Damaged-Ship Survivability: A Step Beyond Wendel

Kostas J. Spyrou, *School of Naval Architecture and Martine Engineering, National Technical University of Athens*

Iraklis Roupas, *School of Naval Architecture and Martine Engineering, National Technical University of Athens*

ABSTRACT

We are proposing to upgrade Wendel's probabilistic concept of assessment of ship subdivision that has been applied in IMO's probabilistic regulatory framework, including the recent harmonized one. Unlike Wendel's concept where the focus is on the ship, here the emphasis is placed on passenger survival. Index *A* is replaced by a new index reflecting passenger risk. Damage scenarios that lead to ship loss may still contribute to safety, according to the relation between time-to-sink and evacuation time. A calculation procedure is proposed that exploits recent research. Demonstration of the methodology through preliminary application to a modern ferry is included.

Keywords: *ship, damage stability, probabilistic, risk assessment*

1. INTRODUCTION

With his renowned probabilistic concept of ship subdivision, Kurt Wendel introduced a rational theory for quantifying ship survivability in relation to collision scenarios. Challenging the prescriptive practice, he put on the table a method for optimizing subdivision without compromising the specification of a potential damage (Wendel 1960, 1961&1968). The theory, targeting originally sinking, was debated extensively and met almost universal recognition (see Comstock & Robertson 1961; Krappinger 1961; St Dennis 1962; and more recently Abicht 1989, Pawlowski 2004a and others). Reflective of its influence was that it inspired initiatives towards the development of probabilistic regulations for subdivision and stability: firstly for passenger ships as an alternative to the deterministic regulation of SOLAS (IMO 1974; Robertson et al 1974); and in the late 80s for cargo ships as Part B1 in Chapter II-1 of SOLAS (IMO 2004). Recently the theory drove the international collaborative effort to harmonize the probabilistic regulations for passenger and cargo ships, leading finally to Res. MSC.194(80) (IMO 2005).

Parenthetically, in the meantime Wendel's theory had found another use by IMO. It was applied for assessing tanker subdivision in terms of potential oil outflow for collision or grounding scenarios (Regulations 13F&13G of MARPOL 73/78; IMO 1992). Physically, this targets the inverse process i.e fluid going out of ship. But like water ingress, the loss of oil is critically influenced by internal subdivision.

During the Madrid Stability Conference (Perez-Rojas 2003) and with the process of harmonisation of the probabilistic damage stability regulations in full thrust, it was felt that perhaps the context of their next amendment could already be foreseen (Spyrou 2003). On the one hand, the emerging assessment framework was:

- taking on-board improved statistics;
- catering for modern ship forms;
- exploiting modern computational tools for assessing the existing fleet of passenger and cargo ships;

- enabling, thanks to the HARDER project, investigation of deeper issues, such as: the practicality of explicit inclusion of the water-on-deck factor s_w in the probability of survival *s*; the observed differences in safety levels between different ship types and sizes; etc. (Russas 2003; Papanikolaou & Iliopoulou 2004).

Nonetheless it let unquestioned the concept of assessment itself, despite that Wendel's theory had been developed in a rather distant point in the past. In the last twenty years the risk assessment "culture" has pervaded the industry, even recommended by IMO for use during new regulation development (IMO 2002a). Whilst IMO has promulgated use of risk-based methodologies, the new harmonised regulations for damage stability move along, at best, with a very hesitant step. In particular, nominal passenger survivability for collision accidents associated with some design solution cannot be deduced. However, such information is meaningful to the recipient of the service and it could stimulate a real change of attitudes.

In a recent Diploma Thesis at NTUA we investigated whether the assessment framework concerning subdivision and stability could be brought up-to-date without losing its practical edge (Roupas 2006). Progress achieved in this direction is reported in the paper. We begin with the definition of theory's gap, as we perceive it, and a discussion on how it could be filled in a substantive way. Thereafter a methodology is shaped-out that incorporates the missing elements. To a large extent we have relied on existing calculation techniques, with some modifications, as our emphasis is on proving the feasibility of integration. Application is undertaken for a modern passenger ferry and some first quantitative results of passenger risk associated with damage stability are obtained.

2. CONCEPTUAL GAP

The calculation of the *attained subdivision index A* is an exercise in conditional probabilities where the occurrence of side damage and flooding are taken as certainty. Location and key dimensions characterise an opening *i*. The probability of occurrence of *i* is multiplied by an estimate of the probability of ship survival given the *i*. Damage scenarios that affect the same group of compartments can be treated collectively because in a static or semi-static context they lead to identical consequence concerning the ship. The same applies, albeit in a more approximate way, about the representation of the true opening by its max dimensions. Eventually, *A* is determined by summing up these products of probabilities. The index *A* (or rather 1-*A*) falls short of reflecting the risk of losing the ship due to a side collision, only because the probability of collision with flooding does not show in the first place.

