Only one tank 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 subjected to damage 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.

Probability of sea-state condition was calculated for waves ranging in height from 1 meter to 4 meters at various wave periods (Table 1).

Table 1. Range of wave heights and periods investigated for the purpose of comparison of the methods

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

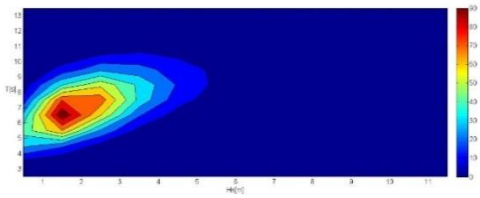


Figure 2. Frequency distribution of sea states in function of wave periods and significant wave height for world-wide trade. (Total number normalized to 1000) (Cramer, 1994)

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.

The flooded tank volume was calculated to be 5847 m^3. This resulted in an increase in submerged volume to 61551 m^3 + 5847 m^3 and an increase in draught to 13.23 m. (at a selected permeability of a flooded compartment equal to 1). The flooding of the tank resulted also in some correction of the centre of gravity position arising from the free surface effect. This was calculated to be 0.52 m. upwards and hence, the corrected centre of gravity shifted to position VCG = 10.16 m.. This new initial condition was calculated numerically. For this condition, the vessel's behaviour on waves was examined in selected most probable weather conditions (Table 1, Figure 2). For the purpose of presentation, the following assumptions were made for the calculations:

- The motion of vessel in waves was calculated in 100 second time and the initial condition of the vessel was at 0 heel and 0 trim. 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 (1) (Faltinsen 1990, Schmitke 1978, Traintafyllou 1983).

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

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

- and

$$\left\{\begin{bmatrix} M & 0 & -Mz_c \\ 0 & I_x & -I_{xz} \\ -Mz_c & -I_{xz} & I_z \end{bmatrix}+\begin{bmatrix} A_{22} & A_{24} & A_{26} \\ A_{42} & A_{44} & A_{46} \\ A_{62} & A_{64} & A_{66} \end{bmatrix}\right\}\ddot{\eta_v}+\begin{bmatrix} B_{22} & B_{24} & B_{26} \\ B_{42} & B_{44} & B_{46} \\ B_{62} & B_{64} & B_{66} \end{bmatrix}\dot{\eta_v}+\begin{bmatrix} C_{22} & C_{24} & C_{26} \\ C_{42} & C_{44} & C_{46} \\ C_{62} & C_{64} & C_{66} \end{bmatrix}\eta_v = \begin{bmatrix} F_2 \\ F_4 \\ F_6 \end{bmatrix} e^{i\omega t}+\begin{bmatrix} F_E \\ M_E/Z \\ M_E/X \end{bmatrix} e^{i\omega t} \quad (1)$$

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 (2,3,4). (Static components of a simplified ship motion equation for heave and pitch (Schmitke 1978, Traintafyllou 1983):

$$C_{33}=\rho*g*\int b\,dl_s=\ \rho*g*A_{WP} \quad (2)$$

$$C_{53}=C_{35}=-\rho*g*\int b*l_s\,dl_s=\ -\rho*g*(z_{LM}-z_G)*A_{WP} \quad (3)$$

$$C_{55}=\ \rho*g*\int b*l_s^2\,dl_s=\rho*g*I_{WPy} \quad (4)$$

Static components of a simplified ship motion equation for roll and sway (Faltinsen 1990):

$$C_{44}=\rho*g*\nabla*(z_M-z_G) \quad (5)$$

$$C_{22}=C_{24}=C_{42}=C_{26}=C_{46}=C_{66}=C_{64}=C_{63}=0 \quad (6)$$

- The static component of the restoring forces 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 called stiffness coefficients 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.
- The maximum recorded heeling angle was compared against the angle of deck submerging which was assumed to be critical for ship survival and with big chances of being repeated in the long run.
- Only the rolling angle was investigated (coupled with the heave motion).
- Only the beam seas condition was modeled.
- The impacts from sloshing and wind were not taken into account in potential-based simulation (sloshing was added in static terms).

3. MOTION CALCULATION RESULTS

Values of roll motion amplitude and roll period were identified on the basis of results presented on Figures 3 - 13 and further used for evaluating the possible impact of sloshing in the flooded tank.

