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FLOODING PROTECTION OF RO-RO FERRIES – PHASE V
Further Development and Implementation of a Risk-Based Approach to Ferry Safety

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Notices Page

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16. Abstract

This project developed a risk-based methodology for ferry safety analysis, using the Static Equivalent Method (SEM) as a capsize prediction tool and employing route-specific environmental, traffic, and loading data to provide consistent levels of safety. The methodology was aligned with existing international practice to facilitate its acceptance and use.

In other tasks, the project extended the validation of the SEM using model test data, and explored techniques for disseminating information on the new safety approach.

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16. Résumé

Ce projet a consisté à développer une méthode fondée sur l'analyse du risque pour déterminer la sûreté d'un traversier, en faisant intervenir la méthode du système équivalent quasi statique (SEM) en tant qu'outil de prédiction de la tenue au chavirement ainsi que les données sur l'environnement, le trafic et le chargement propres aux liaisons étudiées. La nouvelle méthode a été alignée sur les pratiques internationales existantes, afin de faciliter son adoption.

Le projet a également consisté à valider plus avant la méthode SEM, à l'aide de résultats d'essais sur maquette, et à élaborer des moyens pour diffuser l'information sur la nouvelle approche d'évaluation de la sûreté des navires.

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EXECUTIVE SUMMARY

This report presents the results of the latest phase of a multi-year research program aimed at assisting the implementation of new safety standards for Canadian ro-ro ferries. The work took place in parallel with the development of new standards for international ferry services, and reflects the specific characteristics of Canadian operations and vessels.

The principal objective of this phase was the development of proposals for a risk-based methodology for safety evaluation. These take into account the damaged stability of the ship as predicted by the Static Equivalent Method (SEM). In previous phases of the work the SEM was found to provide a more consistent and rational indication of performance than the current international residual stability criteria. In the proposed methodology it is combined with route-specific wave climate data, and – potentially – with traffic data, to provide reasonably consistent risk levels for all Canadian services. Where risk is assessed as being unacceptably high, the methodology allows operating restrictions to be applied if ship replacement is impractical or excessively costly.

The recommended means of applying the methodology is based on the current probabilistic approach used under SOLAS, to facilitate future modifications of both domestic and international requirements. Some further work is needed to finalize an impact assessment for the proposals. The results of such an assessment may themselves lead to modification of the proposed implementation schedules for existing vessels.

Secondary objectives of the project were further validation of the SEM using model test data from European ferry safety research programs and development of information materials to assist in introducing the new methodology.

The European data was found to be of variable quality, but where it covered the conditions and assumptions used in the SEM, results and predictions matched quite well. Two data sets, collected where air could become trapped below the vehicle decks, showed that this condition can have quite negative impacts on capsize performance. It will therefore be important to ensure that air venting arrangements are adequate and function properly, as is currently normally assumed.

The preparation of information materials was scoped and costed.

In addition to the above recommendations, this report recommends that Transport Canada continue to undertake or support research on damaged stability, including the gathering of more and better statistical data on accidents. The trend nationally and internationally towards the use of probabilistic standards should be based on reliable statistics if it is to represent a real improvement over deterministic requirements.

SOMMAIRE

Ce rapport expose les résultats de la phase ultime d’un programme de recherche entrepris il y a quelques années en vue de la mise en oeuvre de nouvelles normes de sécurité pour les traversiers rouliers canadiens. Ces travaux se sont déroulés parallèlement à l’élaboration de nouvelles normes visant les liaisons internationales par traversier, et ils ont pris en considération les caractéristiques particulières des liaisons et des traversiers canadiens.

L’objectif général de cette phase était de proposer des méthodes fondées sur l’analyse du risque pour évaluer la sûreté des navires. Celles-ci prennent notamment en compte la stabilité après avarie du navire, telle que prédite par la méthode équivalente quasi statique (SEM). Lors des phases antérieures du programme, on a établi que la méthode SEM donnait une indication plus cohérente et plus logique de la stabilité après avarie que les critères de stabilité résiduelle actuellement utilisés par la communauté internationale. La démarche proposée ici combine la méthode SEM avec les données sur le régime de houle propres à la liaison et, éventuellement, avec les données sur le trafic, pour produire des niveaux de risque raisonnablement cohérents pour toutes les liaisons par traversier au Canada. Lorsque le risque s’avère inacceptable, la méthode permet d’appliquer des restrictions à l’exploitation du traversier, s’il est impossible ou trop coûteux de le remplacer.

La technique recommandée pour la mise en oeuvre de la méthode se fonde sur l’approche probabiliste SOLAS, ce qui devrait faciliter la modification future des normes canadiennes et internationales. Du travail reste à faire pour mener à terme l’analyse d’impact de la méthode proposée. Les résultats de cette analyse pourraient mener à la modification des calendriers de mise en oeuvre proposés pour les navires existants.

Le projet avait comme sous-objectifs la validation plus poussée de la méthode SEM, à l’aide de résultats d’essais sur maquette réalisés en Europe, et la mise au point d’un dossier d’information pour lancer la nouvelle méthode.

Les données européennes étaient de qualité inégale, mais lorsque les conditions et hypothèses mises à l’essai recoupaient celles soumises à la méthode SEM, les deux séries de résultats et prédictions concordaient assez bien. Deux ensembles de données, recueillies dans des conditions où l’air pouvait demeurer emprisonné sous les ponts-garages, ont révélé que ce cas de figure risquait d’altérer passablement la tenue au chavirement du navire. D’où l’importance de s’assurer que les systèmes de ventilation sont adéquats et fonctionnent correctement, comme cela est normalement tenu pour acquis.

L’ampleur et le coût des travaux d’élaboration du dossier d’information ont été déterminés.

Outre les recommandations ci-dessus, le rapport préconise que Transports Canada continue de réaliser ou de financer des recherches sur la stabilité des navires après avarie, notamment en colligeant des statistiques plus complètes sur les accidents. Il est essentiel que les normes de type probabiliste, vers lesquelles se tournent de plus en plus le Canada et la communauté internationale, soient fondées sur des statistiques fiables, pour qu’elles constituent une véritable amélioration par rapport aux normes déterministes.

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GLOSSARY OF ABBREVIATIONS, ACRONYMS, SYMBOLS AND SPECIAL TERMS

BMT (UK)	British Maritime Technology, United Kingdom
CD ROM	Compact Disc Read Only Memory
CFOA	Canadian Ferry Operators Association
CSA	Canadian Standards Association
DMI	Danish Maritime Institute
DVD	Digital Video Disc
GHS	Stability Analysis Software
GM Values	Vertical Metacentric Height from Centre of Gravity
GZ	Righting Arm
IMO	International Maritime Organization
KG Values	Vertical Centre of Gravity from Baseline
KM Values	Metacentric Height
KMT	Transverse Metacentric Height
LCB	Longitudinal Centre of Buoyancy
MSC	Marine Safety Committee
NPL (UK)	National Physical Laboratory (United Kingdom)
Ro-Ro	Roll on-Roll-off
SEM	Static Equivalent Method
SNAME	Society of Naval Architects and Marine Engineers
SOLAS	Safety of Life at Sea
TC	Transport Canada
UK MCA	United Kingdom Maritime and Coastguard Agency
UK MSA	United Kingdom Marine Safety Agency
USCG	United States Coast Guard
VHS	Vertical Helix Scan (Videocassette Technology)

1. INTRODUCTION

Phase V of this multi-year program of research into Ro-Ro ferry safety has aimed to develop a formal, risk-based methodology for assessing the adequacy of the safety of existing and new ferries on a route-specific basis. This is intended to provide a basis for future discussions between Transport Canada and the Canadian Ferry Operators Association (CFOA) regarding the operations of the domestic ferry fleet.

Internationally, ferries are governed by the provisions of the SOLAS Convention, whose latest amendments have required the phase-out or extensive modification of many existing vessels. However, the nature of Canadian services has always made direct application of SOLAS inappropriate in at least some cases. Two successive programs of research and analysis, summarized in Section 2 of the report, have explored some of the problems with current SOLAS requirements in a Canadian context.

The proposed risk-based methodology is based in part on the Static Equivalent Method (SEM) of damaged stability assessment, which was the focus of Phases III and IV of the prior work. In the current project, one of the major tasks undertaken has been the further validation of the method. As described in Section 3, this validation has used a number of model test data sets provided by the U.K Maritime and Coastguard Agency (MCA), another of the leading sponsors of stability research. Several of the test series were undertaken as part of the Joint North-West European Project on Ferry Safety, within which the SEM was initially developed. Thus, the Canadian research is already aligned with a much broader program of international work, all of whose results will be usable in any further revision of international standards.

The second overall task has involved the development of the risk assessment method, including safety criteria and a proposed implementation approach, as described in Section 4. This has taken as many factors into account as possible, using representative Canadian operational, environmental, and casualty data. The method proposed has also been aligned with current SOLAS procedures in order to minimize the additional analytical effort involved in its application. A further benefit is that the results will be presented in a format that can be readily applied to future reviews of SOLAS by the International Maritime Organization (IMO).

The third major task has involved the development of an information dissemination strategy, based on video presentations of the work and its underlying rationale. Section 5 covers this task. The conclusions of the project, and recommendations for additional work to assess the impact of the method on the Canadian fleet are provided in Section 6.

2. REVIEW OF PREVIOUS WORK

2.1 Overview

The two previous programs noted in the introduction were sponsored by Transport Canada (TC), with support from the Canadian Ferry Operators Association (CFOA). They can be summarized as follows:

- **Residual Stability of Ro-Ro Ferries.** This research program was initiated in 1989 to examine the compliance of eight Canadian ferry designs with the damaged stability requirements incorporated in SOLAS 90. This was a multi-phase program, including both deterministic and probabilistic approaches to the rule applications. Only one of the vessels had been designed to these standards, and as was expected, the degree of compliance varied, with some ships failing to meet one or more of the criteria. In the current investigation, it is principally the deterministic results covered by the first phase of the above program that are taken into account, though probabilistic approaches are also reviewed. Results are provided in References 1-3. These are “protected” documents, due to the commercial confidentiality of some of the data.

- **Flooding Protection of Ro-Ro Ferries.** This program was begun in 1991 to further examine the destabilising effect of water on the vehicle decks of Ro-Ro ferries designed to meet the damaged stability rules of SOLAS 90. The program started with model tests of “idealized” large and small ferries to determine the limit of their capsize survivability in waves when damaged and open to the sea amidships (Phases I, Iext, and II). The results, available in full in references [4-6], were applied in Phase III to test the validity of an analytical method for determining such survivability originally developed by Strathclyde University, known as the static equivalent method (SEM) [7]. Good correlation was found between the model and analytical results (Ref. [8]). The method was then applied to the set of ships from the previous program (with one new ship, and one previous vessel dropped) in order to explore any correlations with ‘SOLAS adequacy’. This work was reported in Phase IV [9].

2.2 Requirements of SOLAS 90

The passenger ship damaged stability requirements contained in SOLAS 90 were adopted from IMO Resolution MSC.12(56) and came into force on April 29, 1990, applicable to *new* ships on international voyages – Convention vessels. These standards were later adopted by Transport Canada for domestic voyages, and came into force on April 1, 1991. Again, they are applicable only to *new* (non-Convention) domestic ships. In summary, SOLAS 90 addresses the residual stability requirements of the GZ diagram in the damaged condition and includes minimum requirements for the residual righting lever, positive range of stability and area under the righting arm curve.

These are defined in Figure 2.1, taken from [1], which illustrates the requirements of a typical righting arm curve for a compliant ship in the final condition after damage.

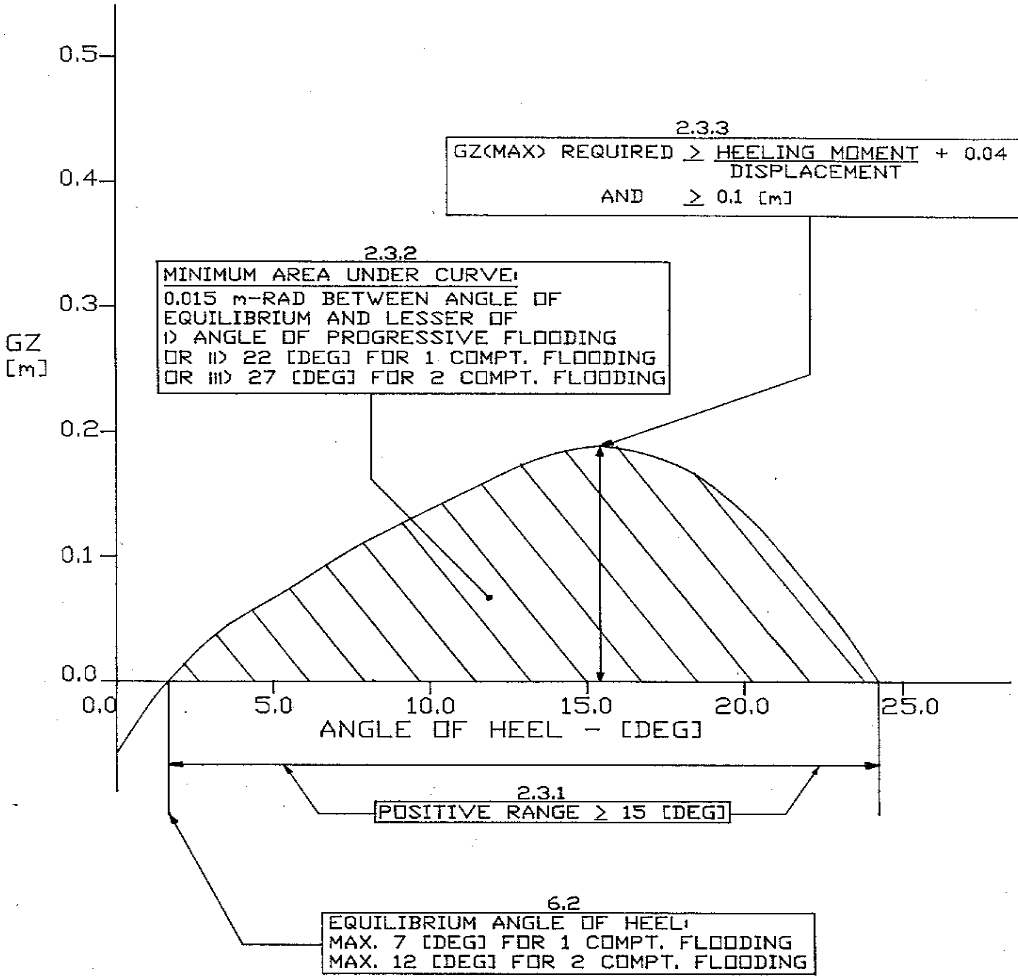


Figure 2.1: Illustration of SOLAS 90 Damaged Stability Criteria

2.3 Requirements According to IMO Circular MSC 574

SOLAS 90 permits the use of deterministic stability criteria for new ships, but allows the use of the probabilistic assessment method as an alternative. In the light of several high profile accidents after the introduction of SOLAS 90, supplementary requirements for existing ships were introduced based on their level of compliance with the simplified probabilistic method described in MSC Circular 574 [10].

The general probabilistic version of the SOLAS criteria [11] attempts to take into account the different probabilities of damages of various extents and locations. Distributions of damage size and centre are assumed, based on statistical data. Qualitatively, it is assumed that:

(a) damage is more likely towards the bow and less likely aft of amidships;
(b) a large damage is less probable than a small one; no account is taken of damages extending over more than four adjacent compartments;
(c) inboard penetration is related to damage length, and wing bulkheads will contribute to survivability to varying degrees depending on their position.

For any case (which may damage one, two, or more compartments) a somewhat different set of residual stability criteria is applied to assess whether the condition is acceptable or not (the criteria are presented in detail in [11], one additional feature that is covered is residual freeboard). An overall index is built up from the weighted summation of pass (= 1) fail (= 0) and 'marginal' ($0<x<1$) conditions; though again 'fail' is a relative rather than an absolute or probabilistic concept due to the criteria applied. The value of the 'attained index', A, is then compared with the 'required index', R, which is itself a function of ship size and the number of personnel embarked.

In the 'simplified probabilistic method' [10] that has been adopted by IMO for the evaluation of existing Ro-Ro ships, the 'required' value is replaced by the more manageable 'A_{MAX}', and the stability analyses are restricted to the analysis of 1 and 2 compartment cases. This procedure is explained in MSC Circular 574, [10]. The pass/fail criterion for any damage case is expressed as:

$$s = c*2.58*(GZ_{MAX}*Range*Area)^{0.25} \text{ (not to exceed s=1)}$$

where c = 1 if the final equilibrium heel angle, Θ, is $\leq$ 7 degrees
0 if final heel angle is > 20 degrees

else c = $((20-\Theta)/(20-7))^{0.5}$

A_{MAX} is the value which would be attained if all relevant damage cases had s = 1, and is determined by adjusting the KG of the ship until the worst case passes. For a one compartment ship it is necessary that all one compartment damage cases have s = 1, while for 2 compartment ships both 1 and 2 compartment cases must survive.

The results of these analyses – the A/A_{MAX} ratio - is used as one of the criteria dictating when an existing ship requires to be phased out, or to be modified to attain a higher survival probability.

Both the general and the simplified methods of probabilistic assessment existed at the time of the Residual Stability Study, although how they would be applied had not been determined. Therefore, the results of its second phase [2, 3] covered both possibilities.

2.4 Results of Residual Stability (Phase 1) Study

Phase 1 of the Residual Stability Program investigated the degree of compliance of eight Canadian ferry designs against the deterministic criteria defined in Section 2.2. In all cases, pre-1990 designs were chosen for this investigation, spanning the full range of vessel sizes in service in Canadian waters, and having up to three compartment floodable subdivisions. The standard SOLAS damage criterion was used, and worst case conditions for the extent of flooding were found by extensive analyses. The results of the study and the comparisons with the SOLAS 90 criteria are provided in Table 2.1, derived from [1].

Table 2.1: Damaged Stability Summary

Ship	Max Heel	Act. Heel	Req. Range	Act. Range	Req. GZa	Act. GZa	Req. GZmax	Act. GZmax
	(deg)	(deg)	(deg)	(deg)	(mrad)	(mrad)	(m)	(m)
1	*<12*	2.76	*15*	23.9	*0.015*	0.1796	*0.189*	0.684
2	*<12*	0.05	*15*	15.0	*0.015*	0.0551	*0.193*	0.337
3	*<12*	4.60	*15*	**1.0**	*0.015*	**0.0001**	*0.110*	**0.001**
4	*<12*	0.00	*15*	**7.1**	*0.015*	**0.0065**	*0.100*	**0.081**
5	*<7*	6.69	*15*	37.8	*0.015*	0.0181	*0.100*	0.216
6	*<12*	0.24	*15*	19.8	*0.015*	0.0269	*0.144*	0.156
7	*<7*	2.41	*15*	**6.9**	*0.015*	**0.0026**	*0.114*	**0.033**
8	*<7*	0.41	*15*	23.9	*0.015*	0.0383	*0.100*	0.189

Note: Non-compliant results are in **bold** type

The table shows that, of the eight designs investigated, three failed to meet the full range of SOLAS 90 criteria. In the case of the five compliant designs, there was considerable variability in the degree to which each of the criteria was met. For example, in the case of GZ area, the 'best' ship had twelve times the required area under the GZ curve, while none of the others was as much as four times better.

2.5 Results of the Residual Stability (Phase 2) Study

The same set of ships was assessed against both the simplified and full IMO probabilistic methods, as described in [2] and [3] respectively. The outcomes were broadly similar, though somewhat better compliance was found under the full than under the simplified method. Since the simplified method is the more relevant, its results are summarized in Table 2.2.