As well-known, *A* may not go less than the *required subdivision index R*. Such an index is not mentioned in Wendel's papers. According to IMO, for cargo ships *R* should be a function of length; while for passenger ships it should be based, in addition, on the number of persons in peril as represented by two figures: the number of those on board for whom life-boats are provided; and the number of the remaining passengers plus the officers and crew. Index *R* (or better 1-*R*) is reminiscent of an "acceptable risk" figure. For passenger ships in particular, it addresses empirically both the ship and the passengers; albeit in such a way that, the actual units of (let indirect) risk measurement may not be deduced in a consistent way (see on this Pawlowski et al 2005). The weighting factors that appear in the *R* formula result from regression analysis of *A* values of the current world fleet of passenger ships. Safety is thus warranted by placing the *A* value of the contemplated ship, deeply into the domain of *A* values of ships with similar length and number of passengers.

In summary, Wendel's probabilistic concept and its offspring IMO assessment procedures go some way towards achieving a quantification of a ship's ability to resist sinking and capsize on a relativistic basis (in the sense that a higher A or R generates a higher prospect of survival – even this however is disputed by some). Yet, they tell little concerning the probability of loss of life which should be the primary concern and a more appropriate unit for quantifying safety as far as passenger ships are concerned. Instead of R, one would prefer to know the acceptable probability of loss of life concerning a random collision accident.

Another point is that, all damage scenarios resulting in ship loss are treated uniformly as non-contributors to the attained index A. However, even for such unfortunate damage scenarios the probability of loss of life is not unequivocally 1.0, unless the time in distress is unduly small. Ship layout, life-saving equipment, standard of training of officers and crew, all influence quantitatively the probability of safe abandonment.

Reference is finally worthy to the global picture: a risk-based approach offers a wider scope and the opportunity of setting a uniform platform for ship safety assessment; i.e. system imperviousness to hazards can be measured under a single roof. The analysis of damage stability could thus be interfaced with those of intact stability, fire safety etc. where progress is already noted in convergent directions (e.g. Fukuchi & Imamura 2005). The setting an overall risk level associated with a specific ship (real or on the drawing board) may already be foreseen. However, the development of reliable and robust assessment methods for the individual hazards should precede.

3. RELATED WORK

The idea of interfacing distress time with evacuation probability is not heard for the first time. To the authors' knowledge, this was dealt firstly in a systematic way by Alexandrov (1970) in the context of assessing the effectiveness of life-saving equipment. In discussing this paper, Wendel noted that the issue had been considered also before, but at a rather speculative level.

Prediction methodologies of the "time-to-sink" as function of ship layout, significant wave height etc, as a step toward setting passenger survival criteria, have been discussed by the Strathclyde group (Vassalos et al. 1997; Jasionovski et al. 2004), by van't Veer et al. (2002 & 2004) and others. Models for the process of accumulation of water on the vehicle deck have been proposed by Vassalos et al. (1997), Hutchison (2000), Pawlowski (2003). The trend is to assume weir type and "through submerged opening" flows with some empirical correction; then to determine accumulation by subtracting the rate of outflow from the rate of inflow.

Evacuation time is currently regulated according to MSC/Circ.1033 (IMO 2002b). In parallel there is growing interest for a more global characterisation of ship "evacuability", expressed through an index combining several evacuation simulation runs (e.g. see Vassalos et al. 2002; Doliani et al. 2004).

It should be noted that the debate for "risk-based" damage stability assessment and the possibility of a unified context with other hazards is already underway. See Vassalos (2004) and recent DnV publications (Vanem & Skjong 2004; Rusas & Skjong 2004).

4. OUTLINE OF METHODOLOGY

In the rest the discussion is confined to damage stability only. The key points of the approach are summarised next (see also Fig. 1):

The attained index A as well as the required index R is converted to reflect directly the level of risk: the attained risk level (AR) must be lower than the required maximum tolerable risk of passenger loss (TR) proportioned to collision scenarios. Therefore, instead of $A \geq R$ the new condition to be satisfied will be: $AR < TR$.

The attained risk will be determined from the summation $\sum P_i \cdot NPL_i$ where P_i is the probability of occurrence of the i damage scenario and NPL_i is the subsequent nominal passenger loss. To exploit damage statistics and/or analytical studies, P_i could be regarded as the product $P_i = P(c) \times P(hr|c) \times P[f|(hr|c)]$, where c stands for collision, hr for hull rupture and f for flooding.

