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TIME-BASED SURVIVAL CRITERIA FOR PASSENGER RO-RO VESSELS

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SUMMARY

This paper outlines the study undertaken within the framework of research aiming to address the compound problem of the absolute time available for passenger evacuation on a damaged passenger/Ro-Ro vessel undergoing large scale flooding of car deck spaces. Deriving from extensive experimental information and utilising SEM principles, a methodology for predicting ship survival time is proposed that accounts for wave characteristics, water ingress/egress and vessel survivability. The progress achieved to date is discussed and aspects needing further investigation are highlighted.

NOMENCLATURE

H_s	Significant wave height
T_z	Zero crossing period
T_p	Modal period
α	Significant wave steepness
λ	Wave length
γ	Spectral peakness parameter
f	Residual or instantaneous freeboard
ξ	Wave elevation
a	Wave amplitude
Q	Flooding rate
K	Flooding coefficient
dA	Flooding opening area
l	Flooding opening length
$\overline{\omega}$	Mean wave frequency
ω	Wave frequency
m_j	jth spectral moment
$S(\omega)$	Wave energy spectrum
σ_n	Random phase angle
$\rho(t)$	Envelope process
H_a	Number of waves in a high-run
G_a	Number of waves in a group
ε	Spectral bandwidth

1 INTRODUCTION

As history has repeatedly shown, maritime disasters bring about highly emotional societal response, in particular when large number of casualties is involved, leading to grief and often anger that overwhelms the ensuing political processes. These in turn often provoke imprudent deployment of efforts to improve safety, ultimately leading to new legislation that disregards many evolutionary aspects of ship design and operation primarily due to inadequate understanding of the complex processes involved in ship foundering.

Serious deficiencies in safety standards, regarding in particular ship and passenger survival, are exemplified by recent well-publicised accidents of Ro-Ro passenger vessels, notably that of *Herald of Free Enterprise* and the *Estonia*, where due to very rapid deterioration in their stability no adequate time to orderly evacuate passengers and crew was available, resulting in large number of casualties in both accidents. Although strict new regulations have since been adopted internationally, arguably leading to safety improvements, the question of how long it takes a vessel to capsize from a breach in her hull has yet to be answered satisfactorily.

Deriving from the above, it is the aim of this paper to call for a pro-active philosophy towards the problem of passenger survival and to encourage, through stimulating discussion, more research effort to better understand the processes involved in the loss of stability of Ro-Ro passenger vessels in case of large scale flooding in order to ensure that the minimum required time for such vessels to maintain their function as safe passenger-carrying platforms is provided.

As mentioned above, to date no direct guidelines or regulations have been proposed as regards minimum ship survival time, which seems to defy logic in face of the new SOLAS Regulation 28-1-3, [4], in force since 1 July 1999, which together with the IMO MSC/Circ.1033 set maximum evacuation time of passengers and crew at a level of no more than 60 minutes for newly built Ro-Ro vessels. A series of full scale evacuation trials, e.g. [5] as well as simulations by means of state of the art numerical techniques, [6], have confirmed that this level seems to appropriate.

The subject of survival time has recently been investigated in [2], whereby limited experimental data, supplemented with extensive time-domain numerical simulations, [7], have allowed for better understanding of concepts associated with survival time, as well as for proposal of quantitative survival time criteria. The developed formulae was based on the Static Equivalent Method (SEM), [1], with the relationship between the SEM floodwater elevation, *h*, and the relevant critical sea conditions, H_s, adjusted according to the available statistics on survival time. These statistics, in turn, were derived based on the concept of a band of critical sea states, see Figure 1, in which a ship with breach in her hull would sustain an acceptable attitude (heel less than 20deg) for time varying from above 60 min ("Safe Region"), down to a number of seconds ("Unsafe Region"), with associated probability of capsize in a given sea state varying from nearly zero to nearly 100%, respectively.

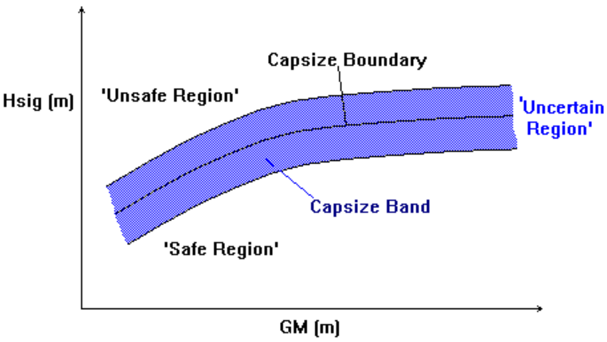

Figure 1 Definition of Capsize Band and Survival Boundaries

Further studies [3], however, led to better understanding the inadequacy of directly applying SEM to estimate ship survival time. This derives mainly from lack of highly accurate and consistent physical-model experiments allowing for precise quantification of the survival band. In the absence of such data a simplified numerical model was used instead leading to somewhat hasty generalisations of ship behaviour in near-capsize sea states.

Although the approach pursued in [2], associating survival time with survival bands is still valid, the availability now of the aforementioned experimental data, coupled with improvements in the modelling of damaged ship dynamics, [8] to [11], allow for new line of thinking as regards dynamic behaviour of damaged ships in waves and consequently of the concept of ship survival time and factors determining it.

2 HYPOTHESIS

Capsizing of a damaged ship is an extremely complex phenomenon, arising from interactions of highly non-linear ship-floodwater-waves system, thus displaying characteristics of an apparent chaotic behaviour. However, contrary to this notion, research results presented in [1] created a breakthrough by identifying that damaged ship capsizing was of quasi-static nature with the dynamic processes involved of secondary importance. Thus, ship survival was defined by correlation of static stability related features (the SEM floodwater elevation *h*) with the mean significant wave height in which the ship capsized.

With the question of survival time posed, a hypothesis is put forward in this paper that this method can be improved if the wave environment is considered on the basis of individual waves or groups of waves as an integral element of the capsizing process. Incidence of these groups can then be used to more accurately identify when a capsize event is likely to occur whilst encountering a random sea and hence to statistically determine the survival time.

In other words, it is suggested here that the vessel capsize is governed predominantly by two interacting phenomena, namely (a) ship slow attitude variation (quasi-static) due to water accumulation and (b) the ability of waves to pump water onto the Ro-Ro deck in rates higher than the water egress, such ability being primarily a function of the statistical characteristics of wave groups. This concept, put in the context of a risk-based approach, is illustrated in Table 1 and Figure 2, and discussed thereafter in the following sections.