Table 2.2: A/A_{max} Ratios (MSC Circ 574 Method)

Ship	A	Amax	A/Amax
1	0.687	0.687	1.00
2	0.776	0.777	0.99
3	0.324	0.653	0.49
4	0.577	0.688	0.83
5	0.841	0.841	1.00
6	0.770	0.770	1.00
7	0.410	0.507	0.80
8	0.786	0.786	1.00

It can be seen that the same ships that failed the deterministic criteria (Table 2.1) were also non-compliant with the probabilistic requirements, though their relative weighting changed somewhat. Ship 2 could be regarded as compliant under both approaches, the 0.001 deficiency found for the probabilistic approach being within the margin of error of the calculations (in fact, if the index is less than one the ship must also, by definition, be non-compliant with SOLAS 90 too).

Where a Convention ship (undertaking international voyages) shows an A/A_{MAX} ratio of less than one, it is subjected to a phase-out schedule, discussed in more detail in Section 4.

2.6 Overview of the Flooding Protection Program

The SOLAS 90 criteria provide for residual stability after damage to the hull but do not specifically address the destabilizing effect of water ingress onto the vehicle deck. It was this phenomenon that is considered to have caused the loss of the *Herald of Free Enterprise* and the *European Gateway* and that may have contributed to the *Estonia* disaster. Several international programs were undertaken to explore this concern. Transport Canada initiated the Flooding Protection Program in 1991 to investigate the effects of water entry onto the car deck, and possible means of mitigation.

In the first phases of this program, tank tests were carried out using simplified models of two sizes of ferries, as follows:

Phase I	Length 160 m	Displacement 11,650 t
Phase II	Length 85 m	Displacement 4,450 t

The models were subjected to an extensive program of tank testing, in irregular waves up to 7 m, with varying degrees of midship flooding damage resulting in varying residual freeboards down to the margin line. The principal factors under investigation were:

- Effect of water on deck;
- Influence of centreline casing;
- Effect of freeing ports.

The test results showed that there was a clearly defined boundary between safe and capsize conditions, dictated by the volume of water accumulated on the deck. Capsize also seemed to be a hydrostatic process. It was also found that survivability was usually enhanced by the removal of the centreline casing, and by the use of non-return freeing ports. These results prompted a search for an analytical expression of damaged survivability of a Ro-Ro in a seaway, which could take into account configuration differences between ferry designs. The outcome is covered in the next sub-section.

In the meantime, results from similar programs of work elsewhere led a number of European nations to introduce additional regional safety requirements, related to the possibility of water entering the vehicle deck. Often referred to as SOLAS 90+50, this requires vessels either to meet the SOLAS 90 criteria with a nominal 50 cm of water on the vehicle deck (reduced with increasing residual freeboard), or to use model tests in a representative sea state to show that the damaged ship would be expected to survive. Canada (and the U.S.) have not adopted similar requirements, due to concerns that they may be (a) unnecessarily stringent, and (b) equally unrepresentative of 'true' safety levels.

2.7 Overview of the Static Equivalent Method

In its present form, the static equivalent method (SEM) of predicting the brink of capsize due to water on the car deck was reported in Ref. [7]. The method postulates that the condition of capsize can be predicted in hydrostatic terms as being the volume of water on the deck which would create an upsetting moment equal to the maximum righting lever moment as defined by GZ_{max} in the vessel's residual stability diagram. The SEM method completes the predictive process by providing an explicit relationship between the head of the volume of water on the deck and the exterior wave height. Diagrammatic representation of the forces at work is provided in Figure 2.2, slightly modified from an original in [7].

The basic stability equation to be satisfied is as follows:

$$v_{ad}.l_{ad} = V.GZ$$

where

v_{ad} = volume of head of water on deck above the still waterline WL_o
l_{ad} = heeling lever due to head of water on deck , equal to the horizontal distance between the centre of flotation F_{wl} of the waterplane WL_o (undamaged above the car deck) and the centre of gravity C_{ad} of the head of water on deck
V = volume displacement of the ship
GZ = righting arm calculated by the constant displacement method, allowing for free flooding of the vehicle deck

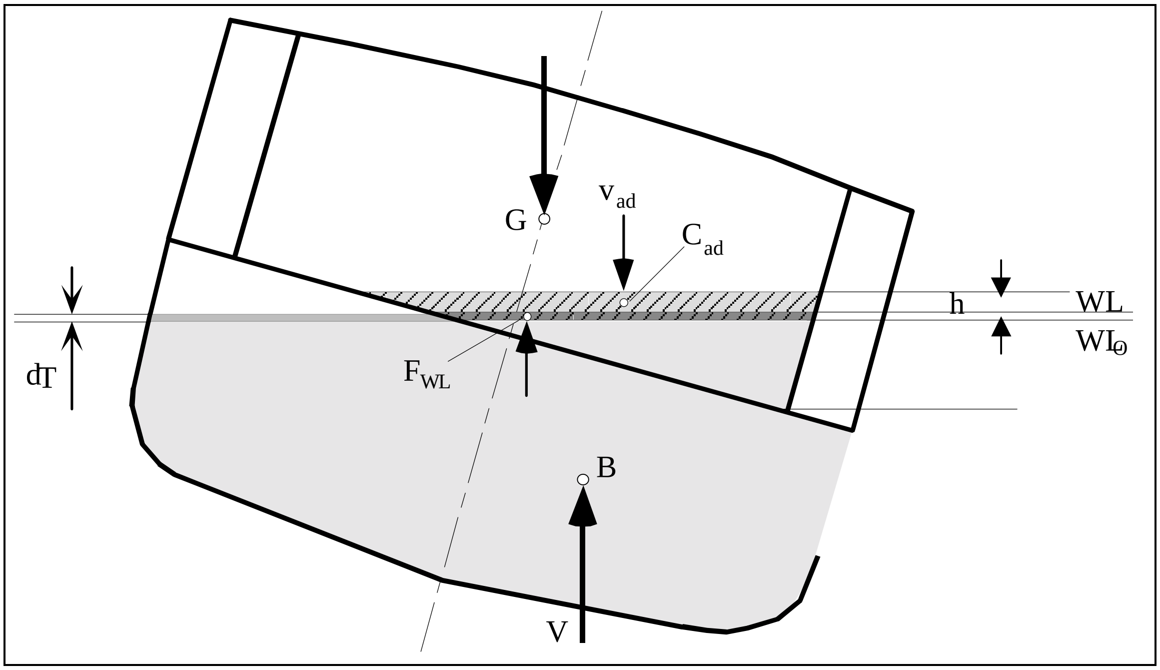


Figure 2.2: SEM Calculation Principles

Solution of the above equation leads to calculation of h', the head of water on deck above the static waterline WL_o.. This, in turn, allows h to be calculated by allowing for the effect *d*T of sinkage due to the added head of water v_{ad} on deck (i.e., h = h' - dT).

In order to provide a prediction of the capsize condition, it is necessary to relate the elevation of the internal water surface above mean sea level in terms of the sea state that will generate this. The SEM provides a connecting equation of the following form:

$$h \quad = \quad C.H_s^x$$

where C is a coefficient (determined experimentally at 0.085) and H_s is the significant wave height which is raised by the exponent x (determined experimentally at 1.3). The critical significant wave height at which h equals the value required for capsize is taken as representing a 50 percent capsize probability, when the results are interpreted probabilistically.

2.8 Validation of the Static Equivalent Method

The results obtained from the model tests conducted in Phases I and II of the Flooding Protection Program, as described in Section 2.4, were used to validate the SEM in the Phase III project. To that end, the SEM was utilized to predict the capsize wave-height corresponding to particular capsize tests conducted with the models. The predicted and measured wave-heights were then compared, as shown in the following Figures 2.3 and 2.4, taken from [8].

Note that the experimental program gave low and high wave heights that straddled the actual capsize condition. These low and high test results are plotted as vertical bars on Figures 2.3 and 2.4, with the actual capsize point being located somewhere within each bar.

As can be seen in the Figures 2.3 and 2.4, almost all the measurements bracket the predicted value for both the models tested, with only a few exceptions. This correspondence between prediction and measurement validates the SEM method and its ability to account for a range of ship design variables in providing a single, simple approach to capsize prediction due to water on deck.

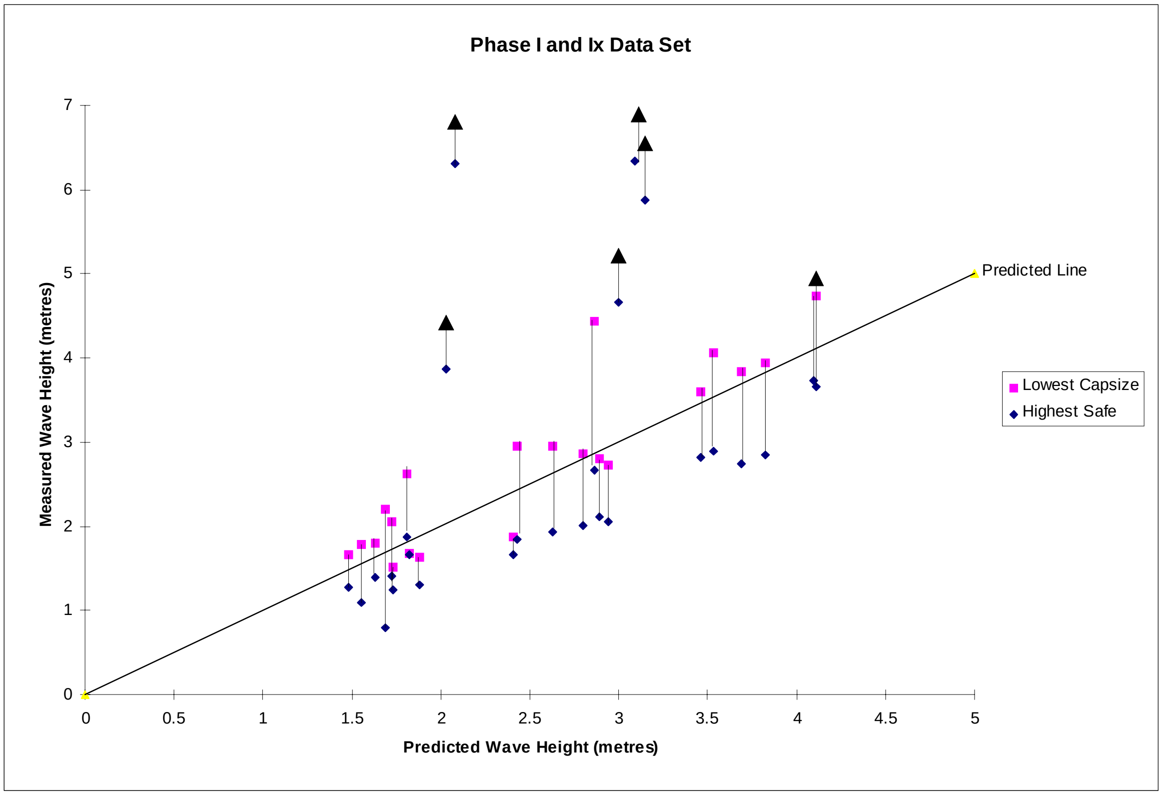


Figure 2.3: Predicted and Measured Capsize Wave Heights, All Phase I Data

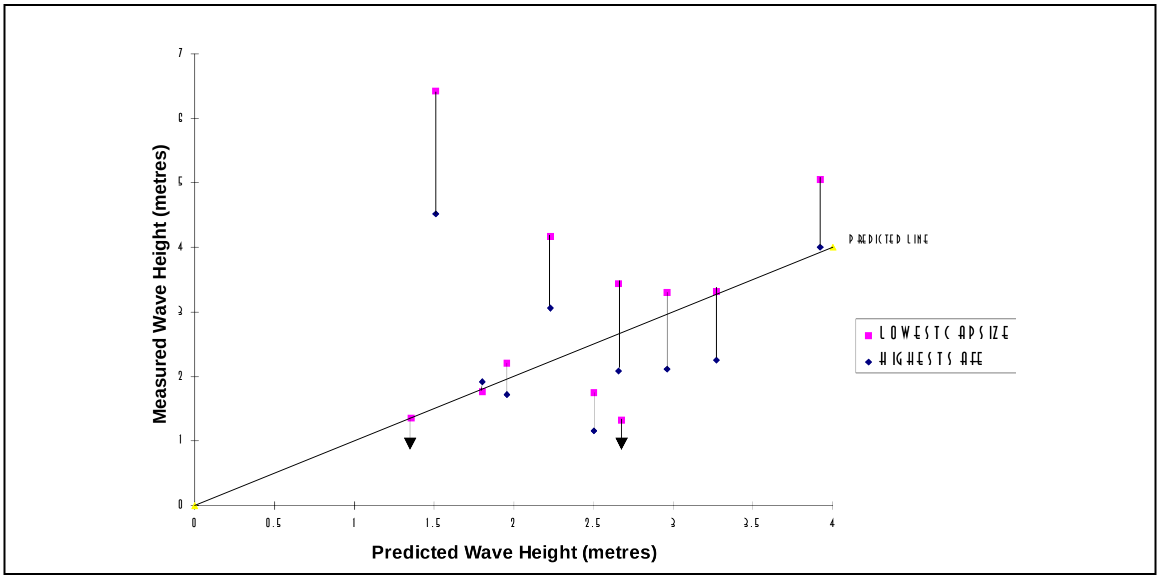


Figure 2.4: Predicted and Measured Capsize Wave Heights, Phase II

2.9 Phase IV Comparisons

The final element of the work on the program prior to its current phase combined its own results and conclusions with those of the Residual Stability Study. The same set of Canadian ferries (with one substitution) was examined using the SEM, though focusing only on the single worst damage condition in a manner similar to deterministic SOLAS 90. For this condition, the capsize wave height was predicted. In subsequent steps, this height was matched to the actual wave climate for the route on which the ferry had been operated, and the capsize wave height was also modified to take account of the statistics of vessel loading on an annual or monthly basis, where such data were available. The results of this exercise were used to construct a partial Safety Index for the service, derived as shown below:

Safety Index, S_I = $1 – (p_H * p_c * p_l)$
where p_H = probability of exceedence of critical wave height at a given loading condition;
p_c = probability of capsize (=0.5), and
p_l = probability occurrence of loading condition (where available)

Table 2.3 shows the relative safety levels of each ship, where a value of 1 implies no risk of capsize under the assumed scenario (worst SOLAS damage), while fractional values provide the probability of survival. The first column takes loading data into account where available, the second only addresses the wave data.

Table 2.3: SEM Safety Index

Ship	SEM Safety Index	SEM Safety Index
	1 – (pH*pc* pl)	1 – (pH*pc)
1	1.00	1.00
2	1.00	1.00
3	n/a	1.00
4	0.99	0.58
6	1.00	0.99
7	n/a	0.74
8	1.00	1.00
9	1.00	1.00

Results with the wave data alone show a similar pattern to the results of the residual stability study, with the ships non-compliant with either form of SOLAS showing the worst performance. The apparent exception of Ship 3 results from this vessel having been tested against a one-compartment damage case (its CSA criterion) rather than the two compartments of SOLAS 90. Adding the loading data improves the apparent safety index of the ships significantly. However, the main question left unanswered by the work was ‘how safe is safe enough?’ Some means is needed to relate any new safety criterion both to more traditional approaches and to societally acceptable criteria. Establishing a firmer basis for defining acceptable safety levels was therefore a key objective for this phase of the work.

3. ANALYSIS OF ADDITIONAL DATA SETS

3.1 Objectives: Data

A major task within this phase of the program has been the analysis of additional ship model data produced by various European researchers into ferry stability problems. The principal objective of this work was additional validation of the basic SEM, to justify its use within a safety methodology. However, there were a number of supplementary objectives, including:

(a) Exploration of differentiation between ship/casing configurations;
(b) Identification of limits to range of validity;
(c) Enhancement of accuracy of predictions for ‘safer’ ships;
(d) Assessment of scatter in results;
(e) Identification of additional parameters warranting inclusion in SEM formulations (for future development).

The ship sets involved are:

1. The *Holyhead Ferry* tested by NPL (UK), [Ref. 12]
2. The *Herald of Free Enterprise* tested by BMT (UK), [Ref .13]
3. The *St. Nicholas* tested by DMI (Denmark) and Marintek (Norway), [Refs. 14-16]
4. The *Nora*, again tested by both DMI and Marintek, [Refs. 17-19]

The particulars of these ships are outlined at Table 3.1. It can be seen that they cover a reasonably wide range of sizes; they also represent a number of quite different configurations from very traditional (the *Holyhead Ferry* being a 1960’s design) to state-of-the-art.

Table 3.1: Ship Particulars

SHIP	Disp.	LBP	Beam	Draft
Holyhea	4082	105.	16.7	3.87
H. of	8600	126.	22.7	5.7
St.	1220	131	26	6.1
Nora	1173	130	25.5	5.75

The models of each ship were tested in a number of ways. For all but the first ship, a range of damage compartment lengths was generated using movable partitions. For all the ships, a number of different KG values were simulated. For several of the ships, different intact displacements were selected at some or all flooding conditions. There is thus a matrix of damaged freeboards, GM values, displacements, etc., for each ship, and the cells of this matrix were tested in different wave heights to find the capsize boundaries.

In order to apply the SEM, models of each ship model had to be created using the stability analysis software, GHS, used in all previous phases of the program. This exercise was not simple, as not all the necessary data was available for any of the ships. This required certain assumptions to be made for each, as described in the following sections. In some cases, the comparisons were also made more complicated by errors in the reports themselves, some examples of which are provided below. However, in general it proved possible to obtain a reasonable match between the basic hydrostatic particulars in both the intact and damaged conditions, giving an adequate basis for comparisons between the numerical and physical modeling results.

Results obtained for each ship are summarized below. The physical model data is compared with the SEM predictions using the same format employed in Phase III of this project, as shown in Figures 2.3 and 2.4. This collapses results for a variety of different initial conditions onto a single plot. More data is provided at Appendix A (model parameters) and Appendix B (analysis results). For the physical tests, [13-18] provide a great deal of additional information on the test procedures and on the conclusions which were drawn from the work.

3.2 *Holyhead Ferry*

3.2.1 Ship Description and Modeling Approach

The *Holyhead Ferry* model is illustrated in Figure 3.1. It is a traditional design, with deck sheer on the vehicle deck and a centreline casing. The physical model was slightly unusual (compared to others tested in more recent projects), having a single damaged compartment length and assuming that the ends of the car deck (outboard of the inner doors) remained watertight during the tests. Tests were also conducted with damage nearer the bow, but these have not been reanalyzed in the current work.

The GHS model was developed from the lines plan provided in the report [12], with the buoyancy of the appendages (excluding the rubbing strake) modeled approximately to reproduce the reported overall intact hydrostatic properties. The damaged compartment and car deck were modeled from the lines and from the reported compartment size. A shell thickness correction corresponds to the ‘approximately ¼ inch’ value quoted in the report. The double bottom height had to be estimated from a small scale drawing, as no better information could be obtained. However, it proved possible to obtain quite good comparisons between the GHS damaged hydrostatics and those reported for the physical model over most of the draft range, once cross-checks had been made to assess which of the contradictory data sets in [13] was most likely to be correct. The published hydrostatics include a variety of misplotted curves, notably for the KM values, where the values shown for the model and the full-scale ship have completely opposite trends.