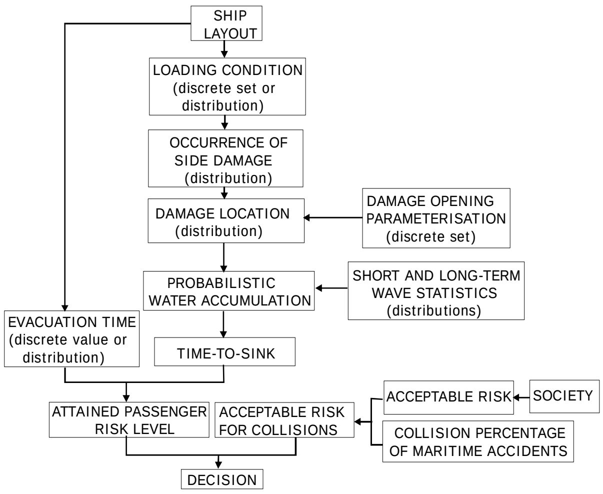


Fig. 1: Concept of assessment.

There is little prospect in parameterising an arbitrary shape. For practical reasons the true opening could be represented by an "equivalent Euclidean" shape. But, unlike the basically static viewpoint of Wendel (and of current regulation), generally the consequence is critically dependent on the rate of accumulation of water on the vehicle deck that is a dynamic process. The role of opening's shape (let alone the size, setting in question the principle of geometric similarity, see Katayama et al 2006) should be investigated as it may hold influence.

To determine the nominal passenger loss associated with the i damage scenario, NPL_i, we need the corresponding time-to-sink and the curve of passenger evacuation rate as function of time. The time-to-sink is the time to reach the critical water accumulation. IMO have urged ITTC to carry out benchmarking of simulation tools that claim to predict this. Nonetheless, from a dynamics viewpoint, the sinking process is very slow and perhaps a semi-static approach might be of some utility.

Flooding could be split into a first part where the affected lower compartments are filled (the sinking process is monitored from the damage freeboard, i.e. through recordings in time of the mean sinkage, list and trim); and a second part where water accumulates on the vehicle deck, as soon as the damage freeboard has become small. Simplified modelling of these processes is customarily based on Bernoulli's equation with water ingress and egress mechanisms considered separately (e.g. Pawlowski 2003). Then, for some damage scenario i, the flooding model is used in order to calculate the probability of accumulation of the critical (for capsize) quantity of water on the deck.

More specifically, water ingress could be expressed as:

$$\frac{dV_{in}}{dt} = Q_{in} = k_{in}\, A(t)\sqrt{2g\left(\eta(t) - f_r\right)} \qquad (1)$$

f_r is the residual freeboard that is a slowly decreasing variable in time; $A(t)$ is the area of the opening above the mean waterline that has a fast periodic time dependence (with the wave cycle) and a slow one as the ship sinks; $\eta(t)$ is water elevation at the opening; and k_{in} is an empirical correction coefficient accounting for the "non-stationary" character of the flow and all "other" effects. For linear upward variation of the area A we obtain:

$$A(t) = \begin{cases} A_{\max}\left(\dfrac{\eta(t) - f_r}{z_{\max}}\right), & f_r < \eta(t) < z_{\max} - d + f_r \\[2ex] A_{\max}\left(1 - \dfrac{d}{z_{\max}}\right), & \eta(t) > z_{\max} - d + f_r \end{cases} \qquad (2)$$

$A_{\max}$ is the total area of the opening, z_{max} is the height of the opening and d is ship's depth.

With combination of the above and integration we should arrive at the following expression of water ingress per wave cycle:

$$q_{in} = \frac{\delta V_{in}}{\delta n} = \frac{A_{\max}\, k_{in} \sqrt{2g}}{z_{\max}} \left[\int_0^{t_1} \left(\eta(t) - f_r\right)^{\frac{3}{2}} dt + \int_{t_1}^{t_2} \left(z_{\max} - d\right) \sqrt{\eta(t) - f_r}\, dt \right] \quad (3)$$

with $t_1 + t_2 = T_Z$. The time intervals of the integration are the parts of a period where the opening is partially or fully submerged. In the calculation of (3) it is convenient to substitute $t_1 = \tau_1 T_z$, $t_2 = \tau_2 T_z$. For the current analysis, sea surface elevation could be assumed as Gaussian with zero mean. A direct attack based on elevation is computationally more intense than using the crest statistics and assuming (superficially) harmonic elevation. Then, the Rayleigh distribution for the wave amplitude η_0 can be used, expressing $\eta(\tau T_z)$ ($0 \le \tau \le 1$) and τ_1, τ_2 directly as functions of f_r and η_0.