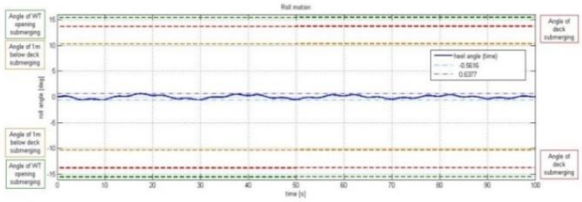


Figure 3. Hs=1m, Tn=5 sec – Roll motion

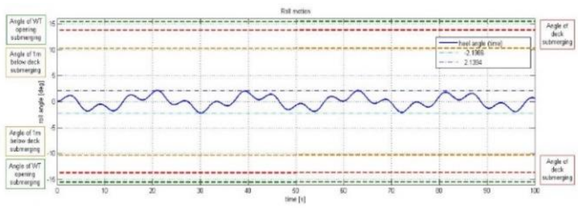


Figure 4. Hs=1m, Tn=6 sec – Roll motion

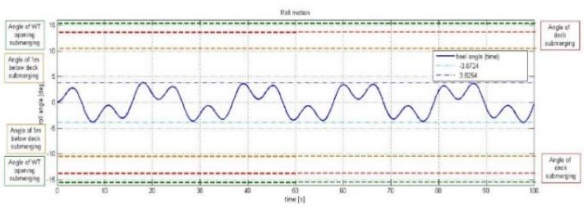


Figure 5. Hs=1m, Tn=7 sec – Roll motion

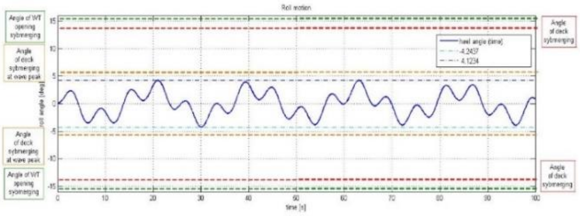


Figure 6. Hs=2m, Tn=6 sec – Roll motion

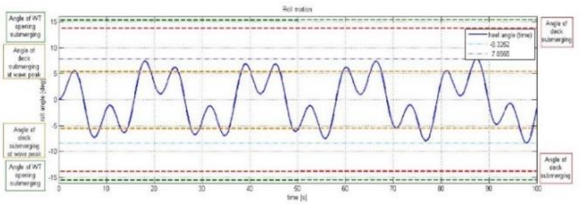


Figure 7. Hs=2m, Tn=7 sec – Roll motion

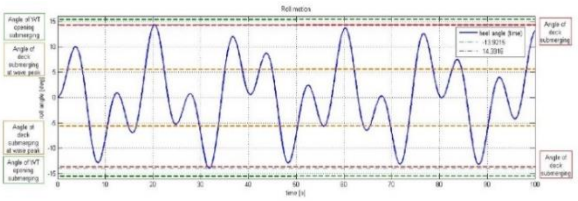


Figure 8. Hs=2m, Tn=8 sec – Roll motion

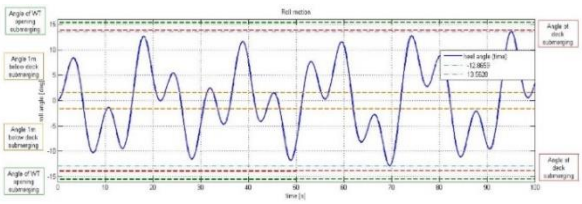


Figure 9. Hs=3m, Tn=7 sec – Roll motion

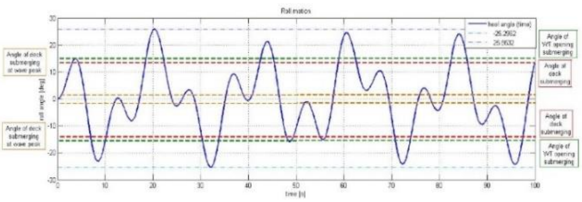


Figure 10. Hs=3m, Tn=8 sec – Roll motion

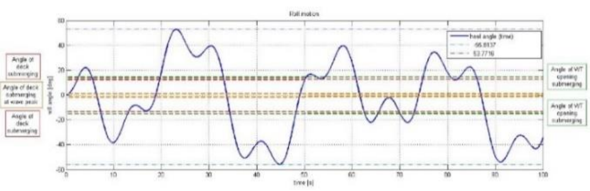


Figure 11. Hs=3m, Tn=9 sec – Roll motion

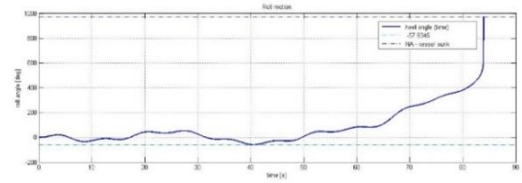


Figure 12. Hs=4m, Tn=8 sec – Roll motion (vessel capsized due to excessive heeling force)