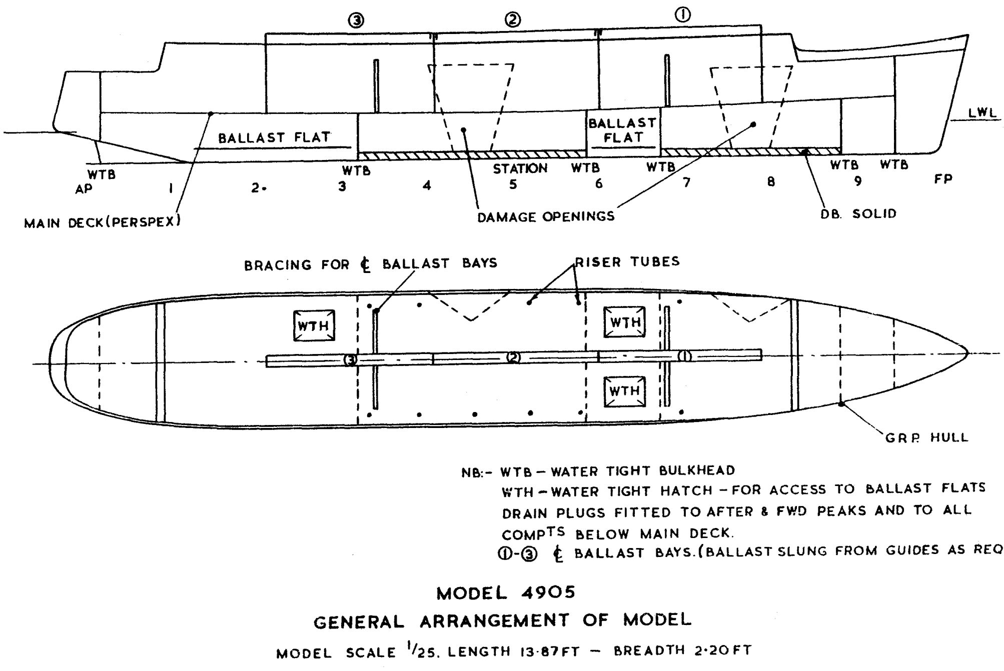


Figure 3.1: ***Holyhead Ferry*** **Model**

Basic stability data for the GHS model is presented at Appendix A to allow comparison with the values from [13]. The only significant differences are in damaged KM at upright drafts close to the margin line, all other results being within 1-2 percent of each other.

The physical model of the ferry was tested with a variety of intact displacements and centres of gravity, giving different damaged freeboards and GM values. The model was run in the tank at different wave heights with a short sea wave spectrum, with the damage facing both into and away from the waves. SEM predictions have been developed for the same freeboard conditions, and with an equivalent range of centres of gravity at each freeboard. Comparative results are summarized below and presented in more detail at Appendix B.

3.2.2 Comparison of Capsize Predictions

SEM predictions were developed for a set of initial displacements and for a range of KGs at each. The basic hydrostatic particulars for each displacement are as shown in Table 3.2

Table 3.2: Hydrostatic Particulars for the Damage Conditions used in the Analysis

Intact KMT (m)	Displacement (tonnes)	Damaged Draft (m)	KMT damage (m)	Residual Freeboard (m)
8.002	4425.25	5.572	7.892	0.078
8.139	3962.65	5.148	7.698	0.502
8.253	3702.33	4.899	7.572	0.751
8.396	3450.99	4.651	7.443	1.0

The consolidated plot of SEM predictions against model test results is shown in Figure 3.2. This shows generally quite close agreement between the predictions and results at lower capsize wave heights, and worse results for the higher sea states. This trend was found in previous work, though in a less marked fashion than is seen in these comparisons. It is also noteworthy how close the model test results for capsize and non-capsize results are to each other. This was apparently achieved by very fine tuning of the KG values and by using very consistent wave climates.

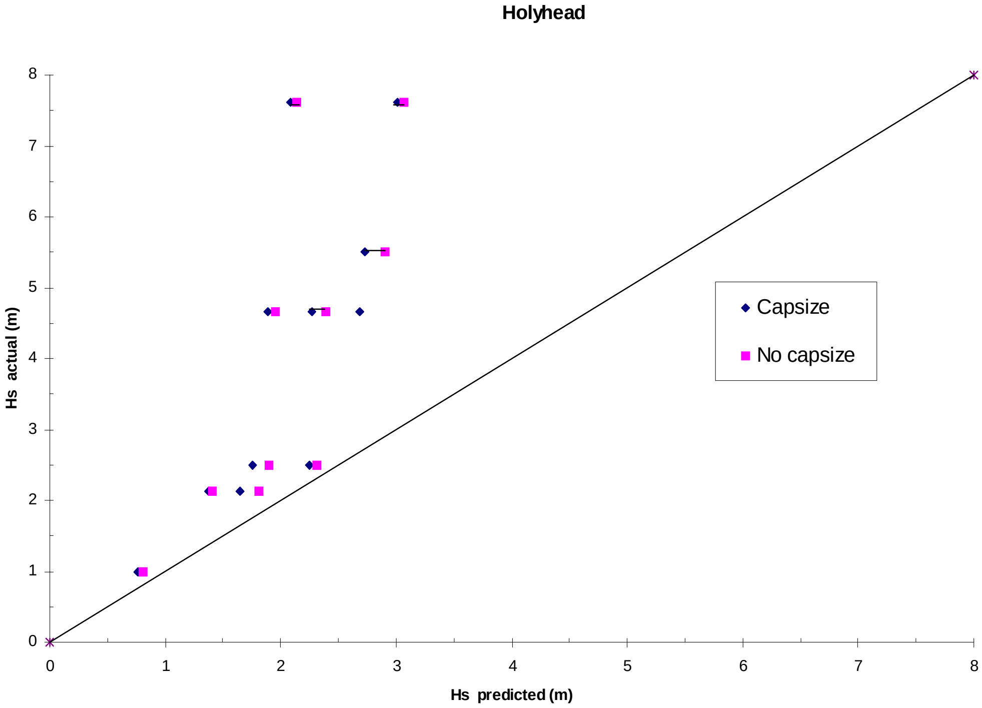


Figure 3.2: SEM vs Model Test Results, *Holyhead Ferry* Model

3.3 Herald of Free Enterprise

3.3.1 Ship Description and Modeling Approach

The *Herald of Free Enterprise* capsized in 1987 with considerable loss of life, an event that stimulated much of the research into ferry stability. Model tests of various aspects of the ship's characteristics were undertaken in the aftermath of the disaster. Although this did not result from damage, damage stability was the focus of a series of tests conducted by British Maritime Technology (BMT) using the model shown at Figure 3.3. The ship is a triple screw vessel, with a fairly complex casing configuration as shown in the plan view.

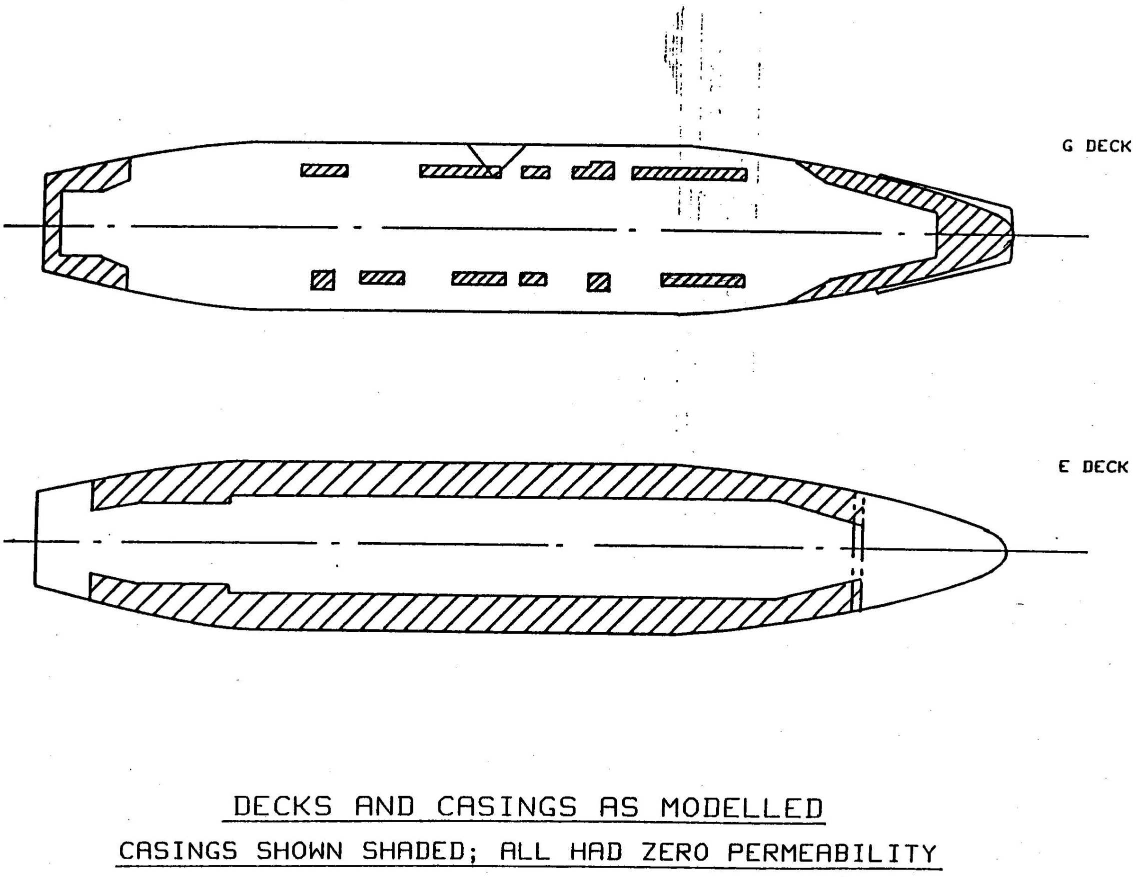


Figure 3.3: Configuration of *Herald of Free Enterprise* Decks and Casings

The GHS model for the *Herald* is based on the lines plan included in the report. This is at a relatively small scale but has the advantage of being supplemented by more detailed lines of the bow and stern. The report provides no details of the appendages that were fitted to the model, and the sketches included are inconsistent with each other. Their volume has therefore been estimated and applied at locations that produce values close to the reported volumes and centres for the ship as a whole. The most important intact hydrostatics for the GHS model and the physical model (as reported) are shown in Table 3.3. The comparisons are reasonable though not exact. Unfortunately, the original report contains no hydrostatic particulars for the flooded ship, and so no comparisons were possible for any flooded conditions.

Table 3.3: *Herald* Hydrostatics

Parameter	**Reported Value**	**Derived Value**
Displacement	8807 tonnes	8807 tonnes
KM_T	11.6 m	11.7 m
VCB	3.32 m	3.33 m

The damage conditions for this ship were developed both by varying the damage lengths and by adjusting the dry weight, in order to produce a desired set of residual freeboards. The former is the ‘base case’, and full information is provided in the report only for this approach. It proved possible to replicate some, but not all of the reported damage cases with the GHS model. The higher freeboard conditions differed considerably when the reported compartment lengths were flooded, and no obvious reason for the discrepancies could be found. Therefore, the SEM analyses were undertaken with compartment lengths that produced the desired freeboard, rather than those reported. The reported and modelled cases are compared in Table 3.4.

Table 3.4: Comparison of Flooded Lengths

Residual Freeboard (m)	**Reported Flooded Length (m)**	**Derived Flooded Length (m)**
0.076	27.7	27.7
0.25	25.7	25.7
0.50	21.1	21.1
0.75	15.0	16.9
1.00	7.1	12.2

3.3.2 Comparison of Capsize Predictions

The *Herald* data contains numerous peculiar results and exhibits a high degree of scatter, particularly at low and medium residual freeboards. At the same freeboard, in many cases, the ship survived high wave heights with low reported GM values, and capsized at lower wave heights with higher GMs. In some extreme cases, the ship capsized with relatively high GM and with a freeboard greater than the (small) significant wave height.

There is somewhat more consistency in the results at higher freeboards, but anomalies still exist. It is difficult to determine the reason for them, as the presentation of the results is not detailed, and does not reflect the description of the test procedure provided in the text of [13].

A comparison with the SEM predictions is presented at Figure 3.4. For this test data, the SEM does not predict the behaviour well at all, and is non-conservative. As this was both unexpected and undesirable, considerable effort was devoted to a search for the explanation. Two candidate hypotheses were available:

(a) capsize is promoted by the type of casing arrangement used on the ship, as compared to more typical side or centre casing layouts;
(b) capsize is promoted by trapping the air below the vehicle deck.

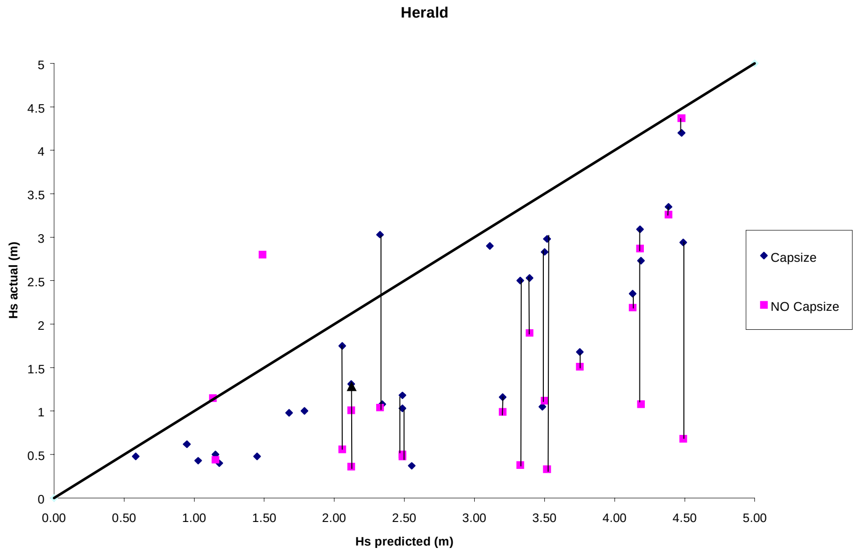


Figure 3.4: SEM vs Model Test Results, *Herald of Free Enterprise* Model

The first hypothesis was supported in part by the observation in the report that sometimes incoming waves would reflect off the casing and become trapped between the casing and the superstructure side. This led to heel towards the subsequent waves, and promoted capsize. However, in other tests the model would heel away from the damage, and be relatively safe. There is no means of distinguishing between the two types of behaviour in the results presented, but the two types of behaviour would appear to promote scatter rather than systematic changes in outcome.

The second hypothesis was based on discussions with the European originators of the SEM during Phase III of the program. They had emphasized the need to ensure that the compartments below deck are properly vented during model tests, an approach taken in the Canadian work and for the *Holyhead Ferry*. For the *Herald*, vents were provided and were used during model calibration. However, they were closed for the actual tests. Both the *Herald* results and those for the *St. Nicholas* (see below) show that this does appear to have a considerable impact on capsize safety.

3.4 *St. Nicholas* Ferry

3.4.1 Ship Description and Modeling Approach

The *St. Nicholas* is an idealized model of a modern European Ro-Ro ferry, with a twin skeg configuration. The physical model was constructed by the Danish Maritime Institute (DMI), who undertook two series of tests with the model. A further test series was conducted on the same model by Marintek in Norway.

The GHS model of the ferry was developed from a table of offsets provided in one of the project reports [16]. These proved to be incomplete in way of the aft end and were somewhat ambiguous above the vehicle deck, and so significant effort was required to produce a set of lines that gave a reasonable match with the reported data. A schematic of the physical model is shown in Figure 3.5.

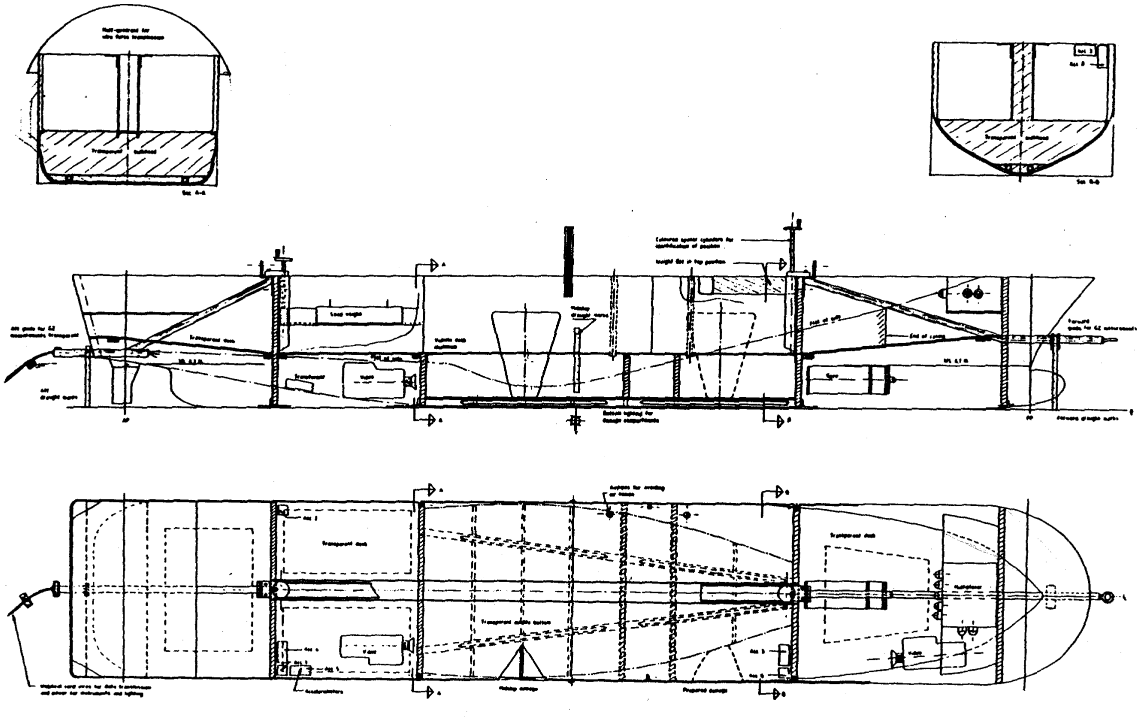
Five GHS models were created with different damage compartment lengths in order to arrive at prescribed damage freeboards used in the tests. The shell thickness correction was estimated using the same approach described for the *Nora*, below. Table 3.5 lists ‘as calculated’ values of KMT and residual freeboards obtained at equilibrium condition for each flooded damage compartment.

Table 3.5: Summary of Damage Conditions

	Compartment Length (m)	KMT (m) Calculated	Residual Freeboard (m) (achieved)
Intact Draft=6.1 m Displacement=12229.63 KMTintact=13.882 m	13.5	13.725	1.07
	18.3	13.775	0.82
	22.8	13.836	0.57
	27.1	13.938	0.32
	28.7	13.965	0.19
Intact Draft=5.7 m Displacement=11125.61 t KMTintact=13.981 m	18.3m	13.643	1.273
	27.1 m	13.78	0.785

The correlation in hydrostatic particulars between the numerical and physical models was not particularly good in this case. The GHS obtained displacements and waterplane areas are within 99.95 percent of the reported values; however, differences are apparent in LCB location, and (more importantly) in KM. The former error is consistent over the full range of drafts, at approximately 0.3 m. The latter appears to vary, but it was difficult to find a good basis of comparison for all the conditions, due to problems within the Phase I DMI report. It appeared (and this is confirmed to some extent by the Phase II report) that errors were made in data transcription, and these propagated throughout the reported results. There is, therefore, limited confidence in either the physical or the numerical model data for this vessel, which is summarized below.

More detailed stability data for the *St. Nicholas* GHS models are presented in Appendix A.



DTP-Model F10 Showing Construction Principles and Instrumentations.

DEPARTMENT OF TRANSPORT
RO-RO PASSENGER FERRY. SAFETY STUDIES. MODEL TEST
GENERAL ARRANGEMENT MODEL F 10 TEST SHIP NO 2
86116-SHIP 4677

Figure 3.5: *St. Nicholas* Ferry

3.4.2 Comparison of Capsize Predictions

Experiments with this model were done at five different damage freeboards, which were established by changing the length of the damage compartment. The DMI Phase 1 experimental test matrix included:

- two initial drafts (displacements);
- five damage freeboards (Table 3.5);
- varying KG values;
- 4 nominal significant wave heights (0.5, 1.0, 2.5, and 5.0 m); and
- wave orientation.