Table 1 Procedure of determining survival time based on wave group statistics

Input	Hs, Tz, JOHNSWAP, m_j, Average group length G_a and average high run H_a for different height levels, $V_{critical}$ from SEM
Step 1 **(C)** vs **(B)**	Water ingress per wave group? Water egress per wave group? Net inflow per wave group?
Step 2 **(A)** vs **(D)**	How many wave groups ($N_{critical}$) are necessary to exceed $V_{critical}$?
Step 3 **(E)**	What is the probability that $N_{critical}$ will occur within $T_{critical}$? in a given sea state?

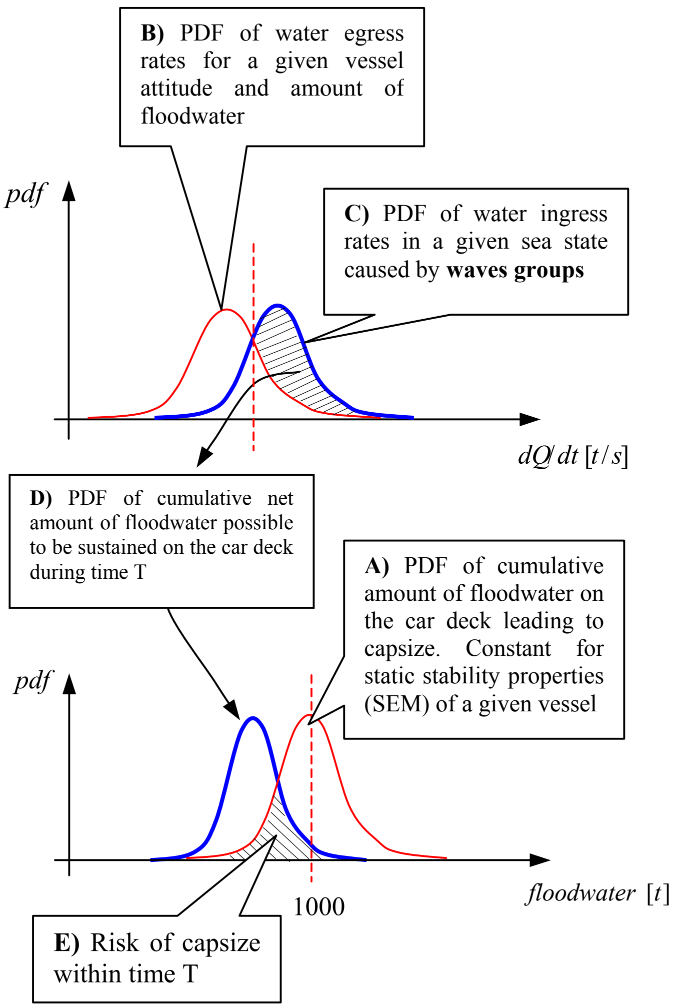

Figure 2 Risk-based concept of ship capsizing

3 THE RISK-BASED APPROACH TO CAPSIZE

In order to systematically explain the methodology adopted in realising the concept presented in Figure 2, an outline is given of the experimental data used, followed by a brief discussion on the assumptions and adopted simplified techniques used for quantification of flooding by waves as well as wave groups, followed finally by discussion of the results and trends obtained.

3.1 EXPERIMENTAL SURVIVABILITY DATA

The model tests were performed at Denny Tank in Dumbarton, the model testing facility of the University of Strathclyde. For the tests a 1:40 scale GRP model of Passenger Ro-Ro (PRR1) was used, see Table 2 and Figure 3 for the details. The model was equipped with 14 wave probes on the car deck and another two wave probes in front of the opening to measure the amount of floodwater on the car deck. Only the bilge keels were mounted as external appendages. The sea conditions were modelled according to JOHNSWAP wave energy spectrum, generated on the basis of linear theory of random processes. The parameters of the spectrum were determined according to the following relations:

$$\alpha = \frac{Hs}{\lambda},\ T_p = \sqrt{\frac{2\cdot\pi\cdot\lambda}{g}},\ T_p = C\cdot\sqrt{Hs},\ C = \sqrt{\frac{2\cdot\pi}{g\cdot\alpha}},$$

$$T_z = \frac{T_p}{1.49 - 0.102\cdot\gamma + 0.0142\cdot\gamma^2 - 0.00079\cdot\gamma^3}$$

Where wave steepness α was chosen as 1/25 and 1/20. The spectral peakness parameter γ was chosen as 3.3. A range of sea states of H_s=1.0 – 6.25 [m], each of which was represented by at least 5 different time realisations, were pre-tested to ensure modelling of the environment with high accuracy ($\pm 1mm$ model scale in Hs). The model was removed from the tank and the wave measured by a fixed wave probe.

Table 2 Particulars of PRR1 vessel

Length between perpendiculars	170.00	m
Subdivision Length	178.75	m
Breadth	27.80	m
Depth to subdivision deck (G-Deck)	9.00	m
Depth to E-Deck	14.85	m
Draught	6.25	m
Displacement intact	17301.7	t
KMT	15.522	m
KG	12.892	m

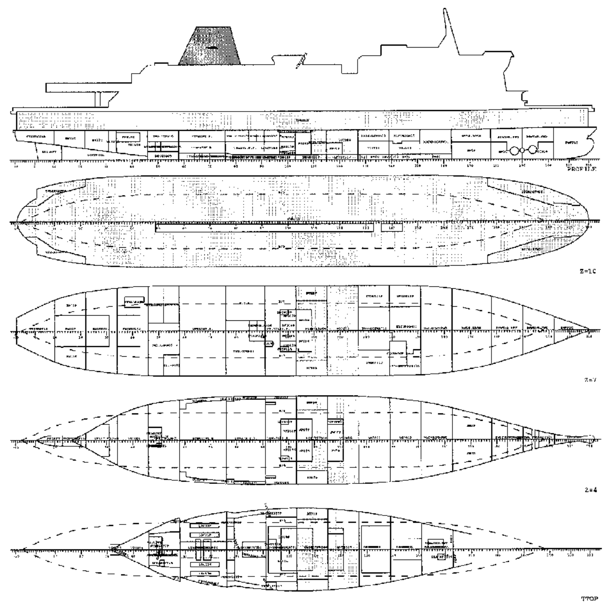

Figure 3 D901 damage case of PRR1

The model was placed in the tank, free to drift, beam-on to the waves and the survivability was tested for approximately five successive sea states, again, each one repeated at least five times, so that a clear distinction between capsize and survival cases could be derived. In total, 627 experiments were performed. The vessel conditions tested are given in Table 3. The reported survivability is expressed in terms of H_s measured at the fixed probe with no model in the basin.