For Gaussian sea, well-known relations hold between standard deviation σ, zero spectral moment m_0, and significant wave height H_s. Since the procedure is not applied for any particular wave environment, a standard spectrum like ITTC's could be selected. In previous analysis the mean period, determined easily from the first spectral moments, has been in used in the calculation of q_{in} [in this case T_z is replaced in (3) by $\bar{T}_z$]. However it is possible to use the distribution of wave period (e.g the parametric model of Longuet-Higgins 1962); or better the joint distribution of height and period (Longuet-Higgins 1983). To what extent the statistics of the wave field near to the ship deviate from the Gaussian is not clear. Furthermore, the significant wave height experienced at the damage opening should be affected by the motion of the ship. Vassalos et al. (1997) used $H_s^{1.3}$ as relative wave height. In Jasionowski et al. (2004) an empirical correction that involved m_0 was proposed.

From long-term wave statistics we can obtain marginal distributions of H_s; such as the 3-parameter Weibull. Introducing long-term statistics into the flooding calculation enables to seek a probabilistically-based design solution for ship life-cycle, instead of assessing for any particular sea-state.

Knowing the distribution of the period (or the joint of period and height), we find the pdf of q_{in} by a transformation of variables:

$$f_{q_{in}}(q_{in}) = \int_R n(q_{in}, z)\, dz \quad (4)$$

$$n(q_{in}, z) = f_{H, T_z}(H; T_z)\, |J| \quad (5)$$

The auxiliary variable z is some function $z = g(\eta_0, T_z)$, with domain R. Their choice is basically arbitrary. The Jacobian J of the transformation is:

$$J = \begin{vmatrix} \dfrac{\partial \eta_0}{\partial q_{in}} & \dfrac{\partial \eta_0}{\partial z} \\ \dfrac{\partial T_z}{\partial q_{in}} & \dfrac{\partial T_z}{\partial z} \end{vmatrix} \quad (6)$$

Assuming that the transformation is strictly one to one, the Jacobian does not change sign over the sample spaces of q_{in}, z. If a constant (mean) period had been used in (3), and since the q_{in} is strictly increasing function of η_0, its pdf is obtained from the 1d version of (5):

$$f_{q_{in}}(q_{in}) = f_{\eta_0}\left[\eta_0(q_{in})\right] \cdot \left| \frac{d\eta_0}{dq_{in}} \right| \quad (7)$$

In the absence of a more rigorous inflow model, an empirical correction coefficient k_{in} is necessary which however does not seem to behave like a constant (see for example NMI 2001). To circumvent this, Jasionowski et al (2004) considered the lognormal as a good probabilistic description of k_{in}'s variation on the basis of experimental data. It is perhaps unlikely that k_{in} and q_{in} are independent to each other but their joint pdf $f_{k_{in}, q_{in}}$ is unknown. The pdf of the product is:

$$f_{q'_{in}}(q'_{in}) = \int_{-\infty}^{\infty} \frac{1}{|q_{in}|} \cdot f_{q_{in}}(q_{in}) \cdot f_{k_{in}}\left(\frac{q'_{in}}{q_{in}}\right) dq_{in} \quad (7)$$

where $q'_{in} = k_{in}\, q_{in}$. A similar procedure can be applied for the outflow, with some simplification in the calculation of the correction factor k_{out}: this is determined according to the ratio of the accumulated water-on-deck after m wave cycles, to the ultimate quantity that corresponds to the critical height. Then an empirical distribution is assumed that fits experimental data (see Jasionowski et al. 2004 for details).

The pdf of net inflow per cycle ($q'_{net} = q'_{in} - q'_{out}$) is then found with the standard formula of subtraction of probabilistic variables. With the (rather arbitrary) assumption of independence of q'_{in} and q'_{out}, this is simplified to a convolution integral:

$$f_{q'_{net}}(q'_{net}) = \int^{\infty} f_{q'_{in}}(q'_{in}) \cdot f_{q'_{out}}(q'_{in} - q'_{net})\, dq'_{in} \tag{8}$$

To determine the pdf of net inflow after N wave cycles Jasionowski et al. (2004) proposed to use the central limit theorem: as N increases, the distribution of the total inflow q'_N should approach the normal one, with mean and standard deviation determined from q'_{net}.

5. COUPLING WITH EVACUATION

Scenarios that lead to ship loss may contribute differently to the attained passenger risk index, according to the percentage of passengers that could abandon the ship given the corresponding time-to-sink. By shifting the emphasis from the ship to the passenger, there is no need of calculating the conventional s.