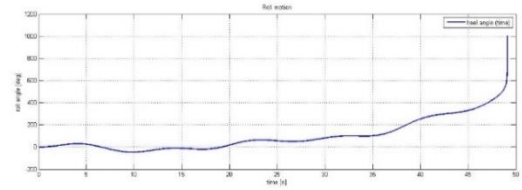


Figure 13. Hs=4m, Tn=9 sec – Roll motion (vessel capsized due to excessive heeling force)

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. In the proposed methodology, a pressure distribution on tank's side and bottom is obtained, by application of InterdymFOAM solver in OpenFOAM program. The forces from fluid in the tank are estimated by a simple integration of pressure on boundaries of the tank. 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.

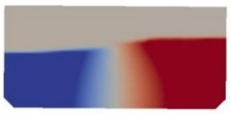


Figure 14. Example of selected tank investigated. Red colour shows area of increased pressure, blue colour of decreased pressure.

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. Kraskowski 2012) (Figure 15).

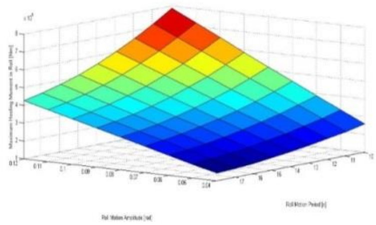


Figure 15. Calculated maximum registered roll moments from sloshing pressure force in a flooded tank (1m length) in function of roll motion amplitude and roll motion period. (The remaining coefficients were fixed for the purpose of this visualization.)

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 model it was achieved with the help of the well-known design formula (6) (Journee 2001, Krata 2013).:

$$\overbrace{2 * n \in N}^{\forall} \omega_{0-TANK} = \sqrt{\frac{\pi * g}{b} * \tanh\left(\frac{\pi * h}{b}\right)} \neq \omega_{roll-SHIP} \quad (6)$$

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.

Table 2. Range of possible values maximum values of sloshing in different weather conditions (in T*m).

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			-	-

Yet another crucial factor to consider is the impact of wind on the motions 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 angle of vanishing stability was calculated to be 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 is taken into account. For the purpose of this simplified model the calculated maximum sloshing force is subtracted from the restoring moment and applied to the GZ curve in static terms. (Figure 16).

For the purpose of risk analysis, three critical angles of heel were identified. The angle at which the wave peak reaches the deck (Jasionowski 2009, Valanto 2003), the angle of static submerging of the deck and static submerging of weather-tight opening on deck (In this case the opening is assumed to be located at mid-ship, 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 obtained are presented in Table 3.

Table 3. 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	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

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 6).

Table 4. Recorded angles of heel prior of taking sloshing in flooded tank into account.

- Green – no risk to survival of ship(no submerging of deck in any condition)
- Yellow – some risk to survival(submerging of deck at wave peak)
- Red – inevitability of loss of ship(submerging of deck 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 5. Calculated maximum angles of heel after applying theoretical maximum impact from sloshing in a flooded tank.

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

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

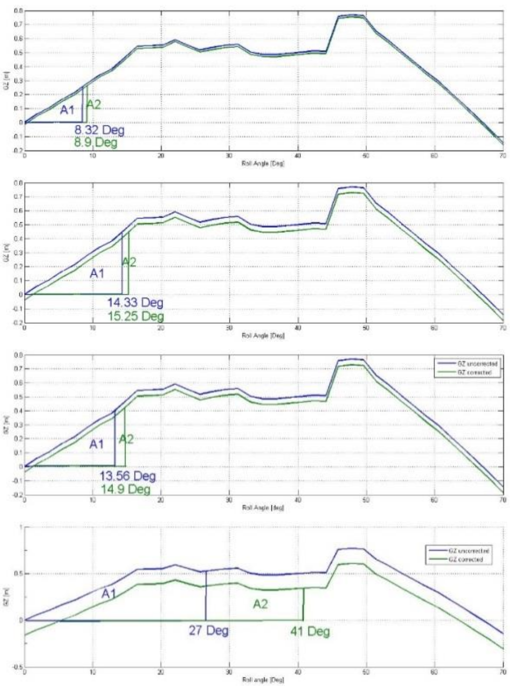


Figure 16. Correction of righting arm curve due to maximum possible impact from sloshing force in investigated flooded compartment

4. RISK CALCULATION

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 P may be calculated on the basis of available worldwide statics for ocean states and for a long period of time.