Table 3 Initial conditions of the study cases

Case No.	Perme ability	Initial Draught (m)	Initial Trim (deg)	KG (m)	Finial Draught (m)	Finial Trim (deg)	Finial Heel (deg)	Residual Freeboard (m)
1	0.95	6.250	0.000	12.200	6.922	0.784	2.500	1.472
2	0.95	6.250	0.000	12.892	6.916	0.788	3.200	1.308
3	0.95	6.250	0.000	13.456	6.904	0.794	4.100	1.102
4	0.95	6.250	0.000	14.114	6.867	0.807	6.000	0.680
5	0.95	6.250	-1.000	12.200	6.942	-1.947	2.400	1.476
6	0.95	6.250	-1.000	12.892	6.937	-1.960	3.000	1.336
7	0.95	6.250	-1.000	13.456	6.927	-1.956	3.900	1.128
8	0.95	6.250	-1.000	14.114	6.893	-1.957	6.100	0.630
9	0.95	6.250	1.000	12.200	6.917	3.353	2.500	1.477
10	0.95	6.250	1.000	12.892	6.910	3.370	3.200	1.314
11	0.95	6.250	1.000	13.456	6.896	3.365	4.100	1.110
12	0.95	6.250	1.000	14.114	6.847	3.375	6.700	0.531
13	0.95	5.750	0.000	12.200	6.391	0.746	2.400	2.027
14	0.95	5.750	0.000	12.892	6.387	0.750	3.000	1.886
15	0.95	5.750	0.000	13.456	6.377	0.758	3.700	1.726
16	0.95	5.750	0.000	14.114	6.352	0.774	5.300	1.364
17	0.95	6.750	0.000	12.200	7.451	0.793	2.600	0.918
18	0.95	6.750	0.000	12.892	7.443	0.794	3.300	0.757
19	0.95	6.750	0.000	13.456	7.429	0.796	4.400	0.505
20	0.95	6.750	0.000	14.114	-	-	-	-
21	0.95	6.250	-0.600	12.892	6.929	-0.842	3.100	1.319
22	0.7	6.250	0.000	12.200	6.735	0.573	1.800	1.828
23	0.7	6.250	0.000	12.892	6.732	0.576	2.200	1.734
24	0.7	6.250	0.000	13.456	6.727	0.580	2.900	1.570
25	0.7	6.250	0.000	14.114	6.708	0.591	4.300	1.250
26	0.7	6.250	-1.000	12.200	6.748	-2.223	1.600	1.864
27	0.7	6.250	-1.000	12.892	6.745	-2.239	2.100	1.746
28	0.7	6.250	-1.000	13.456	6.741	-2.234	2.600	1.628
29	0.7	6.250	-1.000	14.114	6.728	-2.228	3.900	1.327

Only fifteen experiments, 101-116, of Case 2 were analysed with regards to the concept discussed in this paper. The overview of the experimentally derived survivability in terms of critical H_s is given in Table 4 Samples of time series for non-capsize and capsize cases are given in Figure 4 and Figure 5, respectively.

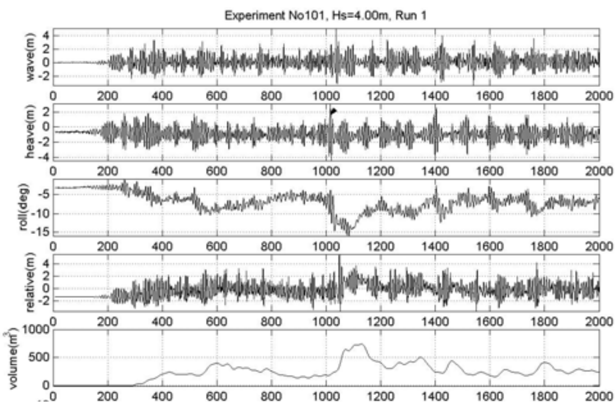

Figure 4 Time series for survivability tests of PRR1 vessel, “survive” case, H_s=4.0m.

Table 4 Ship survivability

Run No.	Target Wave Height Hs(m)	Comments
Run101	4.0	Passed
Run102	4.0	Passed
Run103	4.0	Passed
Run104	4.0	Passed
Run105	4.0	Passed
Run106	4.25	Passed
Run107	4.25	Capsized
Run108	4.25	Capsized
Run109	4.25	Capsized
Run110	4.25	Capsized
Run111	4.25	Passed
Run112	4.5	Capsized
Run113	4.5	Capsized
Run114	4.5	Capsized
Run115	4.5	Capsized
Run116	4.5	Capsized

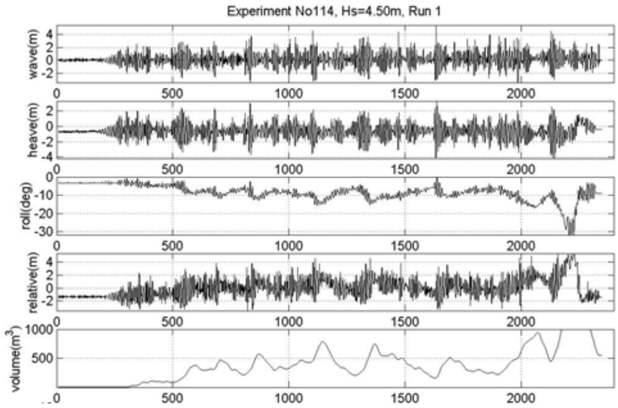

Figure 5 Time series for survivability tests of PRR1 vessel, “capsize” case, Hs=4.5m.

3.2 QUASI-STATIC NATURE OF CAPSIZE

Details of the SEM are given in [1]. The main assumption considers the floodwater on the car deck to be sustained as a result of wave action at a level higher than the average free surface level. Figure 6 demonstrates this concept by comparing the water amounts at the instant of capsize, derived numerically (SEM) or experimentally, with the equivalent volume estimated for standard static conditions. As can bee seen, the amount of floodwater on the car deck prior to capsize at any given vessel attitude exceeds the amount derived from standard static stability calculations.

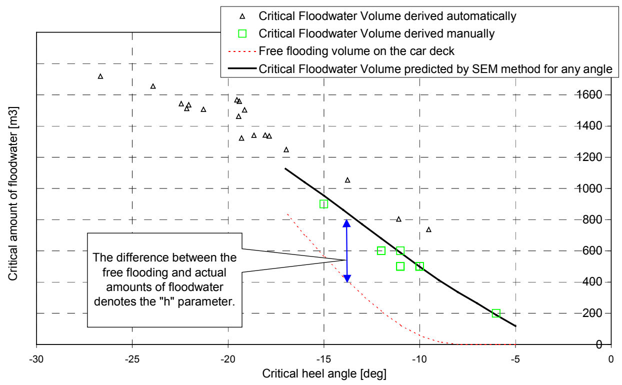

Figure 6 Correlation between critical heel angle and critical amount of floodwater on the car deck at the instant of capsize