The test series in Phase 2 covered various additional damage openings, external/internal devices aimed at improving survivability, and other effects such as wind heeling and transient moments.

Marintek's tests covered:

- three damage lengths (residual freeboards);
- four KG values;
- a wave range from 1.0 to 7.0 m nominal height.

The reported data for nominally similar conditions at DMI and Marintek differs quite considerably for this model, as can be seen in Appendix B.

The comparisons between SEM and experimental results presented in Figure 3.6(a) and (b) relate primarily to the case of midship damage area with waves oriented into the damage opening. The first plot shows results at the deeper initial draft/displacement, and the second the smaller set for the lighter ship. The agreement is not particularly good for the deeper draft, with the SEM consistently overpredicting survivability.

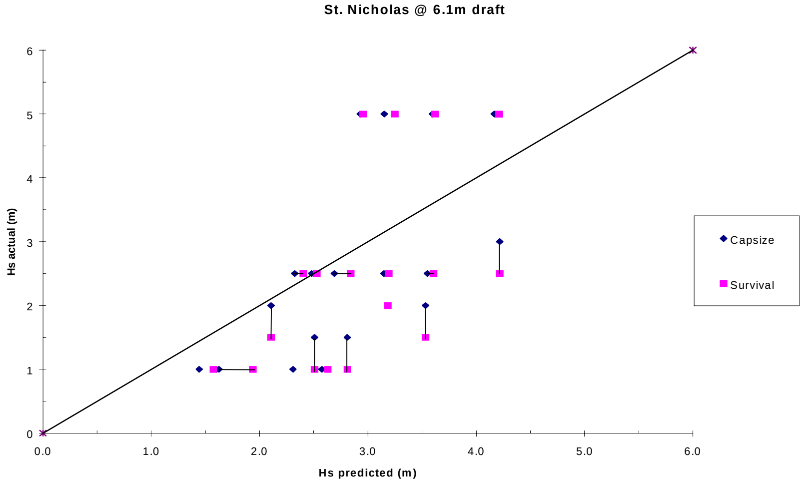


Figure 3.6(a): SEM vs Model Test Results, *St. Nicholas* Model, 6.1m Intact Draft

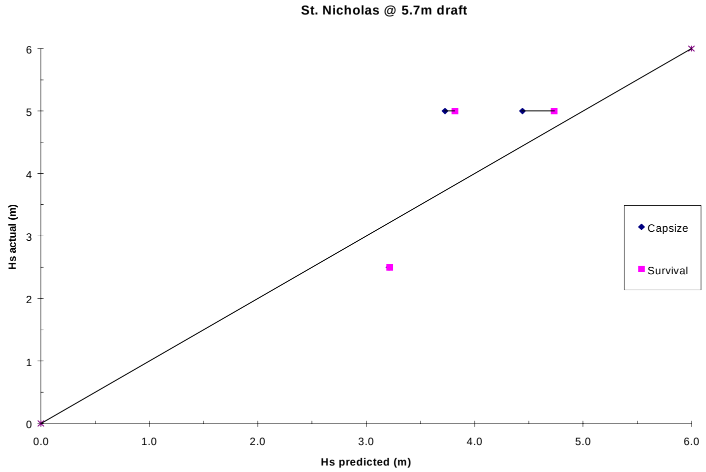


Figure 3.6(b): SEM vs Model Test Results, *St. Nicholas* Model, 5.7m Intact Draft

Both the DMI and the Marintek results for this model were for conditions where air was trapped below the vehicle deck. With the exception of the *Herald of Free Enterprise* (as discussed) all other models including the Canadian series were tested with vents open, to allow the trapped air to escape, this being considered more representative of reality. Although the *St. Nicholas* was fitted with vents, only conditions with the vents closed are reported in the references.

Since the bulk of the *St Nicholas* tests used a centre casing configuration similar to that of many of the other test series, the only major difference was in this air entrapment. This allowed the conclusion reported in Section 3.3.2 to be confirmed – air entrapment reduces survivability.

When air is trapped, it accentuates the vessel's tendency to heel towards the damage, and to roll more about this heel angle. Capsize is thus inevitably at lower wave heights. Although it seems to be generally accepted that this condition is unrealistically severe, this may be an area that warrants some additional research, and/or where specific design or operational direction should be provided. If allowing air escape is important to survivability, then ships should have sufficient venting capacity and this should be kept open at all times when at sea. This will not generally be a problem for machinery spaces, but may require attention for tanks and void spaces.

3.5 *Nora* Ferry

3.5.1 Ship Description and Modeling Approach

The *Nora* is another idealized model of a modern European Ro-Ro ferry, built and tested after the *St. Nicholas*, and after knowledge obtained from this and other test series had been assimilated. The physical model was again constructed by the Danish Maritime Institute (DMI), who undertook two series of tests with the model. These bracketed a further test series conducted on the same model by Marintek in Norway.

The GHS model of the *Nora* ferry was developed from a set of offsets provided through the UK MSA, which were reviewed against the data provided in the DMI and Marintek reports on the model test series [17, 18, 19]. A schematic of the physical model is shown in Figure 3.7. No data was provided on the size of the appendages, and therefore a 'consolidated sponson' was added to the bare hull model to match the reported physical model intact hydrostatic particulars. The sponson vertical location was selected such that it provides buoyancy at large angle of heel, i.e., it does not emerge from the water, and in terms of longitudinal location, places the LCB in proper location. With these modifications to the GHS model, it was found that intact hydrostatic particulars were in good agreement with the corresponding values for the physical model.

For the damage condition calibration process, the length of damage compartment, double bottom height and final residual freeboard were taken as fixed values as these are well documented in reports [17-19]. No data was provided on the shell and deck thicknesses of the model.

Therefore, a shell thickness correction was derived by varying the assumed value until the compartment's lost buoyancy was adequate for the vessel to arrive at a known residual freeboard. The six different damage compartment lengths required six somewhat different shell thickness, and so it was decided to use the average value of the six shell thicknesses and apply this 'uniform' shell thickness correction for all six damage compartments. The obtained hydrostatic properties in damage conditions at full scale are given in Table 3.6.

Table 3.6: *Nora* Hydrostatic Particulars in Damaged Condition

Damage Length (m)	KMT_{dam} (m) Calc.	Res.FB (m) Calc.
24.05	13.506	1.50
26.3	13.474	1.38
32.43	13.382	1.00
34.8	13.357	0.86
40.26	13.298	0.50
42.00	13.267	0.35
Intact Draft=5.75 m Displacement=11740.68 t KMTintact=14.244 m		

These six damage length compartments cover the entire matrix of experimental results conducted with this model by MARINTEK and DMI.

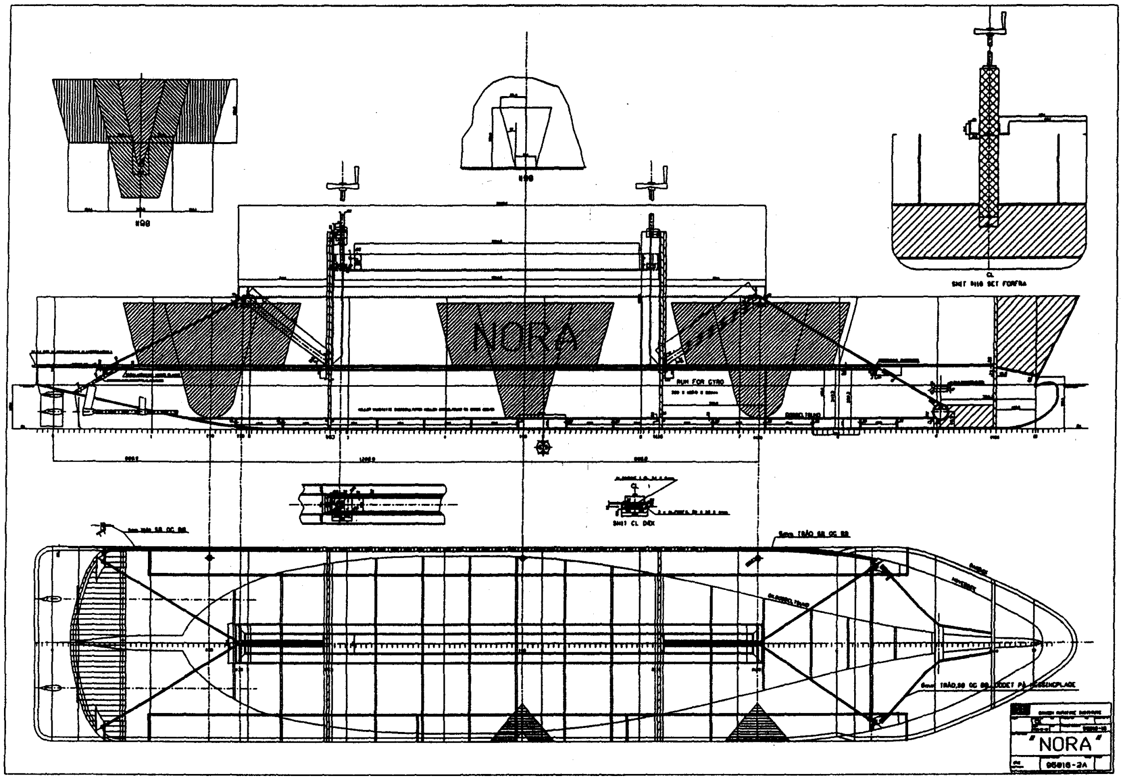


Figure 3.7: *Nora* Ferry

3.5.2 Comparison of Capsize Predictions

As indicated in Figure 3.7, the *Nora* was tested with a variety of damage locations and configurations. The test series also explored different orientations towards and away from the waves, which were modeled as regular and irregular spectra. Altogether, the three series comprised the programs listed below:

Phase I, DMI (101 tests):

- Ro-Ro deck subdivision (6 configurations);
- Damage location;
- Damage size (25, 100, 200% SOLAS);
- Damage freeboard (Table 3.6);
- Seastate (1.5-7 m sig. ht.);
- Intact GM (2.2-5.6m);
- Model Orientation (towards and away from waves).

Phase II, DMI (55 tests)

- Repeat testing to check consistency;
- Damage opening shape;
- Sea spectra.

Marintek (59 tests)

- Damage Freeboard (0.5, 1, 1.5 m)
- KG (11.5, 12.5, 13 m)
- Sea State (1.7-8.5 m sig. ht.)

The investigation strategy differed between the two tanks, with DMI using a constant wave height and finding the capsize GM value, and Marintek holding KG constant and varying wave height. The former approach appears to offer closer identification of the capsize boundary, though this relies on repeatability of the desired wave height and spectrum.

SEM comparisons are only presented for midship damage, and for irregular waves moving towards the damage opening. The other series confirmed findings in Phases 1 and 2 of the Canadian work, and widely reported elsewhere – regular waves generate capsize at much greater wave heights, as do waves moving away from the damage opening. Midship damage tends to be the most severe case. The damage opening configurations had little or no influence on the results.

Figure 3.8 consolidates both DMI and Marintek results on a single plot. The two sets can be distinguished in some cases by the lines joining comparable safe and capsize plots – the DMI technique leads to horizontal lines while those of Marintek are vertical. As can be seen, the two tanks produced very similar results.

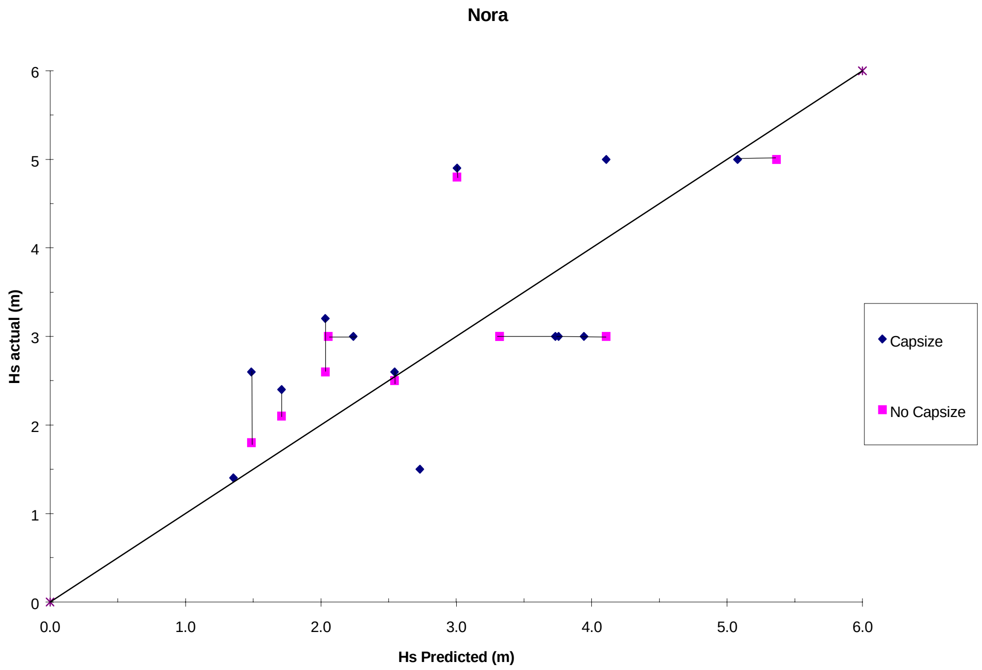


Figure 3.8: SEM vs Model Test Results, *Nora* Model

The correspondence with SEM predictions is also generally very good, over a wide range of conditions. The cases for which the predictions are non-conservative are all from a set of DMI tests at moderate freeboard in which the data seems to contain some anomalies, with lower GMs surviving the same wave heights that caused higher GMs to capsize. No obvious reason for these anomalies has been found in the test reports, which make no comment regarding them.

3.6 Summary of Findings

It can be seen from the results and discussion above that the four ships fall into two categories. In the first of these are the *Holyhead Ferry* and the *Nora*, which were tested in the configuration assumed by the SEM. Here the predictions of the SEM are quite good in comparison with the model test results; for the *Nora* over a wide range of wave hieghts. The *Holyhead Ferry* SEM predictions are increasingly conservative at higher wave heights. This is a trend that was anticipated based on earlier work, though the extent of the divergence in this case is greater than expected.

The physical test results for the other two vessels were obtained under conditions different from those assumed for any of the other test series, where air could become trapped below the vehicle deck. In these circumstances the model test data shows a great deal of scatter, and the SEM predictions are towards the upper bound of the survival cases, i.e., non-conservative. In principle, ferry design should provide for the escape of trapped air, as assumed in the SEM. However, the considerable difference in outcomes means that ensuring air escape should be considered an important element of ferry safety.

The more detailed results included in the Appendix for the two ‘good’ ships in particular confirm a number of the conclusions of previous work, which are:

(a) The quality of predictions by the SEM is largely independent of ship size or configuration;
(b) The SEM tends to underpredict survivability in more stable conditions (i.e., higher GM/wave heights) for all ships, presumably due to the relative importance of dynamic effects;
(c) The collapsing of freeboard and GM influences into a single parametric relationship gives reasonable results.

The data available from these model series was insufficient to address some of the other questions posed in Section 3.1, including the casing influence. Three of the four models had centre casings (for most of the tests) and the fourth had a more complex arrangement, but no differences in behaviour can be conclusively assigned to this difference due to the many other factors that were varied. The *Herald’s* complex casing arrangement may have been a factor in the scatter of its experimental data.

The issue of accuracy and scatter in the results cannot be much clarified by reference to these data sets, as the quality of the reporting is not particularly good for a number of the test programs and the presentations of the data are not consistent among them. In the event that future test programs are undertaken by Canada (alone or in cooperation with other countries and organizations), then some care should be taken in defining the reporting requirements and formats to ensure that the data is comprehensive and unambiguous.

4. SAFETY CRITERIA AND IMPLEMENTATION APPROACH

4.1 Background

The principal objective for Phase V has been the development of proposals for ways in which a risk/reliability-based methodology could be used to assess the acceptability of the safety levels of existing and future Canadian ferry services.

Phase IV of the program showed how the inherent safety of any damaged condition can be combined with environmental and loading data to produce a safety or risk index.

Risk can be defined in many ways, but one of the most useful definitions for engineering projects is:

> *Risk = Probability of occurrence of an event x severity of its consequences*

In the context of ferry safety, overall risk can be built up from a variety of components, as outlined below:

- Probability of occurrence of collision:
  = function of (traffic density, navigation control, environmental conditions, human factors)

- Severity of collision damage:
  = function of (relative energy of striking ship, structure in way of impact)

- Outcome:
  probability of capsize
  = function of (location of impact, residual stability properties, loading condition of ship, relative environmental conditions)
  loss of life
  = function of (number on board, time to capsize, lifesaving equipment, human factors)

In the Phase IV work [9], some consideration was given to how each of these components could or should be treated with the information likely to be available.

Based on the results of Phases III and IV, the Static Equivalent Method (SEM, [7, 8]) has been selected as the calculation engine allowing the capsize probability to be assessed in any damage condition. However, in Phase IV a number of major questions were not resolved:

(i) how the damaged condition(s) for evaluation should be selected;
(ii) how the methodology should be applied; and
(iii) how the required values for a safety index should be set.

Different existing methods address (i) either probabilistically or deterministically; when the application is deterministic the rationale includes probabilistic elements. In this section of the report, the available alternatives are reviewed, the potential differences in outcome are illustrated, and an appropriate approach is recommended. Each of the elements of the risk analysis outlined above is discussed in detail, to allow the rationale for the approach to be understood.

It is always possible to envisage a combination of circumstances that will cause the loss of a ship, improbable though these may be. A safety index of precisely 100 percent, (or 1), is thus not a feasible target. However, there is a need to select a value that is consistent with societally acceptable norms for potential major disasters. Recommendations in this area should be based on an assessment of true historical safety levels and comparisons with other transportation modes, etc.

4.2 Probability of Occurrence of Damage

4.2.1 Accident Types

Damaged stability becomes an issue when a ship loses its watertight integrity due to one of a range of causes, including:

(iv) collision (*European Gateway*);
(v) striking or grounding (*Sleipner*);
(vi) structural failure, including damage to watertight doors (*Estonia* bow visor);
(vii) operational error, such as failure to secure closures (*Herald of Free Enterprise)*.

Each of these will tend to produce somewhat different types and extents of flooding, at least in their initial stages. The focus of conventional ferry damage stability analysis has traditionally been on collision, as being the most likely of the design scenarios to cause dangerous flooding. In this context, structural failure and gross operator error, such as the *Estonia* and *Herald* cases, are not taken into account explicitly, though measures that increase survivability following collision are likely to benefit these situations too.

4.2.2 Probability of Collisions

As noted above, the probability of occurrence of a collision is a function of traffic density, navigation control, environmental conditions, and human factors. As such, it will differ between areas and ship types, depending on how different ships are operated and the level of training that their operators receive.

Collisions are not unknown in Canadian waters, but they are also not particularly common. As an element of this study, the Transportation Safety Board accident statistics have been interrogated for the period 1988-1999 [20]. During this 11 year period, a total of 339 collisions were recorded, or an average of roughly 30 per year. However, the majority of the incidents involved relatively small craft. Only 80 collisions involved ships the size of Ro-Ro ferries, and less than 50 percent of these involved two large ships.

In general, a large vessel is only likely to be damaged seriously in collision with a ship of similar size. In fact, out of this sample of 80 large vessel collisions, only 15 vessels were reported as being holed and nine sank or were declared total constructive losses; i.e., an average of slightly less than one sinking per year. All but two of these nine were small craft, the others being a coaster and a factory trawler. There were also nine incidents involving vessels classed as ferries or passenger vessels (again on average fewer than one per year), four of which were Ro-Ro ships. None of these involved death or injury to the ferry passenger or crew.