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 7).

Table 7. Values of probability for selected sea states (not greater than) (See Figure 2) (sum equal to 0.797). Remaining sea states were outside of the investigated domain.

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

At the same time and as presented in multiple studies and supported by statics [eg. Cichowicz 2012], 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). The percentage contribution of each type of hazard is summarized in Table 8.

Table 8. Percentage breakdown of serious accidents.

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

From the above assessment of risk and hence consequences, it was concluded that it is essential to address all the hazards listed in Table 8 separately and risks of serious accidents that lead to damage to property, environment and loss of life without prioritizing any of them. Therefore, a consequence matrix is split into 4 categories, namely:

- Life
- Environment
- Property – cargo
- Property – ship

A corresponding model of risk to life, property and environment (Szulczewski 2017) is utilized. Assuming that the damaged tank was empty before the collision, the risk matrix may look as below (7).:

$$\mathbf{R} = \mathbf{P} * \boldsymbol{V}^{\boldsymbol{T}} * \mathbf{C} = \begin{bmatrix} p_1 \\ \dots \\ p_n \end{bmatrix} * \begin{bmatrix} v_1 & \dots & v_m \end{bmatrix} * \begin{bmatrix} c_1 \\ \dots \\ c_m \end{bmatrix} = \begin{bmatrix} p_1 v_1 c_1 + \dots + p_1 v_m c_m \\ \dots \\ p_n v_1 c_1 + \dots + p_n v_m c_m \end{bmatrix}$$

$$\mathbf{R} = \mathbf{P} * \boldsymbol{V}^{\boldsymbol{T}} * \mathbf{C} = \begin{bmatrix} 0.140571 \\ 0.08296 \\ 0.053002 \\ 0.127449 \\ 0.079489 \\ 0.052845 \\ 0.051745 \\ 0.054954 \\ 0.053349 \\ 0.063692 \\ 0.036671 \end{bmatrix} * \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} * \begin{bmatrix} LIFE \\ ENVIRONMENT \\ PROPERTY - CARGO \\ PROPERTY - SHIP \end{bmatrix} = \begin{bmatrix} 0.3927 * LIFE \\ 0.3927 * ENVIRONMENT \\ 0.3927 * PROPERTY - CARGO \\ 0.3927 * PROPERTY - SHIP \end{bmatrix} \tag{7}$$

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: (e.g. ship sinks = 1) <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 – (Tuzcu 2003, Pawlowski 2010, Santos 2005)) was defined as the point of water reaching deck in static position of the ship.

As indicated in numerous publications (e.g. Gerigk 2010, Kuo 2010, Hausen 2006), 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 made dependent on weather conditions and the most unfavourable position the ship may be in within the first 100 seconds after the incident. The response of the ship in the above described condition to a damage will depend on the flooding of compartments and come into the equation as vulnerability. 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. 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 behaviour on waves after measures were taken to counter a possible dangerous floating condition (Table 6) (8). 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.

$$\mathbf{R} = \mathbf{P} * \boldsymbol{V}^{\boldsymbol{T}} * \mathbf{C} = \begin{bmatrix} 0.140571 \\ 0.08296 \\ 0.053002 \\ 0.127449 \\ 0.079489 \\ 0.052845 \\ 0.051745 \\ 0.054954 \\ 0.053349 \\ 0.063692 \\ 0.036671 \end{bmatrix} * \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} LIFE \\ ENVIRONMENT \\ PROPERTY - CARGO \\ PROPERTY - SHIP \end{bmatrix} = \begin{bmatrix} 0 * LIFE \\ 0 * ENVIRONMENT \\ 0 * PROPERTY - CARGO \\ 0 * PROPERTY - SHIP \end{bmatrix} \tag{8}$$

5. COMPARISON OF RESULTS FROM RISK ANALYSIS WITH THE CURRENTLY VALID CALCILATION METHOD AS INCLUDED IN SOLAS 2009 CONVENTION

The current industry standard is to calculate Attained Probability of a vessel surviving damage scenario. The presented above risk calculation shows the risk of a vessel sinking due to a predefined damage scenario. This corresponds to the "s" factor described as probability of a vessel surviving a predefined damage.