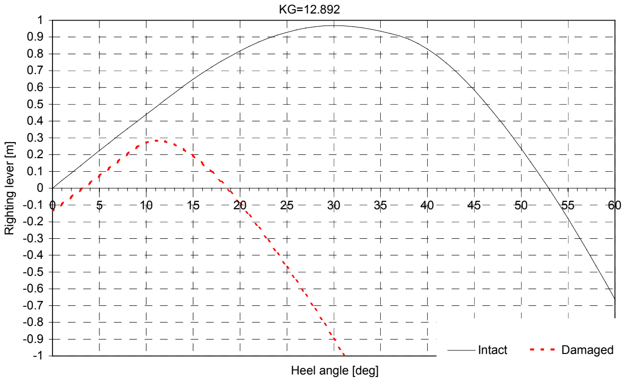

Figure 7 Righting levers of PRR1 vessel in intact and damaged conditions

This quasi-static accumulation of floodwater will lead eventually to capsize, once some critical value is exceeded. For instance it can be seen in Figure 5 that after about 2,000 seconds, about 1,000 tonnes of water is accumulated on the car deck, which however, did not lead to capsize. Once this value is exceeded two minutes later, the vessel capsized. The 1,000 tonnes corresponds to approximately 15 degrees of heel, Figure 6, which is somewhere in the middle between the angle of maximum restoring and vanishing stability, Figure 7. Considering strictly static conditions, the floodwater corresponding to maximum restoring at 12deg (700tonnes), should be capable of capsizing the vessel, provided the water does not flow out as the ship heels. However, since the floodwater will flow out, the actual amount should be described by some form of probability distribution function, PDF, see curve **(A)** in Figure 2, spanning the range between maximum restoring (12 deg; 700t) and vanishing stability (18deg; 1,200t). The form of this distribution should be derived based on observations of ship behaviour during capsize events recorded either experimentally or derived by numerical simulations.

Furthermore, the above distribution will influence the water egress rate distribution, curve **(B)** in Figure 2, which additionally must take into account the geometry of the opening as well as internal distribution of volume on the car deck at a given ship attitude. Clearly, conditions involving trim, for instance, will lead to reduced floodwater egress than when the trim is zero.

Both of these aspects are part of research work at SSRC towards the development of time-based survival criteria.

3.3 DYNAMIC BEHAVIOUR

To further elucidate the viability of an approach based on hydrostatic properties of the vessel, spectral analyses of the sample signals presented in Figure 4 and Figure 5 are shown below, Figure 8 to Figure 11, with some statistics given in Table 5.

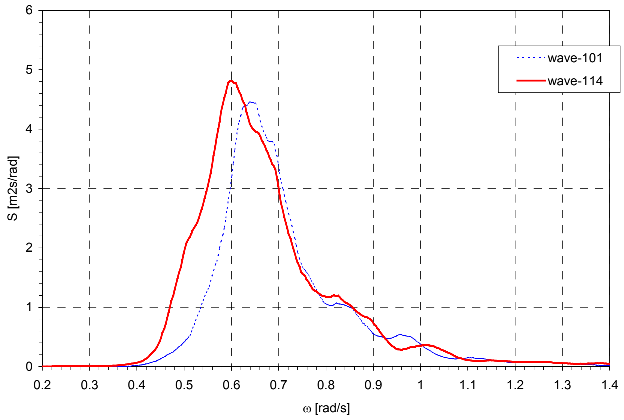

Figure 8 Spectral analysis of wave elevation (Run 101 and Run 114).

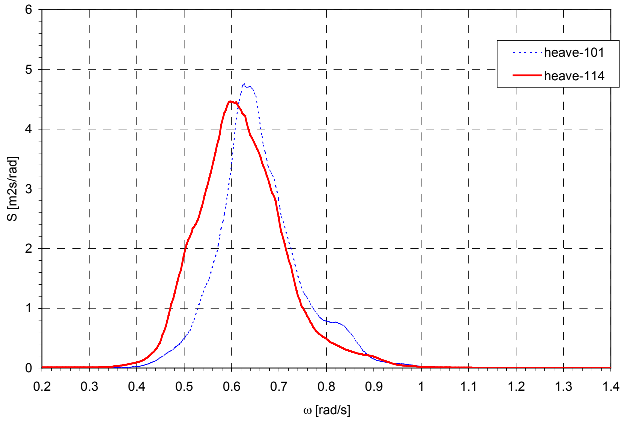

Figure 9 Spectral analysis of heave motion (Run 101 and Run 114).

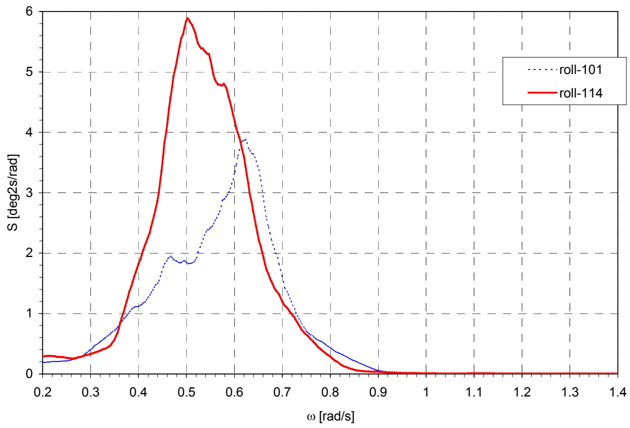

Figure 10 Spectral analysis of roll motion (Run 101 and Run 114).

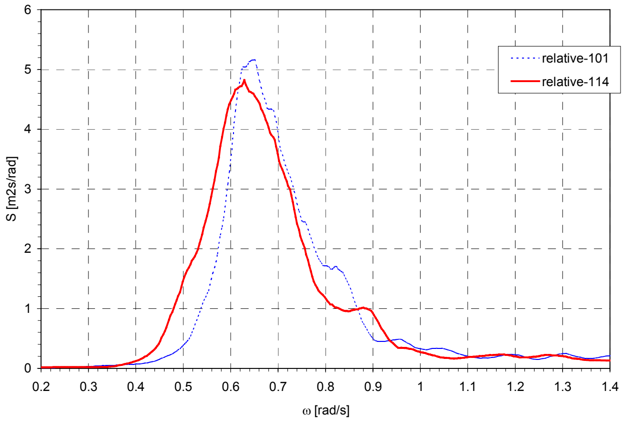

Figure 11 Spectral analysis of relative motion between car deck and wave elevation (Run 101 and Run 114)

Table 5 Significant values

	wave_fx [m]	wave_tr [m]	heave [m]	roll [deg]	relative [m]
Run 101	4.23	3.91	3.57	3.85	4.42
Run 114	4.65	4.35	3.83	4.61	4.51

The two examples, Run101 and 114, correspond to the sea states where the ship survives five successive runs at H_s=4m, and sea states where the vessel systematically capsizes at H_s=4.5m, respectively.