Evacuation time is assessed either by the simplified method of MSC/Circ. 1033 (IMO 2002b) or with use of some certified evacuation simulation software. The first is basically deterministic. The latter could support a probabilistic assessment of evacuability per damage scenario and overall. The current IMO requirement is prescriptive; e.g for Ro-Ro passenger ships, evacuation (for day and night scenarios of passenger distribution etc.) must be completed within 60 mins. Should the evacuation assessment be interfaced with the calculation of the corresponding time-to-sink, such a requirement is relaxed[1]. Qualitatively, the percentage of safe passengers is likely to be ascending slowly with time initially (i.e. when the time-to-sink is much below the purported evacuation time); then to rise steeply upwards and finally to approach asymptotically the “all passengers safe” value for very large time-to-sink. This reminds the sigmoid exhibited for example by the logistic equation, often used for modelling population growth. Also, cumulative probability functions of standard distributions reproduce this pattern. We should note that a damage is likely to restrict access to certain spaces and escape routes. It would make sense therefore, the calculated evacuation time to become specific to each damage scenario.

6. APPLICATION

The test ideas we assessed the damage stability of a modern ferry design, whose particulars are given in Table 1. Vessel layout and a rendered view are shown respectively in Figs. 2 and 3. It was feasible to investigate only a reduced number of damage scenarios referring to the full-load departure condition. We concentrated on damages of two and three lower compartments, with the vehicle deck always damaged. Permeabilities were taken as in the new harmonised regulations.

Table 1: Vessel particulars

Length (*overall*):	123.8 m	*Passengers*:	1500
Breadth (*mld.*):	18.9 m	*Trailers*:	21
Depth (*mld.*):	7.25 m	*Cars*:	94 (199)
Design draft:	4.9 m	*Service speed*:	23.8 Kn

The calculations were carried out as follows: The probability of collision was taken as the statistical frequency of collision based on historical data, determined by Olufsen et al (2003) as 5.16×10^{-3}. For the probability of

[1] Of course, fire safety requirements should also affect strongly the specification of evacuation time.

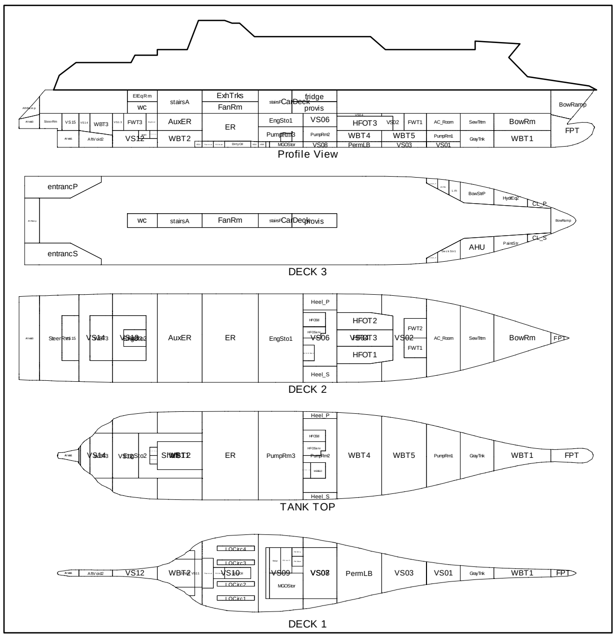


Fig. 2: Ship layout

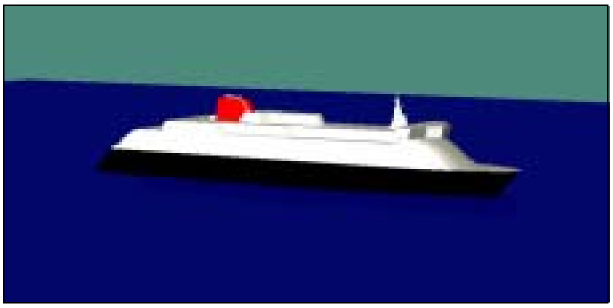


Fig. 3: Rendered view of ferry

flooding given the collision, it is suggested by Vanem & Skjong 2003 to take it simply as 0.5. Here however flooding was assumed as certain. Thereafter, given the flooding, the critical accumulation of water on the deck up to the height where restoring capability is brought to naught ("point-of-no-return") is determined for each damage scenario. The flooding process is broken into discrete intermediate stages (around 10, plus the 'final' one of the critical water accumulation). The first stages refer to the flooding of lower compartments; flooding of the vehicle deck begins later, as soon as the mean waterline comes near to the deck. For each discrete stage of flooding the hydrostatic characteristics of the ship are calculated in TRIBON M2. The time elapsed between stage *j* and stage *j*+1 is determined according to the rate of influx of the additional quantity of water. Intermediate results for one damage scenario are collected in Table 3.