In general the "s_i" is defined as the minimum of the values presented (3) (SOLAS 2009):

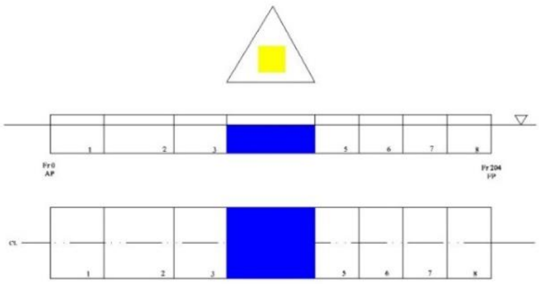
$$s_i = minimum\{s_{intermediate,i}, s_{final,i}, s_{mom,i}\} \tag{9}$$

For cargo ships however, only the "$s_{final,\, i}$" is taken into consideration. The formula for "$s_{final,\, i}$" (10) is a function of stability parameters of vessels at the final stage of flooding.

$$s_{final,i} = K * \left[\frac{GZ_{max}}{0.12} * \frac{Range}{16}\right]^{\frac{1}{4}} \tag{10}$$

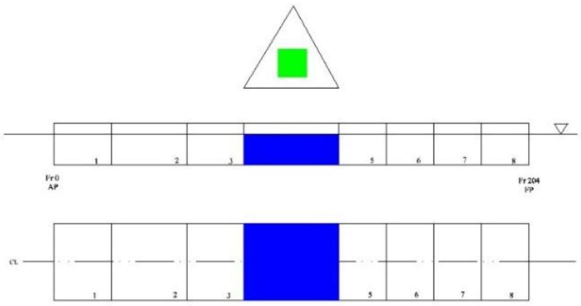
In both cases above, if values of either GZ_{max} or "Range" are larger than the denominatives, the values for calculations are not to be taken greater than these denominatives. Consequently, there is no additional benefit for the value of "s" factor from the values of the above mentioned stability parameters being greater than the values stipulated in the above equations.

Full subdivision draft:



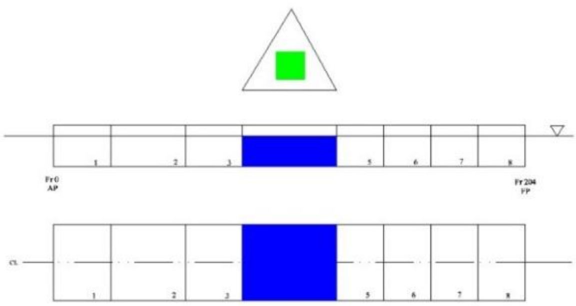
$$p_{1d} \approx 0.024$$
$$s_{1d} \approx 0.992$$

Partial subdivision draft:



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

Light service draft:



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

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

Figure 17. Calculation of A index contribution from flooding the investigated compartment in accordance with the method included in SOLAS2009.

The calculated righting arm properties for the deepest subdivision draft, as defined by the regulation, and corresponding to the one used for the above risk calculations was equal to 0.992 and was just below the value corresponding to full survivability from this damage case. At this stage it is important to mention that as per the current regulation, the calculations are to be carried out for 2 lesser than the deepest subdivision drafts. As the lesser draughts provide greater stability margins the value of "s" factor (9) (Figure 17) for the two of them was equal to one.

The attained "s" factor value is very different from the value of risk obtained from presented in this work methodology. The main reason for that is that the dynamic risk calculations take into account a much greater number of stability determining parameters and are carried out in time domain. Such risk calculation provides information about survivability of an investigated vessel in various weather conditions. The presented calculation of risk of ship sinking after damage may be considered as a more robust and detailed alternative to the method for calculating the "s" factor as it is defined in SOLAS 2009 regulations.

6. CONCLUSIONS

The paper presents a method of assessing safety for a wide range of cargo ship designs. In this work an example of only one vessel is presented and the presented method would still have to be verified for various sizes and types of ships to determine all of its limitations and before introducing it as a valid method for the industry use.

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 in the governing equations 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. With further development, the method presented in this work can become a useful tool for ship designers, insurers and operators.

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