The heave motion in both examples does not display any peculiarities. Since the waves are much longer than the vessel beam the ship simply follows the wave elevation. Hence, the spectra of the heave response correspond closely to the wave spectra.

The roll, on the other hand, shows a considerable relative increase in the response between the two cases. This is a result of considerably more wave energy in the sea state with H_s=4.5m exciting the ship at its natural roll frequency (about 0.5 [rad/s]). However, since the roll motion of a damage ship is greatly damped, there is only about 1deg difference in the significant roll, which ultimately does not contribute noticeably to the signal of relative motion between the wave and the edge of the car deck in both cases, Figure 11.

Therefore, since the motion responsible primarily for the amount of flooding into the ship does not demonstrate a meaningful change, it can be argued that any increase in the ingress rates derive primarily from the wave action.

3.4 PREDICTION OF FLOODING

As mentioned above, water ingress/egress is the reason that a vessel capsizes. Therefore, any time-based survival criterion must take time-dependence of flooding into account. As is shown in Figure 12, the cumulative probability distribution function of flooding rates (ingress and egress) confirm that for the sea states where the ship does not capsize (Run101-105, Hs=4.0m), the flooding rates are lower than for the case when the vessel capsizes for every considered sea state (Run 112-116, Hs=4.50m). How is this conditioned on the sea state is the key question to be established in this study. The corresponding probability distribution functions, Figure 13, reveal a known peculiarity, that water egress is higher than water ingress, thus the PDF of flooding rates take normal-type shape, with non-zero mean.

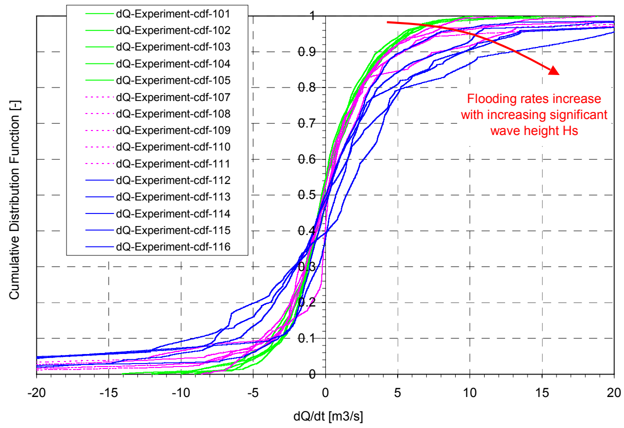

Figure 12 Cumulative probability distribution function of flooding rates (Runs 101-116).

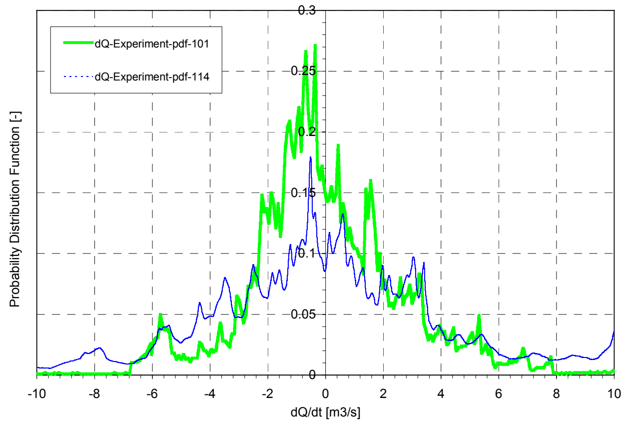

Figure 13 Probability distribution function of flooding rates (Runs 101 and Run 114).

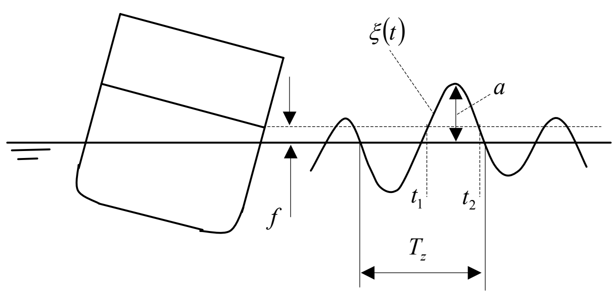

Figure 14 Simplified modelling of water ingress on a Ro-Ro car deck

In addressing the process of floodwater ingress caused by the action of waves, only a simplified modelling was adopted in this research in order to identify any conforming trends in properties of groups of waves, which lead to capsize. More specifically, the following idealistic model was adopted in the first instance.

$$Q = K \cdot \int_{t_1}^{t_2} \sqrt{2 \cdot g \cdot h} \cdot dA \cdot dt \qquad (1)$$

Where:

$$t_1 = \frac{T_z}{4} - d \qquad (2)$$

$$t_2 = \frac{T_z}{4} + d \qquad (3)$$

$$d = \frac{T_z}{4} - \sin^{-1}\left(\frac{a}{f}\right) \qquad (4)$$

$$\xi(t) = a \cdot \sin(\omega \cdot t) \qquad (5)$$

$$h = \xi(t) - f \qquad (6)$$

$$dA = h \cdot l \qquad (7)$$

The level of validity of this simplified approach is demonstrated in Figure 15.

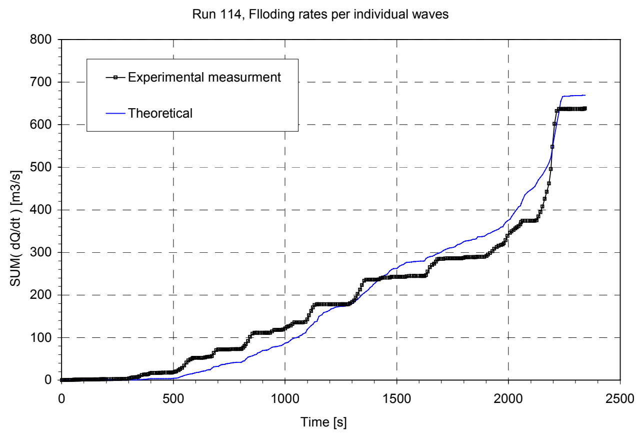

Figure 15 Comparison between experimental measurements with predictions of cumulative water ingress by model (1), K = 0.13, f = f(t) – instantaneous freeboard from experiments

This model was used in establishing relevant flooding rates caused by group of waves for the different cases discussed in §3.5.c.

3.5 ANALYSIS OF WAVE GROUPS

An interesting phenomenon often observed in wind generated seas is a sequence of high waves having nearly equal periods, commonly known as wave groups, [12]. It has been known that such wave groups often cause serious problems for the safety of marine systems when the period of the individual waves in the group are close to the marine system's natural motion period. This is not because the wave heights are exceptionally large but because of motion augmentation due to resonance, which may induce failure (capsizing) of the marine system.