To place these numbers in context, in the same period Canadian ferry operators transported roughly 40 million passengers and 15.5 million vehicles <u>each year</u>, or over 400 million passengers without fatalities due to collision damage [21]. It is difficult to put precise figures on the number of ship movements that led to the 80 large ship collisions, as vessel movement statistics do not capture the same categories as the casualty data. However, there are roughly 75,000 ship movements per year involving at least one Canadian port, <u>excluding</u> ferry services, or in excess of 800,000 over the period covered by the accident statistics. Thus, in the order of 1 per 10,000 movements involves a recorded collision.

To summarize, one per 10,000 cargo ship movements leads to a collision, one per 60,000 leads to a vessel being holed in a collision, and one in roughly half a million leads to the loss of a large ship. Thus, for all ship types in Canadian waters, a general probability of collision followed by loss is in the order of 10^{-5}-10^{-7}. This falls into the category of 'remote' possibilities as classified by many risk-management approaches – see Table 4.1. When a remote possibility is associated with catastrophic consequences, some form of intervention is considered necessary to reduce the probability or to mitigate the consequences, as shown by Table 4.1.

Table 4.1: Risk Matrix

Probability Consequence	**Extremely Improbable** Below 10^{-9}	**Extremely Remote** 10^{-7}-10^{-9}	**Remote** 10^{-5}-10^{-7}	**Reasonably Probable** 10^{-3}-10^{-5}	**Frequent** 10^{-0}-10^{-3}
Catastrophe	Tolerable	Tolerable	**Intolerable**	**Intolerable**	**Intolerable**
Hazardous	Negligible	Negligible	Tolerable	**Intolerable**	**Intolerable**
Major effect	Negligible	Negligible	Tolerable	Tolerable	**Intolerable**
Minor effect	Negligible	Negligible	Negligible	Tolerable	Tolerable

The odds are probably rather better for ferries, which generally make many but short trips, and which are typically manned by more well-qualified personnel familiar with the peculiarities of the route. On many services, they are not likely to encounter many other vessels of comparable size, further reducing the probability of a catastrophic collision. However, the data that is readily available does not allow a great deal of quantification of any differences in the risk of catastrophic collision on Canadian ferry routes. For the balance of this project, the routes will be broadly categorized as High and Low Traffic.

The former encompasses services along or across major arteries such as the St. Lawrence on the Eastern side of the country and the Straits of Juan de Fuca and Georgia on the West Coast. The latter characterizes services across ‘local’ waterways such as the Bay of Fundy, Georgian Bay, Howe Sound, etc.

It is possible that the reduced probability of collision for ferries on Low Traffic routes is sufficient to move these services into the region of tolerable risk without further action to mitigate the consequences of collision (i.e., capsize or sinking). At the very least, it may be justifiable to accept a lower residual safety level after damage to balance the lower damage probability.

4.3 Severity of Damage

4.3.1 Collision Damage

All of the SEM analyses to date, and the bulk of the model test work used in validation, have assumed the ‘worst design damage’. This has been defined as the SOLAS 90 opening (length 0.03L + 3m) located at the point that gives rise to the least residual stability. The SOLAS hole is moderately representative of collision damage to a struck ship; i.e., it takes the shape that might be expected when a bow penetrates another ship’s side. Figure 4.1 shows the SOLAS hole (as generally interpreted) superimposed on the *European Gateway* damage (from [22]) – the similarities are obvious, and it is also noteworthy that the real damage was sufficient to sink the ship (operator error also contributed).

All types of holing may be moderately similar to this, but with different extents depending on the collision velocities, the sizes and configurations of the ships, etc. How the damage distribution is represented is an important issue in the estimation of risk.

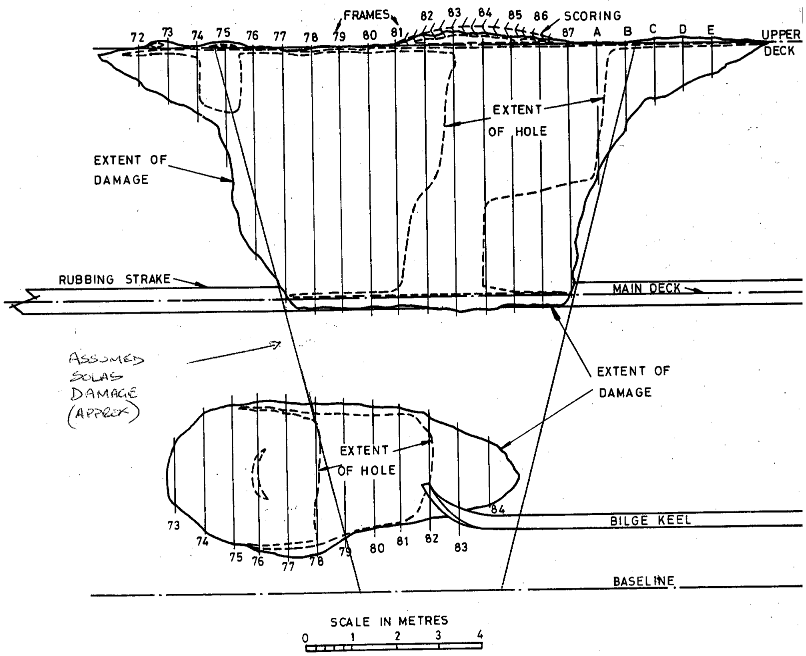


Figure 4.1: ***European Gateway*** **Hole Configuration**

4.3.2 SOLAS Damage Size and Distribution

Under the SOLAS 90 deterministic approach to damage survivability, it is implicitly assumed that:

(a) the cumulative probability of damage extent approaches one for a hole the size of the SOLAS standard opening, i.e., the possibility of incurring a damage any larger than this is too small to justify consideration;
(b) damage is equally probable at any location along the hull (except that it need not be considered to fall on a bulkhead for one-compartment ships);
(c) damage will extend inboard by B/5, meaning that any compartments inboard of this can be assumed intact in stability analyses.

The way in which these requirements were formulated is inconsistent in several respects, and has tended to encourage some undesirable design practices, such as reliance on B/5 subdivision and restriction of number of personnel, length, etc., to justify one compartment design.

The concept of risks inherent in a ‘one-compartment’ design warrants some discussion. Many existing passenger ships were designed to a one-compartment standard, which was quite permissible under international and domestic standards for vessels with restricted service or number of passengers. A one-compartment standard requires that any incident that floods a single major watertight compartment of the ship will be survivable, in that an acceptable level of residual stability will be available (see 4.4 for additional discussion of residual stability). However, there is no requirement to have any level of survivability under conditions that flood two (or more) compartments.

Thus, if 25 percent of holes extend across a watertight bulkhead, 25 percent of holing incidents could lead to loss of the ship (though in practice other factors will tend to mitigate the risk). Where a ship has two-compartment survivability, only holes large enough to extend across two subdivision bulkheads will have the potential to sink the ship.

Thus, moving from a one-compartment to a two-compartment standard means that the possibility that any hole might sink the ship is replaced by the knowledge that only the largest holes could lead to sinking. The risk that a small - 'dinner plate size' - hole could sink a (one-compartment) vessel carrying many hundreds of people is a major concern to many administrations and marine professionals, and is currently the subject of much debate at IMO.

The probabilistic version of the SOLAS criteria [11] attempts to take into account the different probabilities of damage of various extents and locations. Distributions of damage size and centre are assumed based on statistical data. Qualitatively, it is assumed that:

(a) damage is more likely towards the bow and less likely aft of amidships;
(b) a large damage is less probable than a small one (no account is taken of damages extending over more than four adjacent compartments);
(c) inboard penetration is related to damage length, and wing bulkheads will contribute to survivability to varying degrees depending on their position.

The use of the probabilistic method's relationships is better suited to a risk assessment methodology than is the deterministic approach, despite some concerns over the validity of its statistical underpinnings. For example, the database used in constructing the damage size probability distribution ignores the smaller holes that appear from Canadian data to be the most probable types of holing. A number of critiques of aspects of the approach can be found in references [23-25], and in the recent discussions of ways in which the method should be updated at IMO.

4.4 Capsize and Sinking

4.4.1 Residual Stability

Residual stability under SOLAS is itself defined by multiple parameters (Figure 2.2), not all of which will necessarily reach their minimum values under the same conditions. However, for any ferry analyzed to date in this series of projects [1, 9], the worst condition has usually been fairly obvious, and has involved damage at or near amidships in way of main machinery compartments. This condition has almost always minimized several of the key parameters, and when other conditions giving the lowest values for single parameters have been checked, their performance has been better.

It should be appreciated that a ship that fails any or all of these criteria will not necessarily capsize or sink. An actual capsize sinking condition would be defined by:

(a) a righting arm curve that fails to become positive at any angle;
(b) a damaged waterline that immerses one or more downflooding points; or
(c) a negative reserve of buoyancy in the damaged condition.

The SOLAS 90 criteria are thus not ‘absolute’ but rather relative safety indices. One of their deficiencies is that they do not represent consistent levels of safety for different ships, and non-compliances with different criteria also have quite different implications for risk. One of the criteria, the heel angle after damage, has no direct relation to any probability of loss of the ship, but is much more relevant to the ability of the personnel on board to evacuate. In practice, for most Ro-Ro ships, large angles of heel are not survivable for other reasons.

In the SOLAS full probabilistic approach, for any case (which may damage one, two, or more compartments) a somewhat different set of residual stability criteria is applied to assess whether the condition is acceptable or not. An overall index is built up from the weighted summation of pass (= 1) fail (= 0) and ‘marginal’ ($0<x<1$) conditions; though again ‘fail’ is a relative rather than an absolute or probabilistic concept due to the criteria applied. The value of the ‘attained index’ is then compared with the ‘required index’, which is itself a function of ship size and the number of personnel embarked.

In the ‘simplified probabilistic method’ [5] that has been adopted by IMO for the evaluation of existing Ro-Ro ships, the ‘required’ value is replaced by the more manageable ‘A_{MAX}’, and the stability analyses are restricted to the analysis of 1 and 2 compartment cases. This procedure is explained in MSC Circular 574, [5]. The pass/fail survivability criterion for any damage case is expressed as:

$$s = c*2.58*(GZ_{MAX}*Range*Area)^{0.25} \text{ (not to exceed s=1)}$$

where c = 1 if the final equilibrium heel angle is $\leq$ 7 degrees
0 if final heel angle is > 20 degrees

else c = $((20-\Theta)/(20-7))^{0.5}$

In addition, the equilibrium waterline must remain below the bulkhead deck.

The results of these analyses – the A/A_{MAX} ratio – are used as one of the criteria dictating when an existing ship should be phased out, or modified to attain a higher survival probability. Once again, the ‘s = 1’ criterion does not define a consistent level of risk for different ships, and the cut-off at this value is quite arbitrary – for a given vessel this might represent an ability to survive in a 3 m wave height with a 50 kt wind, taking no further account of the possibility of encountering more severe conditions. Both the full and simplified methods are thus pseudo-probabilistic in their treatment of survival probability.

4.4.2 Predictions using SEM

The use of the Static Equivalent Method involves a quite different approach to survivability. For any given damage condition (though see below) it estimates a critical wave height in which the ship has a 50 percent probability of remaining afloat and upright for a significant period of time (at least 30 minutes). There is no ambiguity about what is represented by the criterion – it represents a capsize due to the accumulation of water on deck. Survivability also requires prevention of downflooding at the critical heel angle and final waterline that are part of the SEM calculation process. Adequate reserve buoyancy is a given, as there can be no SEM solution where the ship founders.

In order to apply the SEM, there is thus a need to build up a survival probability from a knowledge of the probability of reaching the damage condition(s) for which the calculation is undertaken, combined with the probability of encountering the critical wave conditions. Some of this work was undertaken in Phase IV, as described in Section 2, and has helped to develop the two alternative approaches presented below.

One issue in following a fully probabilistic approach in the use of the SEM has not been raised before in this series of projects, but should now be noted. The method is based on the inflow and outflow of water through reasonably large holes resulting from major damage. There will be a lower bound of hole size for the flow equations to be valid, though work conducted as part of the SNAME panel's explorations of the issue [26] suggests that this lower bound will be a fairly small hole. It is likely that the SEM will overpredict the consequences of small damages (and that conventional hydrostatic analysis will also do so). Since this leads to conservative results, there is no safety risk associated with such overprediction. However, it may distort the picture of the overall risk of ferry accidents, and its existence should therefore be recognized.

4.5 Loss of Life

SOLAS takes quantitative account of the number of embarked personnel in assessing adequacy of stability. In SOLAS 90 the standard of compartmentation is linked to numbers directly.

The nature of the relationship between numbers at risk and safety requirements is quite tenuous in the full A265 procedure [11]. In the application of the simplified method [10] it is discarded altogether and replaced by a stepwise phase-out criterion. Current work at IMO has not yet arrived at an improved method of dealing with numbers at risk (recent IMO discussions are reported at the web site www.sname.org/committees/tech_ops/O44). It is considered that work should be undertaken to bring the methodology more into line with treatments of risk used in other industries, but for the time being loss of life potential can only be handled to the extent now covered by IMO.

4.6 New Risk-Based Methodology

4.6.1 Principles

The risk-based approaches that have been developed in this project incorporate three key principles:

(i) The risk-based approach should allow for the consideration of as many as possible of the factors listed in Section 4.1;
(ii) The approach should build on existing national/international methods and criteria where possible;
(iii) Any changes to existing methods should be demonstrably more rational than the elements that they replace.

In addition, it has been considered to follow existing methods of damaged stability assessment as closely as possible in order to:

(i) minimize the extent of wholly new analyses that operators and regulators are required to undertake;
(ii) assist in presenting the Canadian results to international bodies in a way that encourages their acceptance;
(iii) simplify the procedure for selecting acceptable levels of safety.

In practice, (i) and (ii) above are limited by a lack of reliable statistical data or analytical tools to handle many of the factors. The list from Section 4.1 is repeated in tabular format below (Table 4.2) with factors categorized as shown. Where the proposed approach uses a methodology that is new, in whole or in part, this is indicated by italicizing the factor. In principle, many of the factors that are treated qualitatively (or not at all) in the proposed methodology could be handled more quantitatively in future. Some of the recommendations for future work made in Section 6 are aimed at improving the treatment of these factors.

Table 4.2: Treatment of Risk Factors in Proposed Approach

Quantitative	Qualitative	Intractable
Probability of occurrence of collision		
	Traffic density	Navigation control, Environmental conditions, Human factors
Severity of collision damage		
Relative energy of striking ship		Structure in way of impact
Probability of capsize		
Location of impact, *Loading condition of ship,* *Residual stability properties,* *Relative environmental conditions*		
Loss of life		
Numbers on board	IMO-based approach	Time to capsize, Lifesaving equipment, Human factors

Two options are proposed below. The first, simpler method is analogous to the deterministic approach of SOLAS 90, while the second is based on several of the elements of MSC 574 as adopted by IMO.

4.6.2 Semi-Deterministic Approach

The simpler of the two options builds directly onto the method used in the Phase IV project, in the light of additional information and analysis undertaken since its preparation.

This approach assumes the existence of a SOLAS 90 hole and derives a critical wave height for the worst damaged condition (location, and ship loading condition). If the critical wave height occurs on the intended route for less than 10 percent of the time (<10 percent probability of exceedence), then the ship is adequately safe. The 10 percent value matches the 'Stockholm Agreement' approach adopted as a regional safety standard in North West Europe, as described in [27].

It could be argued (here and in the more probabilistic method described below) that the criteria need further adjustment, to account for the fact that the SEM critical wave height gives a nominal 50 percent probability of capsize. However, the Stockholm Agreement approach allows vessels to demonstrate adequacy using model testing, in a similar manner to that used in the validation of the SEM. These elements of total probability thus effectively cancel out.

Where this procedure shows a >10 percent probability of exceedence for wave height, loading restrictions can be considered. This could be done by matching the survival load level to an annual, seasonal, or voyage specific wave climate, at the discretion of the safety authorities. In the event that a short-term approach is taken, there would be a need to ensure that sufficient understanding and guidance are available to the master, terminal operator, etc., to ensure that overloading does not take place.

The treatment of one-compartment ships under this approach is somewhat problematic. There is a general international consensus that one-compartment passenger ships are unacceptably risky, for ships able to carry more than 400 persons. (In the North American context, this number itself seems unacceptably high.) Where an existing ship carrying more than a threshold number of personnel has been built to a one-compartment standard, its survivability against two compartment damage can be tested, first to check for residual buoyancy, and then by using the SEM. Load and operational limits can then be developed using the basic procedure. However, it is probable that the worst two compartments damage cases for many ships will lead to foundering at any feasible operating displacement. The only way in which continued operations can be justified for such ships will be to move to a more complex probabilistic approach. This can be based on the latest IMO standards but uses the SEM methodology as a more rational calculation engine, in lieu of the residual stability criteria.

4.6.3 Probabilistic Approach

The latest IMO requirements for ferries undertaking international voyages establish phase-out schedules for vessels that do not comply fully with SOLAS 90, based on the A/A_{max} ratios calculated in accordance with MSC Circular 574. Somewhat different schedules are applied to one- and two-compartment vessels (where the former carries over 400 passengers) as shown in Table 4.3.

Table 4.3: Phase-out Schedule for Existing Ferries

Criterion	**Phase-out date**	
	2-compt (or more)	**1-compt**
A/Amax		
<85%	1 October 1998	1 October 1998
85-90%	1 October 2000	1 October 2000
90-95%	1 October 2002	1 October 2002
95-97.5%	1 October 2004	1 October 2004
>97.5%	1 October 2005	1 October 2010
Persons carried		
>1500		1 October 2002
1000-1500		1 October 2006
600-1000		1 October 2008
400-600		1 October 2010
Age of Ship		20 years

The A/A_{max} calculation for one-compartment ships takes account of both one- and two-compartment damage cases, and though it does not put one- and two-compartment ships on an equal footing, it does provide some indication of relative risk within and across the subdivision categories. A better measure would certainly be preferable, but developing this would require considerable additional data collection and statistical analysis.

Most existing Canadian ferries have now had their probabilistic survivability checked according to the simplified method and/or the full method – see for example the results of the Residual Stability Project [2, 3]. A number of stability analysis programs incorporate routines that accomplish the task fully or semi-automatically.

These checks immediately identify conditions with ‘partial compliance’, i.e., those for which the survival index is between 0 and 1. Although a value of 0 does not necessarily mean that a ship will sink in the given damage condition, and a value of 1 certainly does not represent absolute safety, the analyses provide a valuable filtering that can serve as the basis for subsequent SEM analysis.

Any partial compliance condition can be selected for SEM analysis. The SEM will generate a survivable wave height (one at which there is a 50 percent probability of capsize). If the probability of exceedence of this wave height is less than 10 percent with the selected damage and ship loading, the outcome is acceptably safe.

Any safe outcome can be used to increase the survival index from its fractional value to a value of unity (i.e., s = 1). The overall attained index for the ship will increase in proportion to the probability of that damage event. Any safe outcome can be used to increase the survival index from its fractional value to a greater value, and the overall attained index for the ship will increase in proportion to the probability of that damage event.

The same approach could be applied to all partial compliance cases. Based on previous work with the SEM, however, it can be assumed that any other condition with a higher survival index according to the SOLAS method will also be ‘safe’ for the ship in question, and thus the number of SEM analyses required can be quite small. More than a single case should always be checked to minimize the risk of anomalous results. If a vessel is required to demonstrate a given attained index to meet a desired phase-out date, then the first SEM case analyzed can be the worst case (lowest s value) which, if together with all better cases, would give a summation equal to or greater than the required value.