Evacuation time was predicted with the simplified IMO method. For details of the calculations see Roupas 2006. For the worst-case scenario, the predicted time was 33 min (Table 2); i.e. much lower than the required 60 min (this is because the ship has a very small number of cabins). Evacuation rate was assumed to follow the sigmoid $F(t)$ shown in Fig. 4. A single evacuation curve was used for all damage scenarios. The nominal time-to-sink required for 100% safety might be obtained by dividing the max evacuation time by a safety factor. Here however this factor was taken as 1.0. For the calculated time time-to-sink t_i , the anticipated loss (as a ratio) is $1 - F(t_i)$.

Table 2: Predicted evacuation time per scenario

Condition	*Time* (min)
Day 1	28
Day 2	29
Secondary day	31
Night 1	33
Night 2	32
Secondary night	33

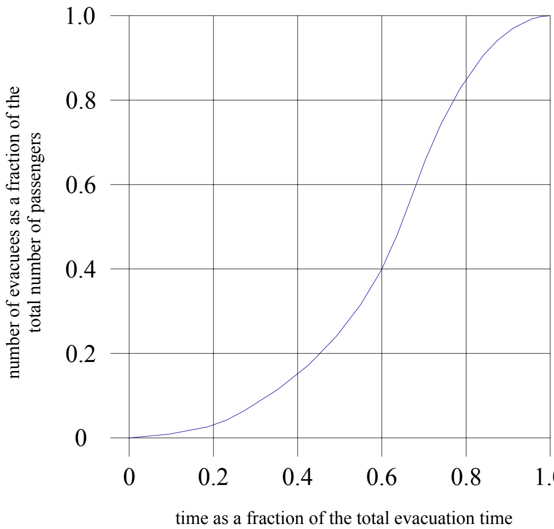
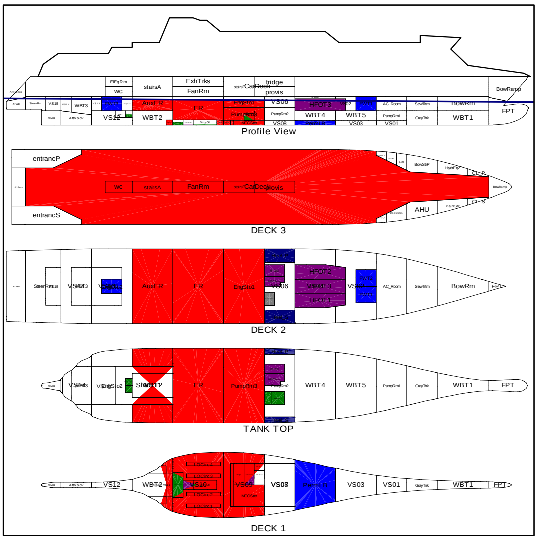


Fig. 4: Assumed evacuation rate



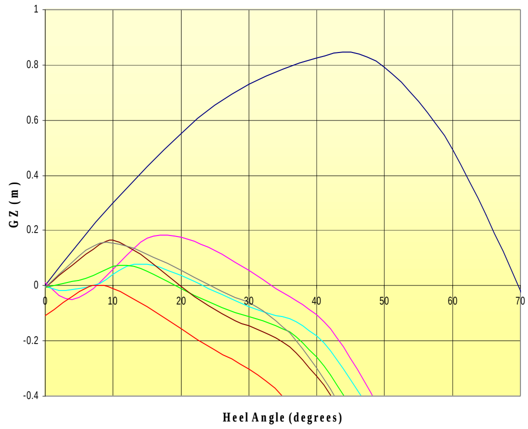


Fig. 5: 3-compartment damage scenario (D000) and GZ curves at various stages of flooding.