The physical explanation of the wave group phenomenon has yet to be clarified, however there are suggestions that the wave field does not consist of independently propagating Fourier components but instead consists wholly or in part of wave groups of a permanent type. As evidence, results are presented of field and laboratory observations indicating that harmonic components of waves propagate at higher phase velocities than those predicted by linear theory.

Many studies on stochastic analysis of group waves in random seas have been carried out, primarily concerning the frequency of occurrence of the phenomenon. These studies may be categorised into two approaches: one treats a sequence of large wave heights as a Markov chain problem, the other considers the phenomenon as a level-crossing problem associated with the envelope of a random process. Only the latter approach is considered in this research.

3.5.a Envelope process

The probabilistic analysis of random phenomena based on the envelope process was first introduced by Rice [14] in communication engineering. It is based on the mathematically rigorous spectral analysis approach in the frequency domain. The wave spectrum is a source of information from which the probabilistic prediction of various wave properties can be achieved in the probability domain. Assumptions most commonly introduced at this stage are that waves are considered to be a steady-state Gaussian ergodic random process, and the wave spectral density function is narrow-banded. Under these conditions, the probability functions applicable to various wave properties such as the frequency of occurrence of group waves, etc, in a given sea can be analytically derived.

The envelope process represents a measure of change of wave amplitudes in the time domain and is defined as a pair of symmetric curves that pass through the wave crests and troughs. For a mathematical presentation of the envelope process, the wave profile can be written as, [12]:

$$\xi(t) = \mathrm{Re}\sum_n a_n \cdot e^{i\cdot\omega_n\cdot t + i\cdot\sigma_n} \quad (8)$$

Where a_n is a normal random variable with zero mean and a variance m_0.

Let ϖ be the mean frequency defined as:

$$\varpi = \frac{m_1}{m_0} \quad (9)$$

Where m_j is j[th] moment of wave energy spectrum (10).

$$m_j = \int \omega^j \cdot S(\omega) \cdot d\omega \quad (10)$$

The wave profile can be expressed as:

$$\xi(t) = \mathrm{Re}\sum_n a_n \cdot e^{i\cdot(\omega_n - \varpi)t + i\cdot\sigma_n + i\cdot\varpi\cdot t} \quad (11)$$

$$\xi(t) = \mathrm{Re}\,\rho(t) \cdot e^{i\cdot\varphi(t)} \cdot e^{i\cdot\varpi\cdot t} \quad (12)$$

Where:

$\rho(t) \cdot e^{i\cdot\varphi(t)}$	is a slow amplitude modulation of the random process
$\rho(t)$	is the envelope process
$e^{i\cdot\varpi\cdot t}$	is a carrier wave

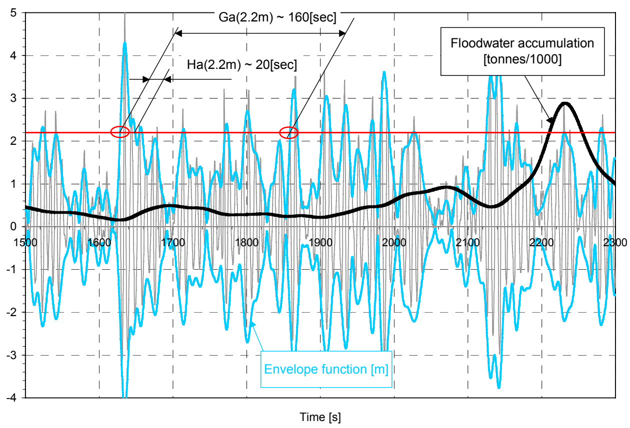

Figure 16 Analysis of wave group statistics. A "group" of waves above a certain level is constituted by at least two successive level crossings (Run 114).

The envelope process for a given wave record can be evaluated from (14) after applying the concept of the Hilbert transform (13):

$$\tilde{\xi}(t) = \frac{1}{\pi} \cdot \int_{-\infty}^{\infty} \frac{\xi(\tau)}{t-\tau} \cdot d\tau \quad (13)$$

$$\rho(t) = \sqrt{\xi^2 + \tilde{\xi}^2} \quad (14)$$

An example of the envelope process derived is shown in Figure 16.

3.5.b Wave groups statistics

Drawing on the concept of envelope process, a wave group can be defined as the up-crossing of the envelope above a certain level, a principle credited to Rice, [14], and Longuet Higgins, [15].

Following this approach various authors have developed methods to evaluate mean values of the length of time a wave group persists, the number of wave crests in the group, etc. The group length is defined as the time interval between two successive up-crossings of a given level by the wave envelope function, see Figure 16, and a run of high waves is formed by a number of successive high waves, which exceed a specified level.

The number of waves in a high-run, H_a, and in a group, G_a, can be found as follows, [13]:

$$H_a(\rho) = \frac{1}{2\cdot\pi} \cdot \frac{\sqrt{1+\varepsilon^2}}{\varepsilon} \cdot \frac{\sqrt{m_0}}{\rho} \quad (15)$$

$$G_a(\rho) = H_a(\rho) \cdot e^{\frac{\rho^2}{2\cdot m_0}} \quad (16)$$

Where:

$$\varepsilon = \sqrt{\frac{m_2 \cdot m_0}{m_1^2} - 1} \quad (17)$$

The corresponding length of a group and the high run can be found by multiplying (15) and (16) by the zero crossing period T_z, (18).

$$T_z = 2\cdot\pi\cdot\sqrt{\frac{m_0}{m_2}} \quad (18)$$

It is important to underline here, that the above expressions having been derived as a level crossing problem, imply indirectly that a wave group can be composed of only one wave.

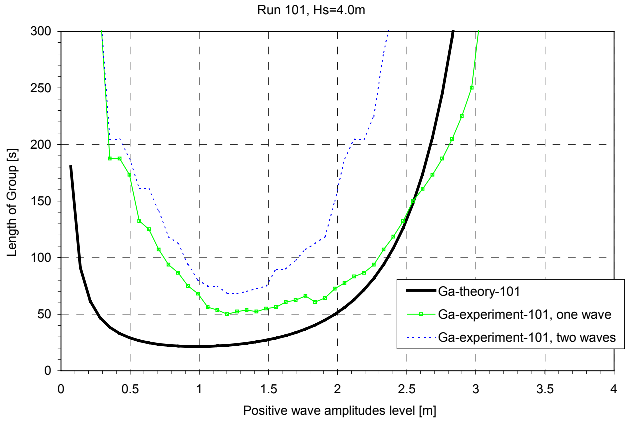

Figure 17 Duration of group for different wave amplitude levels (Runs 101); comparison between theoretical prediction and experimental data, (assumed minimum one wave per group or two waves per group).