In the event that the SEM analysis does not achieve the target survival index at the 10 percent probability wave and the initial loading condition, then it may be acceptable to explore alternative mixes of wave height and loading to establish restricted serviceability limits. As in the semi-deterministic approach this could be done on a seasonal basis; or alternatively in real time where the actual weather conditions are used to dictate allowable loading.

As an illustrative (and rather artificial) example, ship 7 from Phase IV (and from the earlier projects) has been examined using the proposed method. This ship, a one-compartment vessel, certified to carry up to 600+ people, showed an A/A_{max} ratio of 81 percent based on an attained index of 0.4106 and an A_{max} of 0.5076. Under the IMO phase-out schedule, this ship could remain in service until 2008. With an A/A_{max} ratio of 97.5 percent, it would be permitted to stay in service until 2010 (this is not a very dramatic example, but other ships will show bigger changes). At a ratio of 1, it can stay in service indefinitely.

Table 4.4 draws data from [2] (the Residual Stability Project) and from the Phase IV report [9] to show the contributions of 1 and 2 compartment damage cases (.1 and .2 respectively) to the original attained index and to the SEM-based version. By inspection of the original results, it will be necessary to bring the one-compartment damage case where s = 0 (case 4.1) into a condition where s = 1. This case was analyzed in Phase IV, where it was found to correspond to a 0.9 m critical wave height. Using the same wave height for the two-compartment damage cases, the detailed information in [9] indicates that cases 5.2 and 7.2 would also become survivable, and thus contribute to the overall safety of the ship. (However, they are shown in italics to emphasize that no SEM analysis of the conditions has actually been undertaken.)

Table 4.4: Illustration of Revised A/A$_{max}$ Calculation

Damage Case	a	p	s	a*p*s	s (SEM) at 0.9m	a*p*s
1.1	0.4702	0.0301	1	0.0142	1	0.0142
2.1	0.5943	0.0184	1	0.0109	1	0.0109
3.1	0.7562	0.0659	1	0.0498	1	0.0498
4.1	0.9990	0.0971	0	0.0000	**1**	**0.0970**
5.1	1.1835	0.0334	1	0.0395	1	0.0395
6.1	1.2000	0.0168	1	0.0202	1	0.0202
6.1	1.2000	0.0420	1	0.0504	1	0.0504
7.1	1.2000	0.0454	1	0.0545	1	0.0545
8.1	1.2000	0.0184	1	0.0221	1	0.0221
9.1	1.2000	0.0259	1	0.0311	1	0.0311
10.1	1.2000	0.0167	1	0.0200	1	0.0200
1.2	0.5241	0.0357	1	0.0187	1	0.0187
2.2	0.7922	0.0469	0	0.0000	0	0.0000
3.2	0.8911	0.0763	0	0.0000	0	0.0000
4.2	1.0526	0.0637	0	0.0000	0	0.0000
5.2	1.1835	0.0236	0	0.0000	***1***	***0.0279***
6.2	1.2000	0.0264	0	0.0000	0	0.0000
7.2	1.2000	0.0416	0	0.0000	***1***	***0.0499***
8.2	1.2000	0.0336	1	0.0403	1	0.0403
9.2	1.2000	0.0323	1	0.0388	1	0.0388
			Basic	**0.4105**	Revised	***0.5853***
			A/Amax	0.81		1.15 (effectively =1)

The final value of A/A$_{maxs}$ ratio (the 's' designating the SEM-based approach) is in excess of 1 in this case (though values greater than one do not strictly have a meaning under the IMO approach as no additional contribution from two compartment cases is taken into account). However, the critical wave height may not be acceptable as an operational limit. The next step, therefore, would be to repeat the analyses with a partial loading condition and to establish an acceptable operational regime taking both influences into account.

It can be noted that the same overall risk level can be built up from component probabilities in multiple ways. A 10 percent probability of exceedence of wave height combined with a zero percent probability for loading (i.e., maximum – load line – draught) is the same as 10 percent probability for loading and zero percent for wave height, or approximately 5 percent exceedence probability for both. Depending on the nature of the loading and climate statistics for the route, the optimum trade-offs between restrictions may differ.

The final element of the method will involve consideration of traffic densities. It should be acceptable for a non-compliant (A/A$_{maxs}$ < 1) ship to stay in service for longer on a low-traffic route than on one with high traffic. The phase-out schedule of Table 4.3 could thus be modified accordingly, perhaps as shown in Table 4.5 (for one-compartment ships).

Table 4.5: Modified Phase-out Schedule for Canadian Ferries

Criterion	**Phase-out date**	
	High Traffic Route	**Low Traffic Route**
A/Amax		
<85%	1 October 1998	1 October 2000
85-90%	1 October 2000	1 October 2002
90-95%	1 October 2002	1 October 2004
95-97.5%	1 October 2004	1 October 2010
>97.5%	1 October 2010	1 October 2015
Persons carried		
>1500	1 October 2002	1 October 2006
1000-1500	1 October 2006	1 October 2008
600-1000	1 October 2008	1 October 2010
400-600	1 October 2010	1 October 2015
Age of Ship	20 years	20 years

This Table, or Table 4.3, could also be used to govern a phase-out schedule for one-compartment ships if the semi-deterministic method outlined in Section 4.6.2 is used in lieu of the probabilistic approach. The only difference would lie in the deletion of the A/A_{maxs} criterion. All one-compartment ships would be required to demonstrate SEM survivability (as defined above) immediately, and their subsequent life span would then be dictated by either the age or the number embarked criteria.

5. FORMULATION OF INFORMATION MATERIALS

5.1 Objectives

A number of groups should be made comfortable with any new approach to safety assessment, for this to be generally acceptable and reliable in application. These include:

(a) regulators (Transport Canada, HQ and regional inspectors);
(b) operators (CFOA members, including ferry crews);
(c) designers and builders;
(d) international bodies (IMO; USCG);
(e) the travelling public.

The first three are largely self-explanatory. TC must be convinced that a method will achieve adequate safety levels. Operators must be assured that such levels are adequate, but not excessive or economically unfeasible. TC and CFOA head office staff (and some others) have been kept aware of the work in this program as it has progressed. If there is to be a real-time component to their use, then crews must understand their application – in any event, it is obviously essential that designers (and others required to conduct or review performance analyses) do so.

Since ferry safety has been an important agenda item for IMO, it will be important that Canada shares any new approach, and the rationale for this, with the international regulatory community. It is particularly advisable that the U.S. authorities are also made aware of developments, as it would be logical to apply these to international traffic between the two countries to provide a consistent level of safety. New regulations (if any) are required to withstand public scrutiny, and therefore, it is desirable that an explanation of the background is available in a format reasonably clear to the intelligent lay person.

The preferred approach to explanation is to develop a video presentation of the issue and the risk assessment approach. This may be developed in such a way that versions of different length and complexity can be provided to suit different client groups.

5.2 Approach

It is with those objectives in mind that action has been taken within the present project to develop a draft storyboard that could become the basis for a video production not exceeding 30 minutes in length. Having regard to the different interest levels of the various audiences, as described above, it has been concluded that three versions of the video would be needed to cover the information spectrum. This would be achieved by arranging for a main video from which two reduced videos would be extracted with only selected content.

In order to obtain a reasonable indication of the probable cost of such a video set, a number of professional video production companies were approached for advice. The responses were unanimous in advising that the original storyboard lacked the important component of human interest in holding the audience attention. Various recommendations were made to overcome this problem including conducting interviews with professionals involved in the subject area and including news footage of historical events, such as accidents, to better focus the viewer on the problems. These recommendations have been kept in mind in preparing a revised storyboard that is attached as Appendix C to this report. The selection content for the main video and the two reduced videos are also provided in that Appendix.

Clearly, the extent to which the historical and other related issues are included in the video will affect the production cost. Conducting interviews, and even obtaining footage from news archives, rapidly increases the cost. Keeping in mind the range of estimates arrived at by the producers, an appropriate budget has been identified for the production of a professional quality video for the attached draft storyboard using VHS technology. If Multimedia (CD.ROM/DVD) technology was chosen, for greater flexibility in content selection, a moderate increase in cost could be expected.

The contacts and communications made in this task and the resultant budgetary recommendations are contained in a confidential file deposited with the Scientific Authority.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This phase of the project has led to the following conclusions regarding the Static Equivalent Method, its use in a risk-based ferry safety model, and how such a model could be introduced to the Canadian industry:

6.1.1 Validity of the SEM

The tests of the SEM against data sets developed in Europe do not substantively change the conclusions reached using Canadian data. The method is relatively robust in its ability to treat a range of ship sizes and configurations. It is conservative in most cases, and significantly so where there is a high level of survivability after damage, presumably due at least in part to the greater importance of dynamic effects in such situations. It provides a 'worst case' analysis in many respects, in that survivability is much greater than SEM prediction when damage is on the leeward side.

One scenario in which the SEM predictions is non-conservative is where air is trapped below the vehicle decks rather than being free to escape. The results from the 'Herald' and 'St. Nicholas' models show that survivability is much worse under these circumstances. Given that several elements of SOLAS discourage measures that might promote air escape, this may represent an important area for future study.

It was notable that none of the European reports provided as complete a picture of the testing procedures and results as did the Canadian reports from Phases I and II. This leads to several of the recommendations offered in Section 6.2.

6.1.2 Risk Assessment Methodology

Two variants of a methodology for the evaluation of safety in the damaged condition have been proposed.

Method 1 is a straightforward replacement of the residual stability criteria of SOLAS 90, using the SEM capsize wave height prediction. If the survivable wave has less than a 10 percent exceedence probability, the ship is acceptably safe. If the probability is greater than this, then structural modifications, loading restrictions, operating condition restrictions, or some combination of these can be applied to bring the results into the acceptable range.

Method 2 is a more probabilistic approach that follows the procedures adopted by the 1995 SOLAS Conference for existing ships. In this method, the A/A_{maxs} ratio calculated in accordance with IMO Circular 574 determines the degree of compliance and phase-out schedule for existing ships. If the phase-out date falls before the ship's projected end of life, then the SEM can be used to recalculate A/A_{maxs} , with modifications and restrictions again being possibilities if the initial outcome is unsatisfactory. A further adjustment on the basis of traffic along the route could also be considered.

It can be noted that following internationally agreed approaches in assessing the acceptability of safety levels, and phase-out schedules for vessels with shortcomings actually tends to penalize existing two-compartment ships in comparison with one-compartment vessels. This is a somewhat paradoxical situation, as there does not appear to be any basis for considering the risk of accidents as being smaller for the one-comparment ships, and the loss of life in any accident could be quite similar. While a continuation of this approach may be acceptable on an interim and short-term basis, in the future the absolute level of risk should be used to dictate subdivision standards.

6.2 Recommendations

6.2.1 Risk-based Methodology

It is recommended that the more probabilistic Method 2 approach be used as the basis for evaluating the safety of existing Canadian domestic ferries, on an interim basis. Method 2 is preferable to Method 1 for several reasons, including its closer alignment to current international requirements (and ongoing developments).

Method 1 would be more appropriate to the treatment of new ships, if these were intended for use on a specific route. In such cases, it provides a more rational assessment of safety than the current standard for new ships, which utilizes the SOLAS 90 approach.

Before either method can be finalized and formalized as a regulation, standard, or guideline a number of additional steps should be taken, including:

(a) conducting an impact analysis;
(b) finalizing the format and contents;
(c) preparing suitable explanatory materials (as outlined in Section 5).

A partial impact analysis could be undertaken using the materials developed in this program of work, supplemented by suitable cost data. Alternatively, a suitable template could be developed and distributed to CFOA members to allow them to undertake much of the underlying work, for assembly and final analysis by Transport Canada. The finalization of the contents of the resulting methodology would be calibrated against these results to achieve a cost-effective outcome.

6.2.2 Further Stability Research

Any safety standard adopted today should be regarded as an interim measure that is likely to be superseded by a direct or tailored application of new SOLAS standards within the next 5 years. A considerable amount of stability research is being undertaken in Europe and elsewhere in an attempt to provide a better scientific basis for such standards. Canada has been offered the opportunity to participate in this work, and should do so. Ferry damage survivability in particular is the area of marine safety affecting more Canadians than any other issue, and deserves attention on this basis.

Four main areas are recommended for future work:

(i) exchanging data with interested administrations;
(ii) gathering more and better statistics on casualties in particular;
(iii) continuing with research to improve capsize prediction methodologies, including SEM;
(iv) establishing rational criteria for acceptable levels of risk/safety.

The first of these appears self-evident, but needs to include measures to ensure that data can be analyzed and interpreted consistently and with confidence. This requires improved documentation of procedures for all elements of future work. Past Canadian research has frequently been of a very high standard in this regard, and our expertise could be of value to other organizations and administrations.

Damage (and non-damage) statistics are a major weakness of current methods and of efforts to improve these. The gathering of accurate data in a consistent fashion is a major task, but one which is essential not only to this project but to many other initiatives ranging from vessel traffic control strategies and user fees to infrastructure investment decisions. Not all of these are specifically Transport Canada responsibilities, but TC may need to take a leadership role. As noted above, it is also important that Canadian approaches are compatible with international practice.

For future damage stability research one new item has been identified in Phase V, namely the importance of air entrapment and the necessity to ensure that this is precluded by venting arrangements. A number of other issues have been identified in previous phases of the Canadian work (and in the reference materials for this), the most important of which are recapitulated below:

(i) treatments of freeing port arrangements;
(ii) evaluation of casing influences, in both idealized and ‘real world’ situations (e.g., with vehicles also present);
(iii) exploring the SEM water build-up relationship for a wider range of hole sizes, and for various degrees of dynamic response;
(iv) exploring time to capsize/sink with different levels of damage;
(v) combining relative ship/wave/wind headings in overall risk models.

A majority of these should be explored using a combination of numerical and physical modeling; several obviously rely on the collection of improved statistics, as recommended above.

The final recommendation relates to the need to put safety criteria (including those for survivability after damage) on a more consistent and rational basis than currently exists. As noted above, the designations of vessels as one-, two-, or other compartment standards of subdivision has not reflected risk levels, and the ongoing acceptability of one-compartment subdivision for vessels carrying up to 400 people is somewhat surprising. Canada should support current international efforts to put passenger vessel safety on a basis comparable to that for other modes of mass transit.

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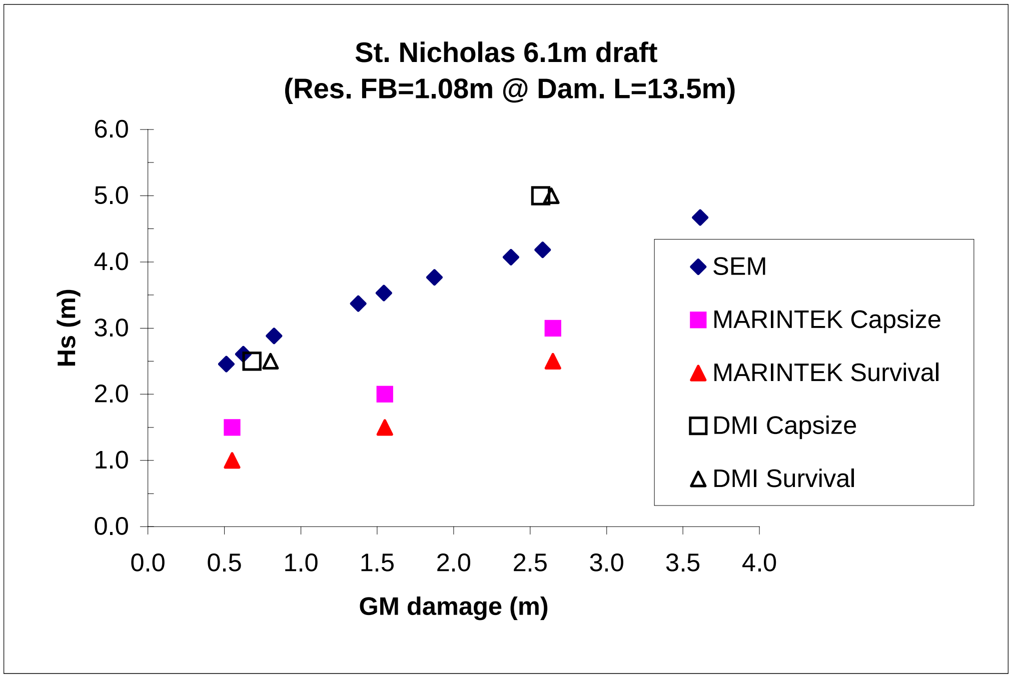
APPENDIX A

MODEL PARAMETERS

(Electronic format not available/Format électronique non disponible)