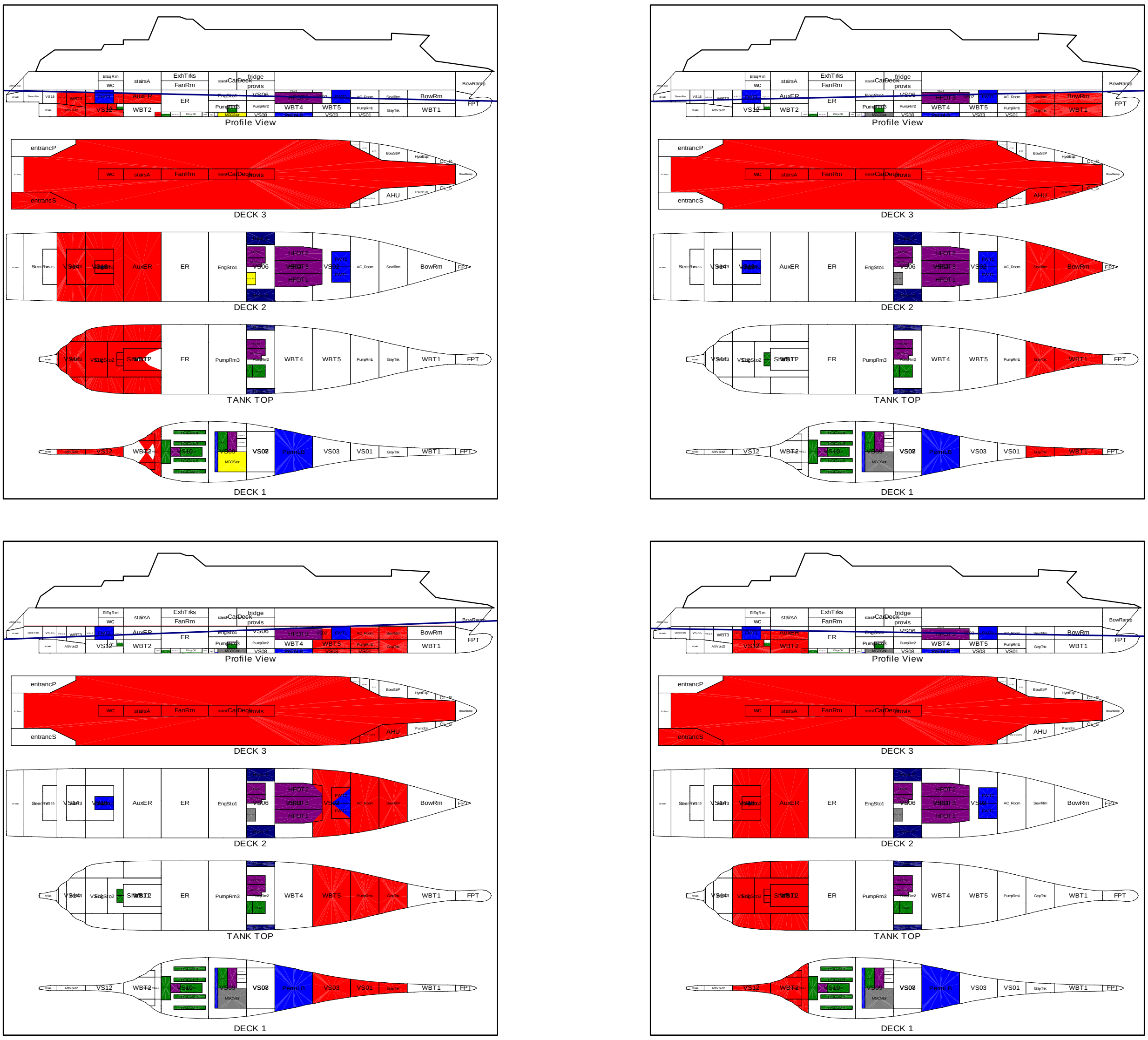


Fig. 6: Other examined damage scenarios

The probabilities of damage and survival, as well as their contribution to the customary index *A* were identified for damages exceeding the deck height (Table 4). As expected, the 2-compartment damages produce *s* values very near to 1.0. In Table 5 on the other hand, is shown the contribution that each of the five presumed damages makes to the proposed "attained risk" index *AR*.

To develop an overall feeling about the method, we have carried out a rudimentary calculation of the overall risk level under some empirical assumptions concerning loss of life per scenario and loading condition. These are summarised in Table 6. The obtained value of the *AR* index appears logical.

As a further test, the procedure was run for different freeboards (by artificially raising deck's height) with all other factors kept unchanged. Depending on the damage scenario, for an increase of height by 30 cm the obtained reduction of risk was between 10 and 45% (Table 7).

Finally, we considered the effect of ship's evacuation time on the attained risk *AR*. Artificially again we raised the evacuation time to 60 mins that is the maximum allowed according MSC/Circ. 1033. The evacuation curve was scaled accordingly. The result was that the risk increased, albeit rather mildly (Table 8). It is concluded that, at least for this particular ship, a change of freeboard bears a more pronounced influence on risk.

Table 3: Accumulation of water per stage, for damage scenario D000.

Damage scenario	p_i	v_i	s_i	*Contr/ion to A*
D000	0.09052	0.5128	0.558	0.0259
D001	0.01953	0.5128	0.068	0.0007
D002	0.06527	0.5128	0.986	0.0330
D003	0.03531	0.5128	1.000	0.0181
D004	0.02161	0.5128	0.997	0.0110

Table 4: Contribution to A of damage scenarios according to the standard method.