The deficiency of this assumption, pointed for instance by Ochi, [12], was determined by simple analysis of time domain signals of the envelope process derived from experimental wave records, Figure 17. The theoretical predictions of group lengths, agrees reasonably well only for higher values of the envelope level, $\rho > H_s/2$.

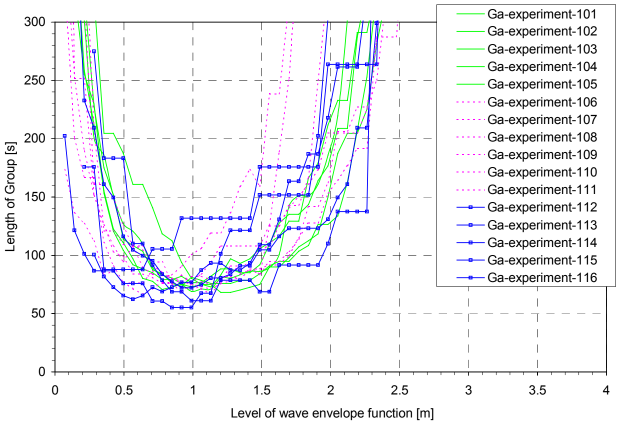

Figure 18 Duration of group for different wave amplitude levels (Runs 101-116).

Demonstrable improvement in theoretical predictions of the statistical properties of group waves can be achieved if (a) exceedance of a specified level and (b) at least two wave crests during the exceedance are considered. Ochi, [12], provides such formulation. However it has not been considered in this study as yet. Instead, the group lengths as well as high-run length for different envelope function levels have been derived based on time series analyses and under the assumption that a group must consist of at least two waves, as shown in Figure 18 and Figure 19.

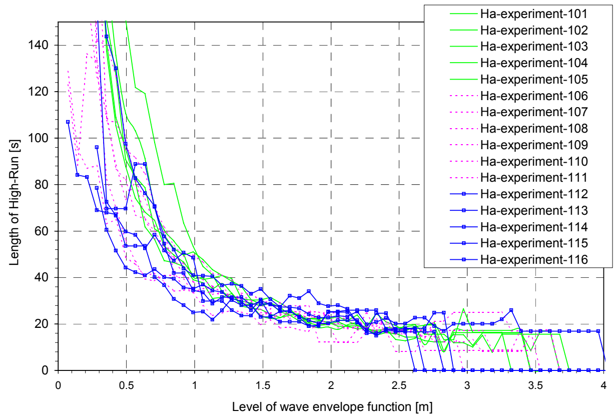

Figure 19 Duration of high-run for different wave amplitude levels (Runs 101-116).

A somewhat disappointing conclusion derived from the above test is that the duration of either the group length or the high-run length, are indistinguishable between the sea states considered. This implies that no inference can be made as to the characteristics of <u>average</u> statistics of wave groups that lead to capsize. This will be further verified with other data during future work.

3.5.c Other analyses

In the meantime more rigorous examination was undertaken of the composition of the wave groups chosen ad-hock based on visual observations from the sixteen runs under examination, see samples shown in Figure 20 and Figure 21. In this case the groups of waves were identified simply by trough-to-crest excursions of the envelope process.

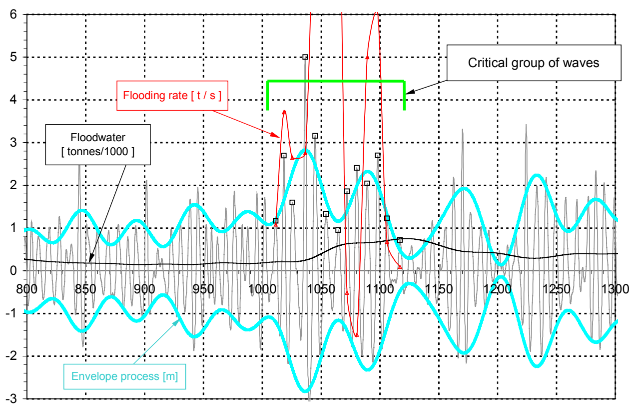

Figure 20 Sample of a wave group leading to near-capsize, Run 101, Hs=4.0m.

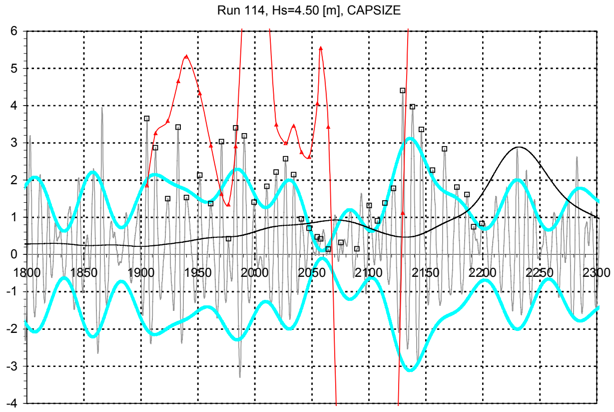

Figure 21 Sample of a wave group leading to capsize, Run 114, Hs=4.5m.

The individual characteristic of each of the groups examined were as follows:

- Maximum, Mean and Total stored wave energy
- Maximum, Mean and Total water ingress
- Maximum and Mean wave height
- Total number of waves

Probability distributions of the above properties in the individual wave groups were also examined.

Figure 22 shows that the wave composition of groups for either near or actual capsizes does not show any distinguishable patterns. In fact none of the examined characteristics for the sixteen runs allowed as yet identification of prevailing trends, e.g. Figure 23 or Figure 24. Reasons for this outcome include the very small data sample size processed to date, the possibility that each of the groups examined could lead to a different event (potentially a capsize) if the conditions prior to encountering the group, e.g. water egress, were different, see Figure 28. Interestingly, the latter implies that the curve **(B)** shown in Figure 2 should be dependent on the wave properties as well.