APPENDIX B

ANALYSIS RESULTS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0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
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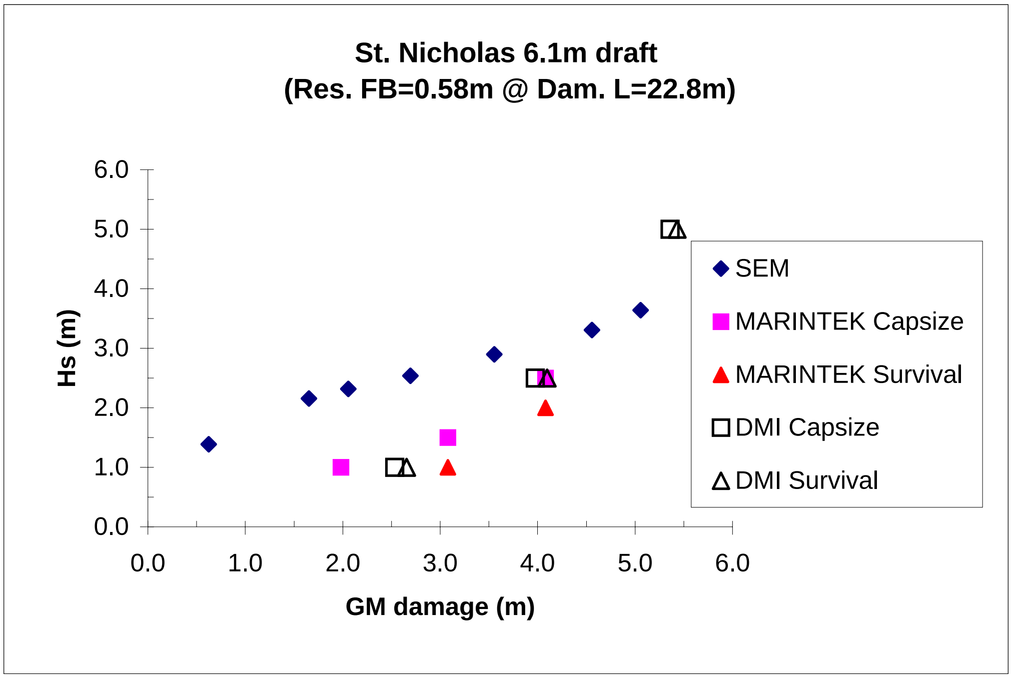
◆ SEM
■ MARINTEK Capsize
▲ MARINTEK Survival
☐ DMI Capsize
△ DMI Survival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2.0
3.0
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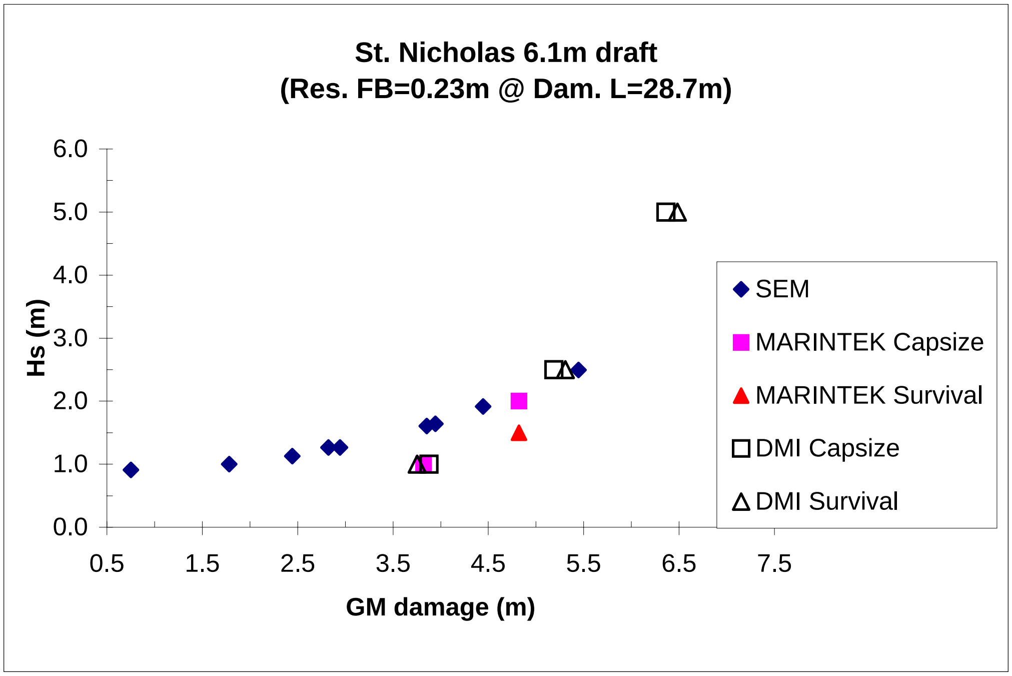
GM damage (m)
◆ SEM
■ MARINTEK Capsize
▲ MARINTEK Survival
☐ DMI Capsize
△ DMI Survival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1.0
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0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
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◆ SEM
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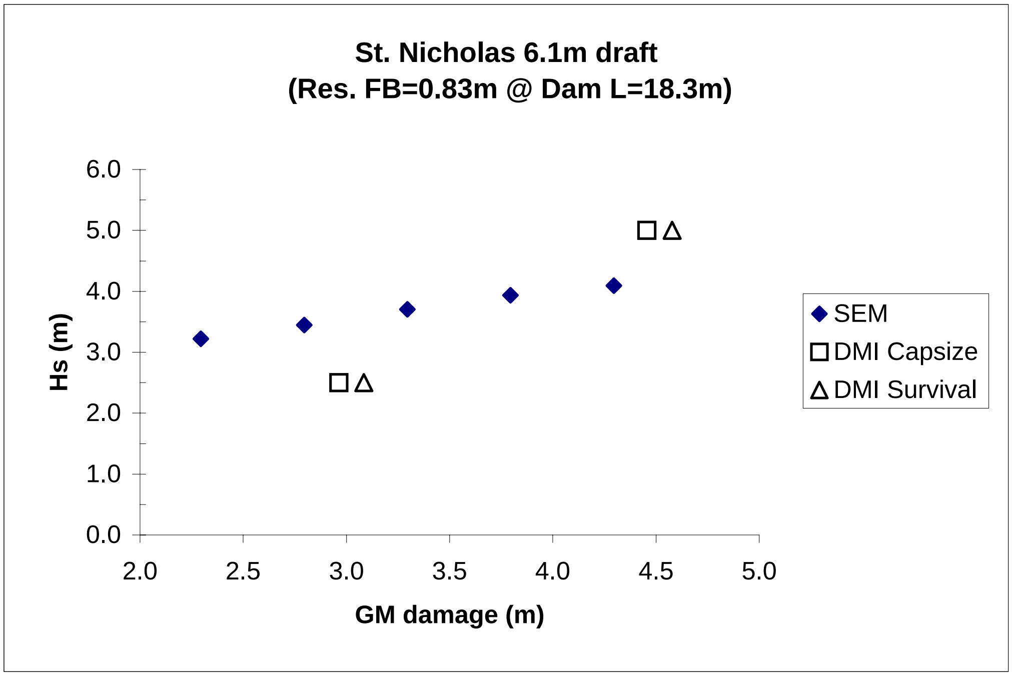
▲ MARINTEK Survival
□ DMI Capsize
△ DMI Survival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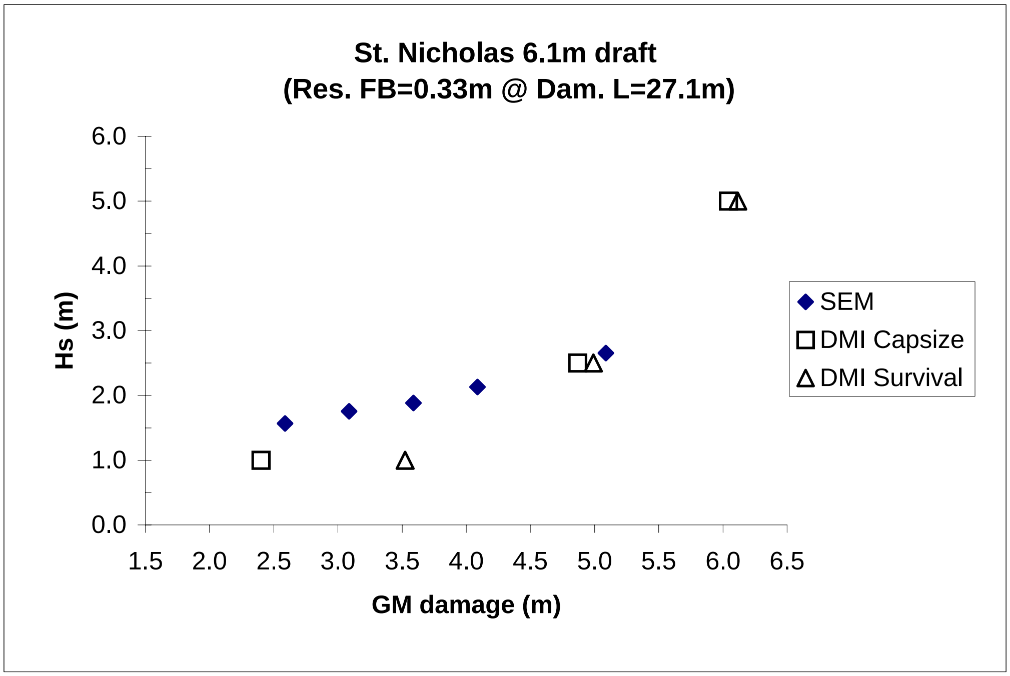
3.5
4.0
4.5
5.0
GM damage (m)
◆ SEM
□ DMI Capsize
△ DMI Survival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1.5
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3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
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◆ SEM
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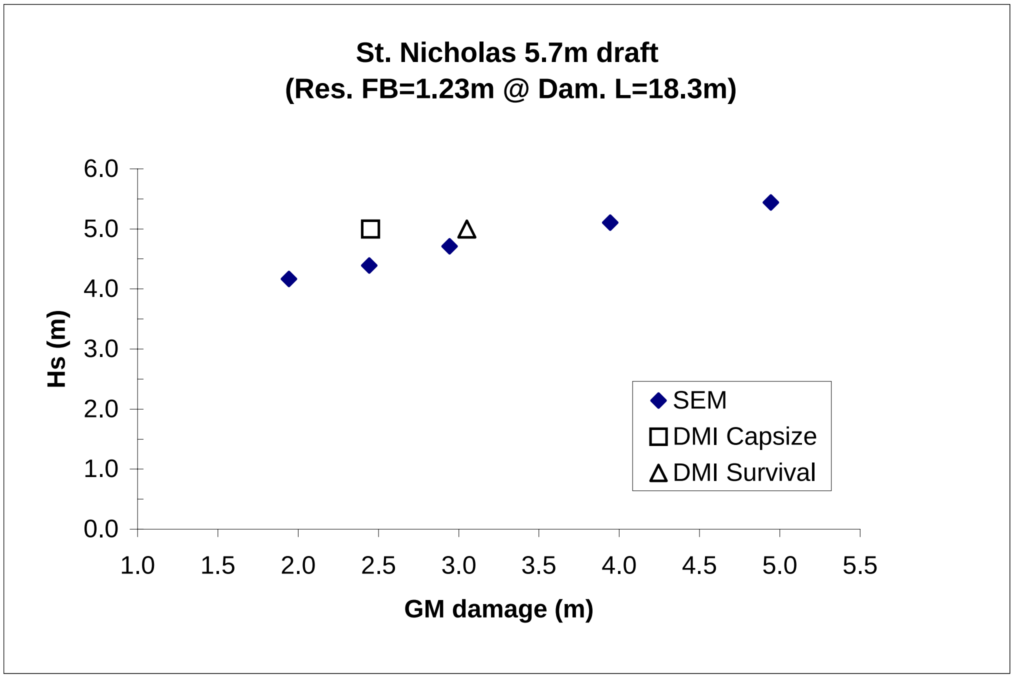
△ DMI Survival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1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
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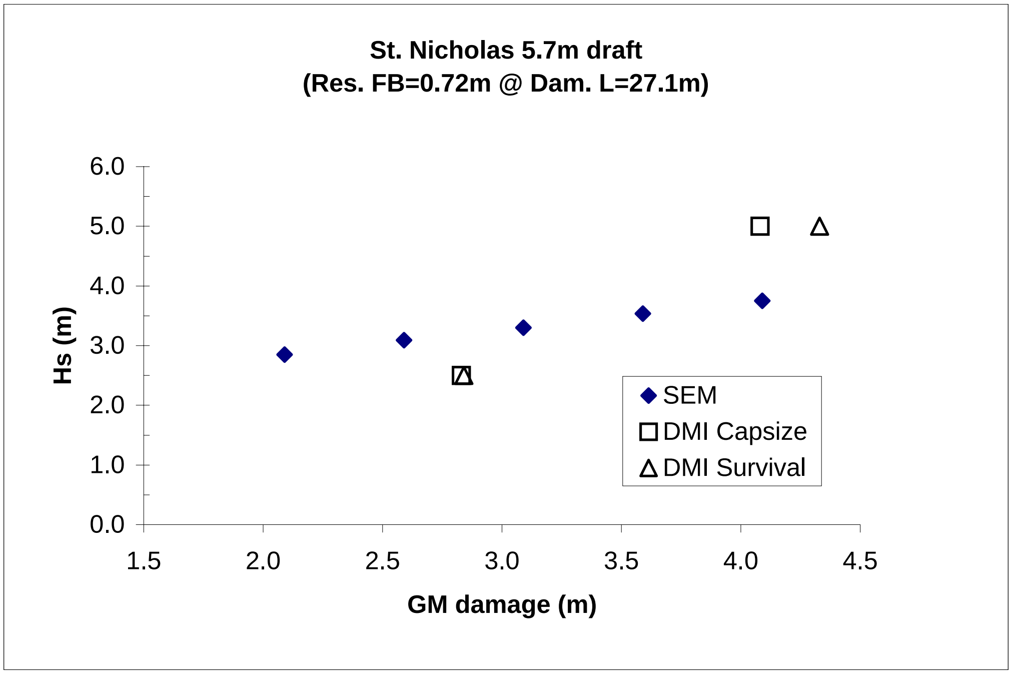
◆ SEM
☐ DMI Capsize
△ DMI Survival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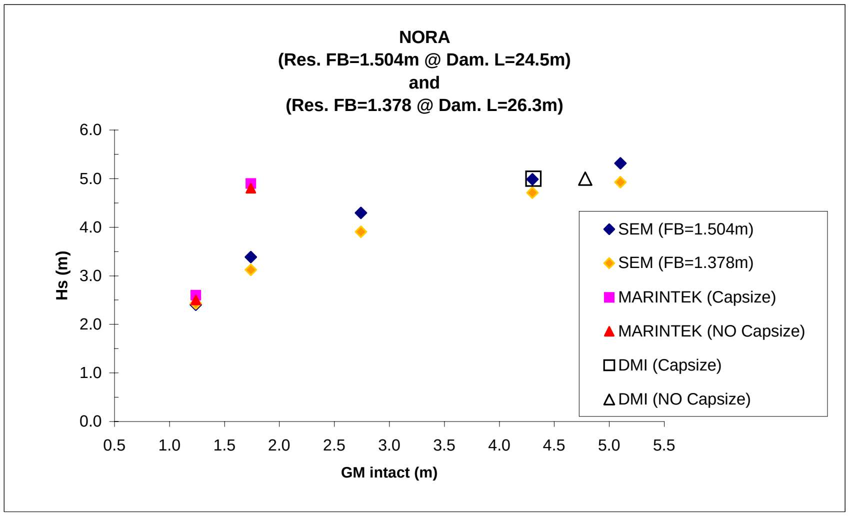
3.0
3.5
4.0
4.5
GM damage (m)
◆ SEM
☐ DMI Capsize
△ DMI Survival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and
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3.0
2.0
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
GM intact (m)
◆ SEM (FB=1.504m)
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☐ DMI (Capsize)
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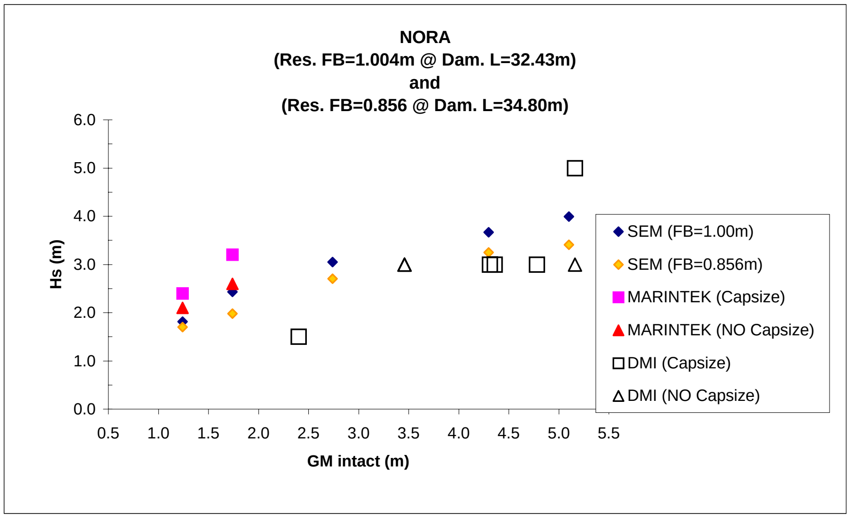
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1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
GM intact (m)
◆ SEM (FB=1.00m)
◆ SEM (FB=0.856m)
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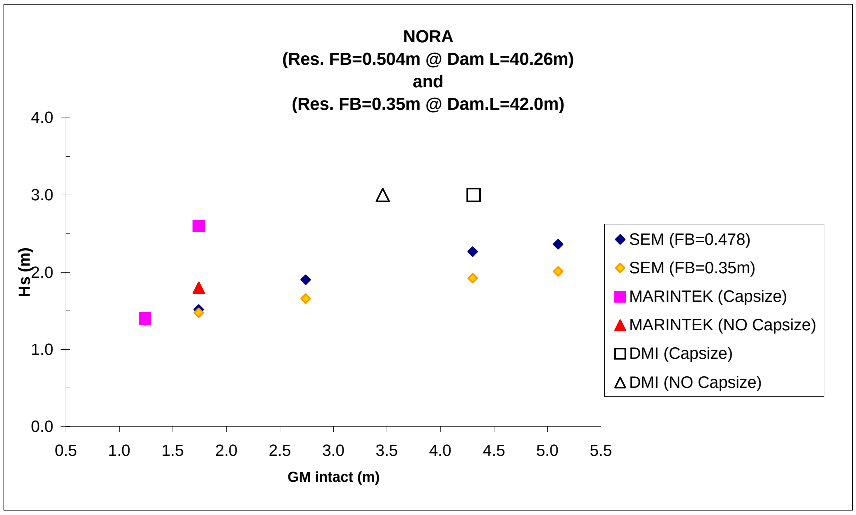
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2.0
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
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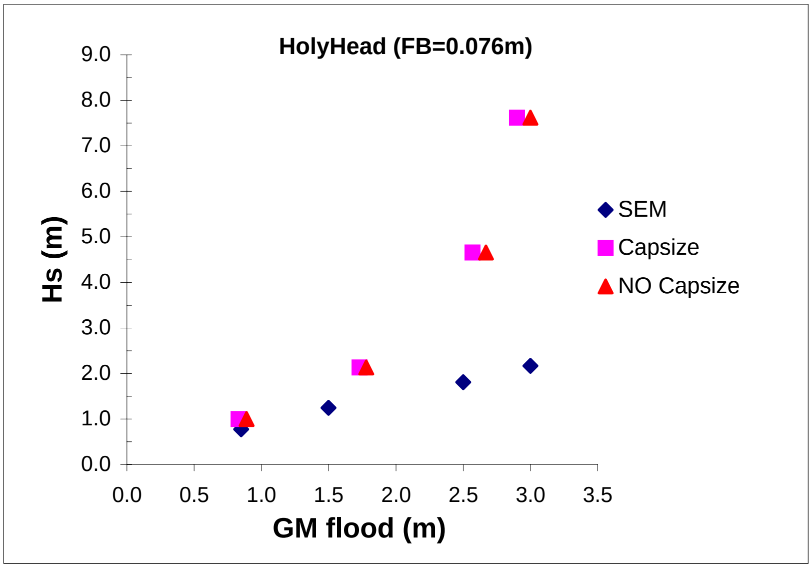
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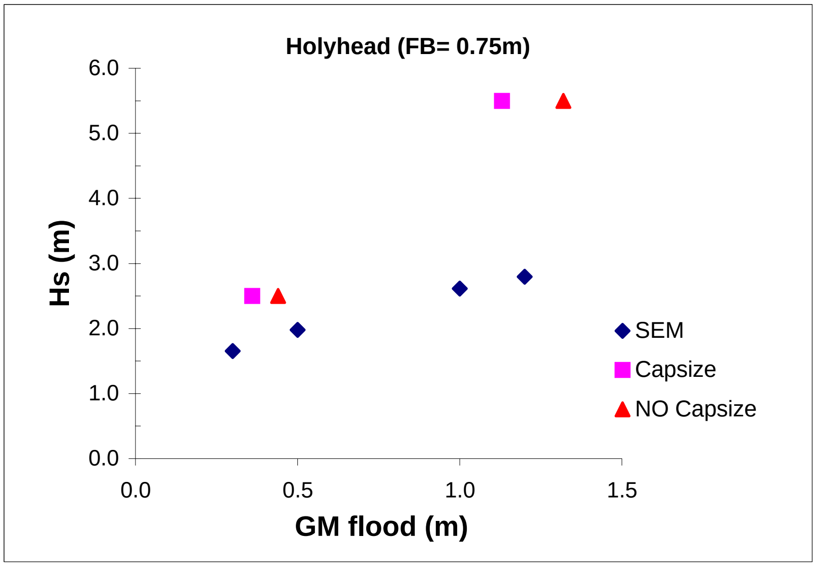
1.0
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
GM flood (m)
◆ SEM
■ Capsize
▲ NO Capsize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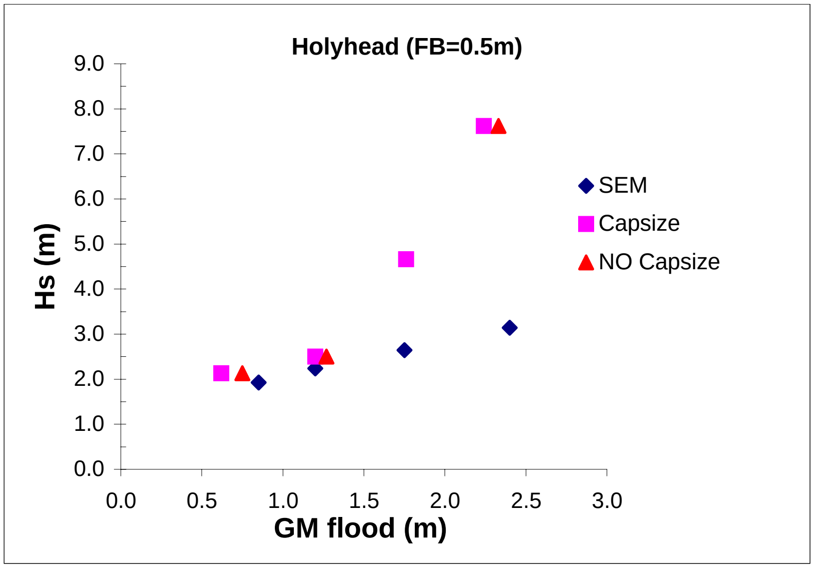
◆ SEM
■ Capsize
▲ NO Capsize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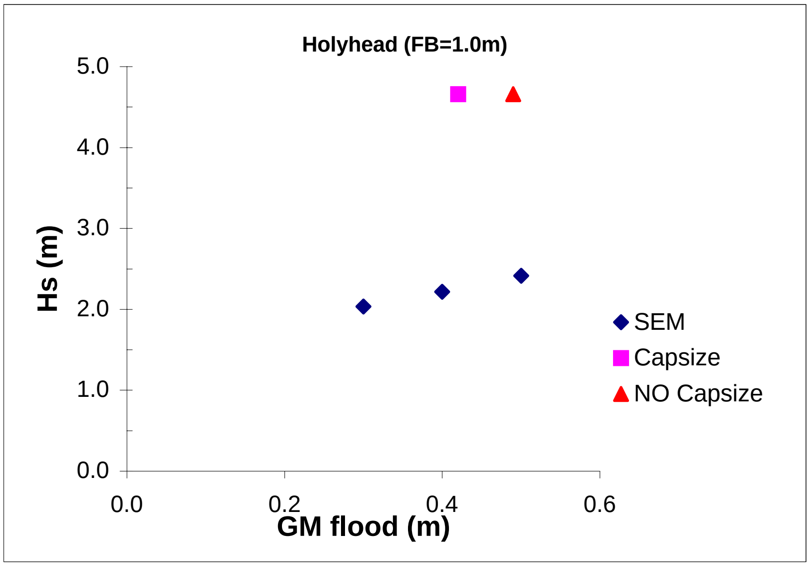
1.0
1.5
2.0
2.5
3.0
GM flood (m)
◆ SEM
■ Capsize
▲ NO Capsize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◆ SEM
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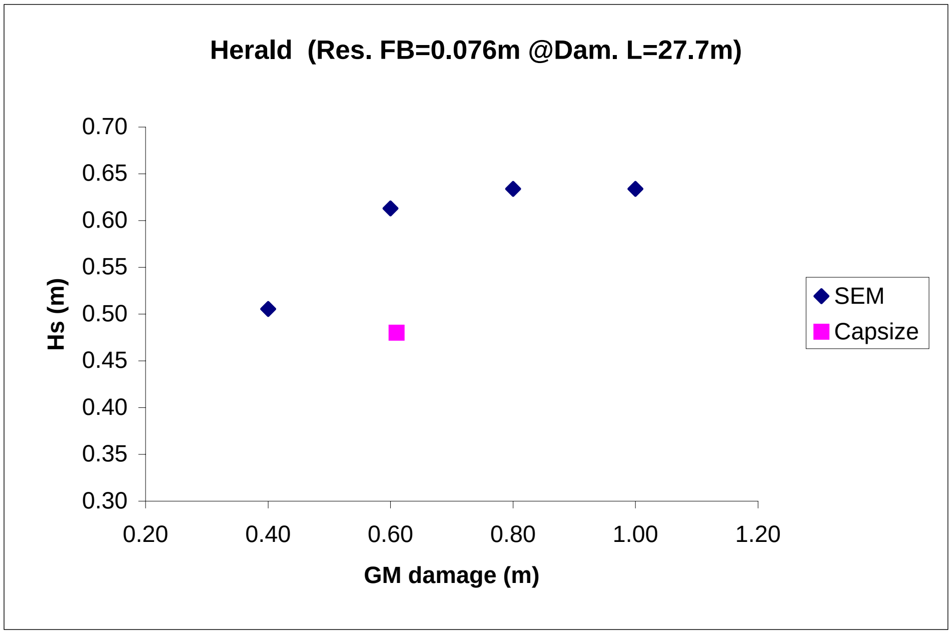
▲ NO Capsize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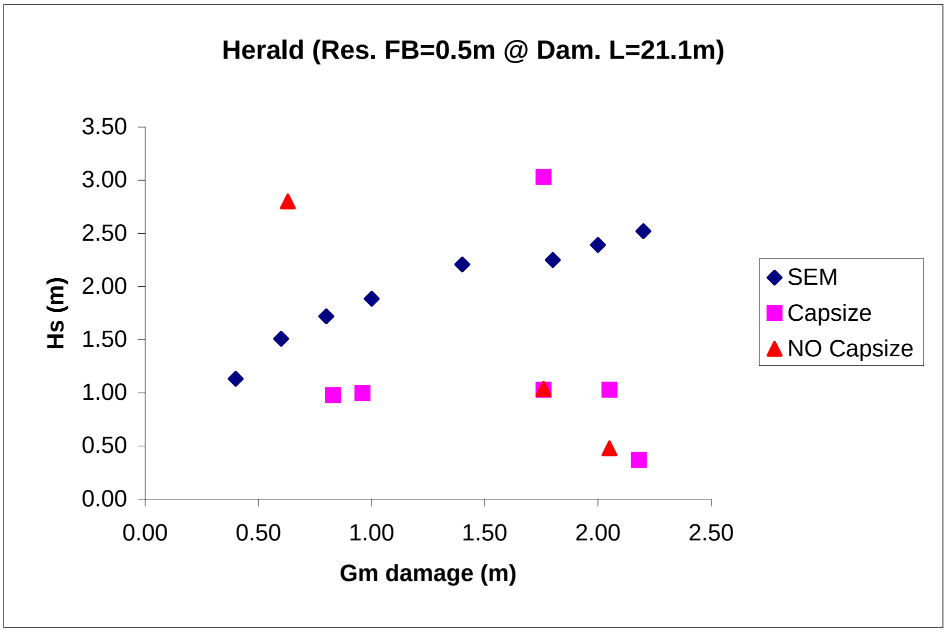
0.80
1.00
1.20
GM damage (m)
◆ SEM
■ Capsize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2.00
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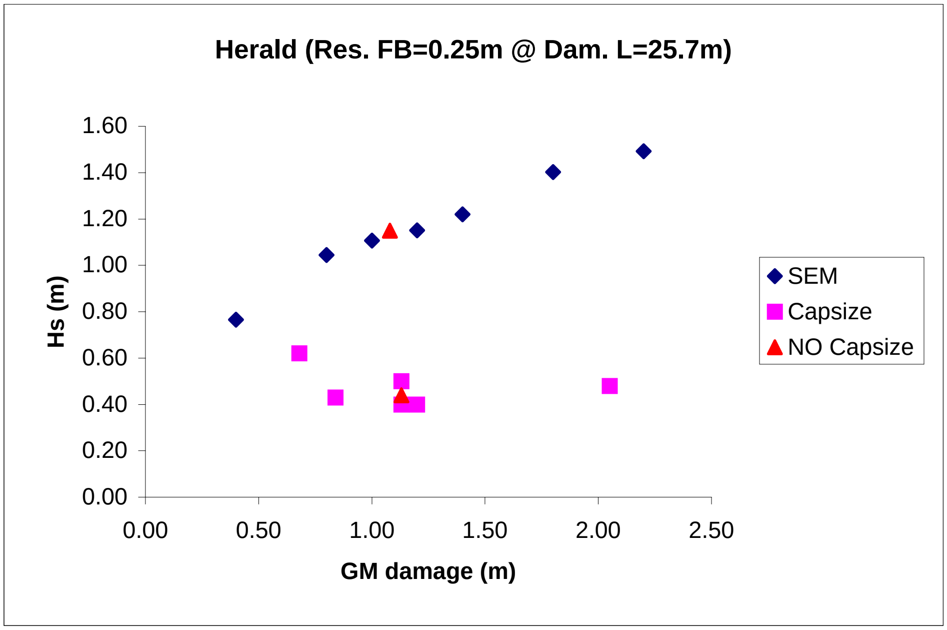
Gm damage (m)
◆ SEM
■ Capsize
▲ NO Capsize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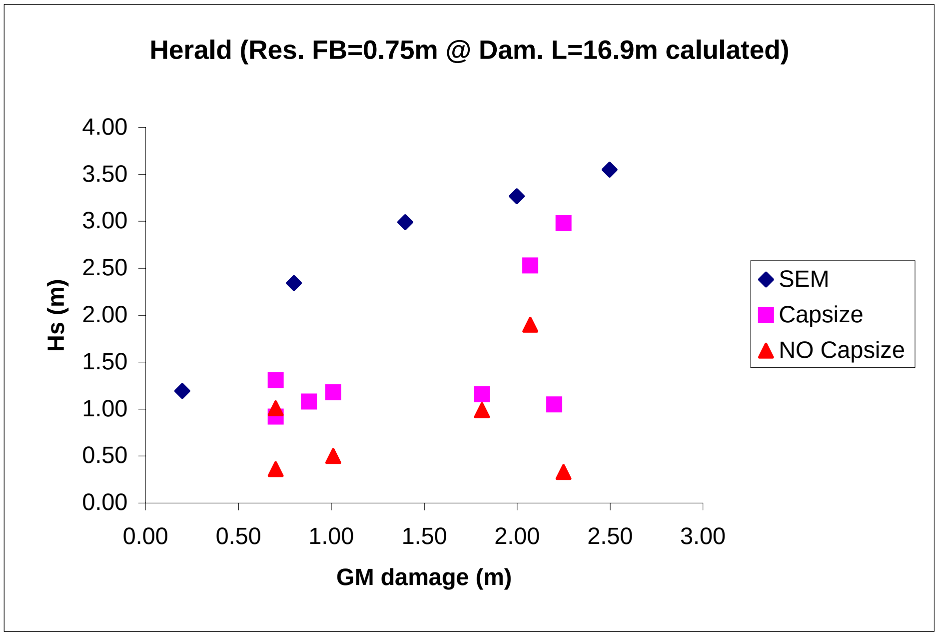
1.50
2.00
2.50
GM damage (m)
SEM
Capsize
NO Capsize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2.00
1.50
1.00
0.50
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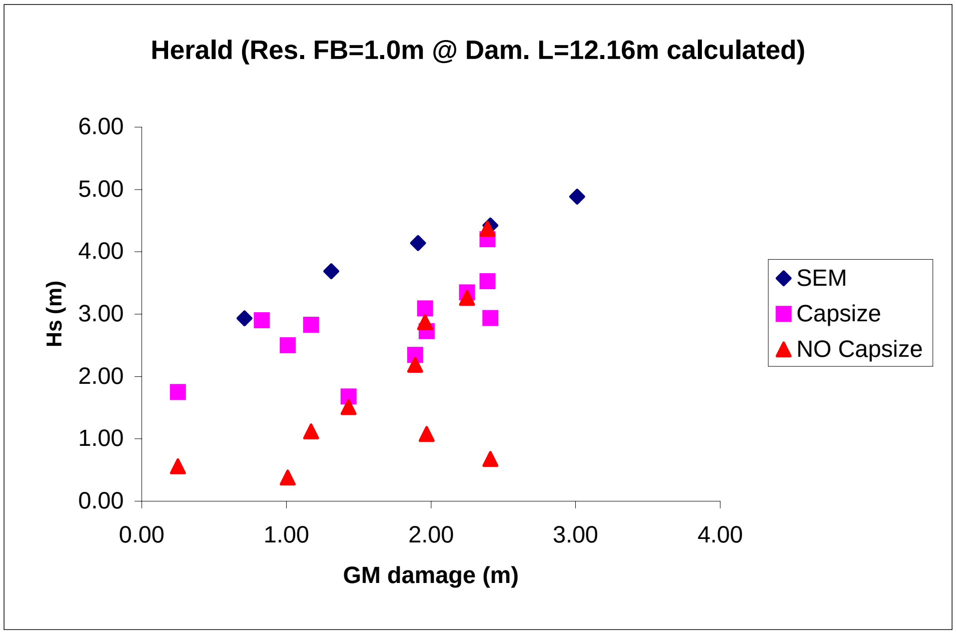
1.00
1.50
2.00
2.50
3.00
GM damage (m)
SEM
Capsize
NO Capsize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1.00
0.00
Hs (m)
0.00
1.00
2.00
3.00
4.00
GM damage (m)
◆ SEM
■ Capsize
▲ NO Capsize