Stage	*Water in*, [tons]	*Draught at AP*, [m]	*Draught at FP*, [m]	*Trim*, [m] *(+ by stern)*	*Heel*, [deg] *(+ to strbrd)*	*Residual freeboard* [m]	*Height of water out* [m]
1	0.0	4.99	5.14	-0.15	0.0	2.21	5.04
2	354	5.15	5.23	-0.08	7.7	0.79	6.46
3	802	5.36	5.33	0.04	10.9	0.09	7.17
4	1043	5.62	5.44	0.18	7.5	0.49	6.81
5	1269	5.77	5.56	0.23	1.4	1.33	5.93
6	1475	5.89	5.64	0.25	1.0	1.28	5.96
7	1656	5.98	5.67	0.31	0.77	1.23	6.00
8	1821	6.09	5.74	0.36	0.3	1.21	6.01
9	2381	6.52	5.85	0.67	0.2	0.83	6.32
10	2483	6.60	5.87	0.73	0.2	0.77	6.36
WoD	2537	6.71	5.84	0.87	7.5	0.44	6.69

Table 5: Contribution of damages to the new risk index *AR*.

Damage scenario	*Critical water on deck*, [tons]	*Critical height of water on deck*, [m]	*Average NPL*, [fatalities per incident]	*Contribution to risk AR* (annual basis)
D000	84.1	0.110	355	2.27E-05
D001	156.5	0.263	502	6.91E-06
D002	674.7	0.472	455	2.09E-05
D003	1817.4	1.150	126	3.31E-06
D004	1014.4	0.777	133	1.90E-06

Table 6: Simplistic calculation of overall risk index AR.

Loading condition	*Type of damage*	*Damage Probability*	*Average NPL (fatities per incident)*	*Contribution to AR*
Subd/sion, DS (× 0.4)	1cf	0.3699	0	0.00E+00
	2cf	0.4412	129	7.83E-05
	3cf	0.1263	437	7.59E-05
	≥4cf	0.0626	1350	1.16E-04
Partial, DP (× 0.4)	1cf	0.3699	0	0.00E+00
	2cf	0.4412	116	7.05E-05
	3cf	0.1263	393	6.84E-05
	≥4cf	0.0626	1215	1.05E-04
Light, DL (× 0.2)	1cf	0.3699	0	0.00E+00
	2cf	0.4412	103	3.13E-05
	3cf	0.1263	350	3.04E-05
	≥4cf	0.0626	1080	4.65E-05
Risk AR= 6.22E-04				

Table 7: Effect of freeboard.

Damage scenario	Contribution to risk index *AR*		Average Nominal Loss [fatalities per incident]		Δ*AR* [%]
	freeboard 7.25m	freeboard 7.55m	freeboard 7.25m	freeboard 7.55m	
D000	2.266E-05	1.889E-05	355	296	-16.63
D001	6.912E-06	4.340E-06	502	315	-37.21
D002	2.093E-05	1.898E-05	455	412	-9.31
D003	3.315E-06	2.236E-06	126	90	-32.54
D004	1.900E-06	1.056E-06	133	79	-44.42

Table 8: Effect of evacuation time.

Damage scenario	Contribution to *AR*		Average Nominal Loss [fatalities per incident]		Δ*AR* [%]
	Evac. time 33 min	Evac. time 60 min	Evac. time 33 min	Evac. time 60 min	
D000	2.266E-05	2.531E-05	355	398	11.70
D001	6.912E-06	8.042E-06	502	606	16.35
D002	2.093E-05	2.292E-05	455	505	9.47
D003	3.315E-06	4.013E-06	126	163	21.05
D004	1.900E-06	2.390E-06	133	175	25.81

7. CONCLUDING REMARKS

A method for improving the current procedure of probabilistic damage stability assessment has been proposed and application was pursued for a modern ferry. Resistance to sinking, layout of passenger spaces for ease of evacuation, effectiveness of life saving equipment, especially in respect to the anticipated time history of sinking, could be integrated within a single procedure. This is one, if not two, steps beyond Wendel's approach.

In the paper we have focused specifically on the various stages of calculation of the attained risk level. Nonetheless, the specification of threshold tolerated risk is also an important one. This matter needs to be debated extensively as different principles may be followed, e.g. a uniform risk across the principal modes of mass transportation; or individual risk level for the transportation of passengers by sea, that respects current safety statistics etc. Norms of individual or societal risk are often mentioned in the literature and possible calculation methods for these norms have been proposed (Safer Euroro, 2003; Skjong & Ronold 1998).

Whilst the evolving method is conceptually strong, the critical question that will determine practicality is whether calculation procedures could be defined that show potential to gain wider acceptance and thus become standardised. Amidst an environment where the urge for performance-based assessments has led to a plethora of numerical tools that do not necessarily converge to identical predictions, it seems that this task should be tackled earlier rather than later.

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