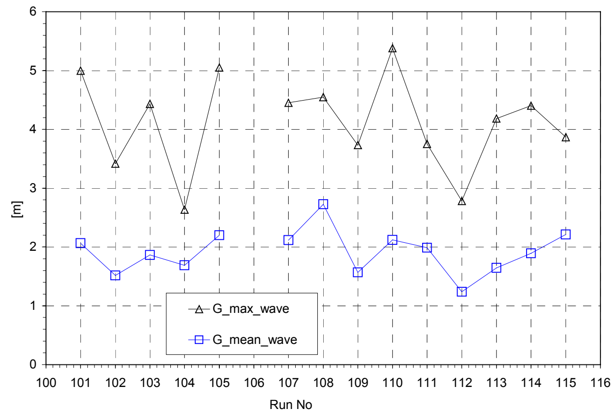

Figure 22 Maximum and mean wave heights in the selected groups

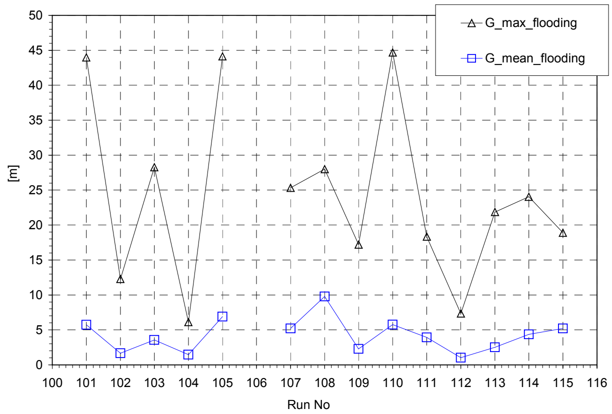

Figure 23 Maximum and mean floodwater ingress rates in the selected groups

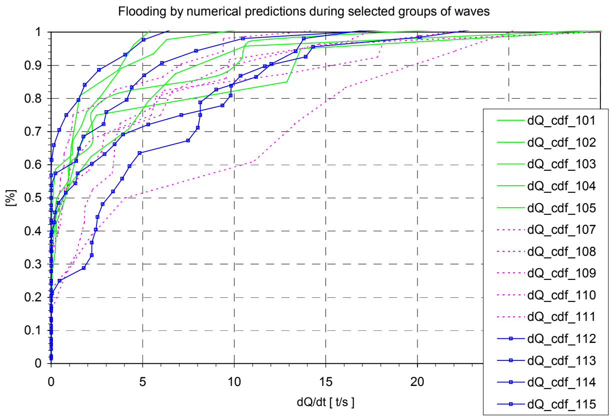

Figure 24 Cumulative probability distributions of the floodwater ingress rates in the selected groups

Notwithstanding the lack of any clear breakthrough in developing the concept discussed in this paper so far, some more general observations indicate that it is a promising approach. For example, Figure 25 shows time series of average wave group height and the flooding rate estimated per group of waves.

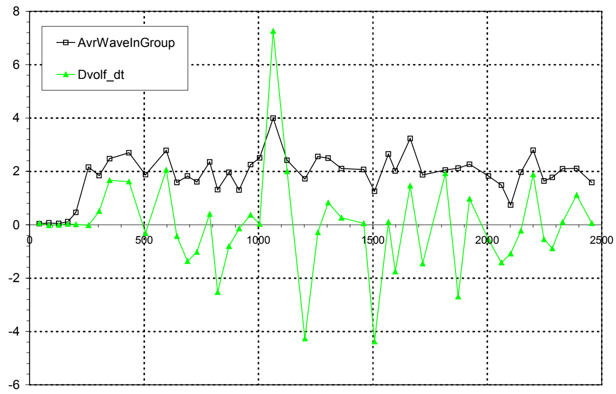

Figure 25 Time series of average wave group height (wave group based on trough-to-crest excursion in wave envelope function) and the flooding rate estimated per group of waves, Run 101.

As can be seen the flooding rates show a distinguishable relationship between inflow/outflow and the average wave height in the group, see Figure 26.

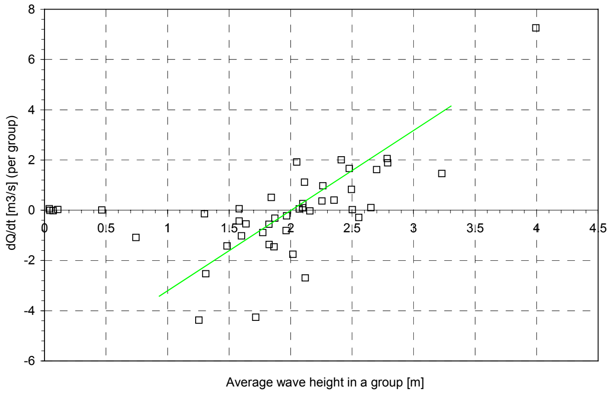

Figure 26 Relationship between the measured water ingress/egress and the average wave height in a wave group Run 101.

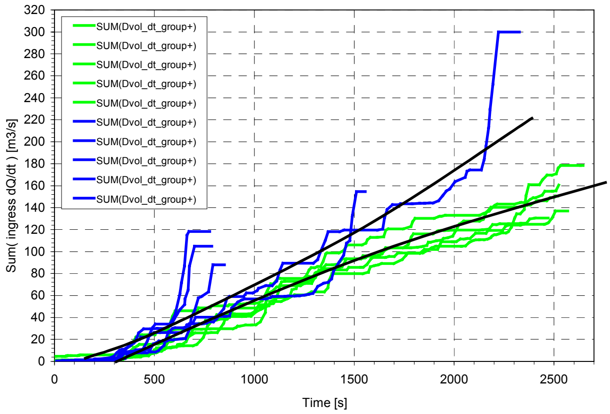

Figure 27 Floodwater ingress measured experimentally [Experiments with "capsize" and "survive" outcomes]

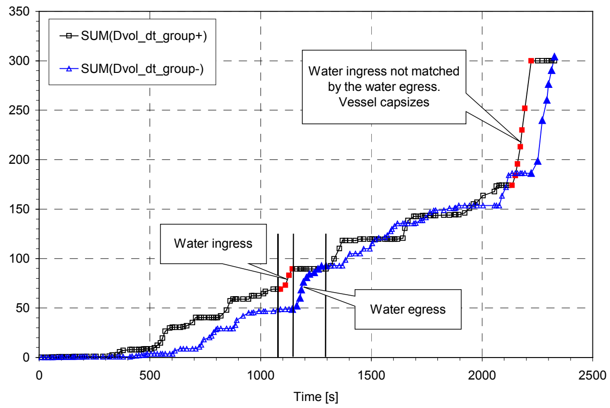

Figure 28 Floodwater ingress and egress measured experimentally ["capsize" case]

Furthermore, as can be seen in Figure 27, the cumulative water ingress, when inspected for each encountered wave group, shows clear differences in the character between the survive and capsize cases. This again underlines the importance of considering both floodwater ingress as well as egress. For instance as is shown in Figure 28, the egress could not deplete the floodwater accumulation on the car deck, and as a result the vessel capsized.

4 CONCLUSIONS

This paper presents a new approach for predicting ship survival time together with the progress achieved to date in its development. Many aspects need further investigation to either validate or disprove different elements of the method.

The main aspect of the new approach, derived from the SEM principles, is direct association of the characteristics of the waves with the process of water ingress and egress, and thus with vessel survivability.

Although vessel capsize is a case of limit state behaviour, a physical process that is highly sensitive to variation of many governing factors, it is anticipated that observed regularities in capsizing will lead to identification of a functional representation of this sensitivity in the near future.

5 ACKNOWLEDGEMENTS

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