APPENDIX C

DRAFT STORYBOARD

FOR

VIDEO PRODUCTION

STORYBOARD

Outline

1. Introduction

2. SOLAS 90 Criteria

3. Treatment of Water on deck

4. Static Equivalency Method

5. Application Examples

6. Risk Analysis Criteria

7. Statistical Sources

8. Route Example

9. Decision Structure

10. Conclusions

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STORYBOARD

1. Introduction

1.1 Title

Risk Analysis of Ro-Ro Ferries

Prepared for
Transport Canada Marine Safety Directorate - Ottawa
Transportation Development Centre - Montreal

Prepared by
Fleet Technology Limited - Montreal
Operational Dynamics - Montreal

1.2 Objective

Minimisation of risk through improved knowledge of
damaged Ro-Ro survivability in a seaway.

1.3 Focus

Applicable range of Ro-Ro ferry types used on
international and domestic routes.

1.4 Canadian Types

(Movie clips)

East Coast - Smallwood
West Coast - Spirit of British Columbia
Inland - Chi-cheemaun
Others - Grand Manan V

1.5 Overview

Interviews (produced footage)

Recorded discussions with experts in the area of ro-ro safety, describing the International and Canadian research programs which have been carried out and the relevance to the following.

European Gateway tragedy (newscast footage)

Capsize and loss of life after being rammed amidships by Speedlink Vanguard in the Harwich deep water channel, during moderate gale force conditions, December 1982
(Both vessels Ro-Ro type ferries)

Herald of Free Enterprise (newscast footage)

Capsize and heavy loss of life due to water entering car deck through the open bow doors whilst underway at speed. Zeebrugge entrance channel in fine weather April 1987.

Estonia (newscast footage)

Capsize and heavy loss of life due to water entering the car deck largely due to damage to the bow doors. Baltic Sea in heavy weather September 1994.

Canadian routes (operator footage)

Selected video records of ferries on main Canadian routes, Maritimes, Lakes, Pacific, showing route conditions and traffic densities.

STORYBOARD

2. Design Criteria

2.1 International Standards

Safety of Life at Sea (SOLAS) standards adopted by acclamation through membership of the International Maritime Organisation, London. These standards are kept continually under review and updated as appropriate. The latest came into force in April 1990 as SOLAS 90 applicable to new ferries on international routes. Canada has adopted the same rules for domestic ferries. Further revisions to these standards are under review in London.

2.2 SOLAS 90 Deterministic Criteria

Sets standards for residual stability in terms of the GZ diagram after damage.

Upper limit to angle of equilibrium
Minimum positive range of stability
Minimum area under the GZ curve
Minimum attained value of GZ

One and two compartment vessels are differentiated by the limits of angle of equilibrium.

Use the same GZ diagram and explanation as in Phase 1 video.

2.3 SOLAS Probabilistic Alternative

In addition to the above deterministic standards for damage stability, a probabilistic method is provided through SOLAS 74 under Resolution A.265(VIII)

This requires the design to attain a Safety Index which is not less than a Required Index based upon ship length and complement.

Due to its complexity, the probabilistic method is rarely used for new designs.

It is, however, used to priorise the phase out of older vessels whose design do not comply with the deterministic standards of SOLAS 90.

STORYBOARD

3. Treatment of Water on Deck

3.1 SOLAS

The destabilising effect of water on the Ro-Ro deck
is not addressed by the SOLAS damage stability standards.

3.2 Main Options

Nominal Allowance - Stockholm Agreement (Solas 90 + 50)

Precise Determination - Static Equivalency Method

Model Tests - Measured Behaviour

Transport Canada has explored the two latter options with encouraging results.

STORYBOARD

4. Static Equivalency Method

4.1 Background

Developed at Strathclyde University under UK Government research program initiated following the Herald of Free Enterprise tragedy in April 1987.

4.2 Description

The Static Equivalency Method (SEM) postulates that the condition of capsize can be predicted in hydrostatic terms as being the volume of water on the deck which would create an upsetting moment equal to the maximum righting moment available in the vessel's residual stability diagram.

The SEM method completes the predictive process by providing an explicit relationship between the head of the volume of water on the deck and the exterior wave height.

The representation of the forces at work is provided in **Attachment 1** (animation coupling water build-up on ship's moving outline with the corresponding upsetting and righting moment diagram to be developed.)
A synopsis of the SEM relationships is provided in **Attachment 2**

4.3 Validation

Model test results obtained during the earlier phases of the Canadian program were used to test the validity of the SEM method and principles.

Models of an 160m and 85m Ro-Ro ferry designs were used. The test programs covered a wide range of loading and damage combinations.

The tests provided clear evidence of the decay of rolling motion as the water on deck builds up and heeling increases to capsize.

The test records show two distinct stages of a typical capsize event. Initially, there is a modest build-up of water on the car deck during which the roll motion is gradually replaced by heeling until the critical angle of GZ_{max} is reached. At that point any additional quantity of water on deck results in a cliff-edge capsize

The full results of these test programs are contained in report TP 13216 published by the Transportation Development Centre, Montreal

The SEM method was used to predict the capsize wave-height corresponding to the particular capsize tests conducted with the models. The predicted and measured wave-heights were then compared and gave good agreement

Comparisons between predicted and measured wave-heights have been made from other European model test results with similar good agreements.

4.4 Conclusions

The validations performed to date have offered convincing indications that the SEM method, in its present stage of development, is able to provide a reasonable prediction of the onset of capsize of a damaged Ro-Ro ferry in a seaway. To some degree, those predictions can distinguish between different deck configurations, such as the presence or absence of casings.

STORYBOARD

5. Application Examples

5.1 Procedure

The following main steps are involved in the application of the SEM method.

1. Establish the hull definition for hydrostatic analysis
2. Determine the stability curve for the selected damage condition.
3. Determine the weight of water on deck which will heel vessel to angle of GZ_{max}
4. Determine the wedge geometry of that weight of water on the heeled side of the deck
5. Assuming ship instantaneously intact, determine height of wedge above still sea level
6. Adjust above height for parallel sinkage due to internal water head, to give ‘h’
7. Apply ‘h’ into equation $\underline{Hs = (h/C)^{1/X}}$ where C and X are SEM established coefficients.

Hs is the significant wave-height with a 50% probability of resulting in capsize.

5.2 Example

The Static Equivalency Method has been applied to a selected Ro-Ro ferry design which is in full compliance with the damage stability of SOLAS 90, both results are given below

SOLAS 90 results

Parameter	Required	Actual
Range	15 deg	24 deg
GZarea	0.015 mr	0.179 mr
GZmax	0.19 m	0.68 m

SEM results

Parameter	Determined
Displacement	6,880 t
Angle for GZmax	12 deg
Deck water head (h)	0.5 m
Critical Wave Ht (Hs)	3.9 m

On the route operated by the above ferry, the seastate did not reach the above figure of critical wave-height at any time of the year. This suggests that the SOLAS criteria are excessive for the service involved.

5.3 Other Applications

The above example concerns a ferry design which complies with SOLAS 90. There are other designs which do not comply with those standards and it is in those cases where the SEM method has particular prescriptive value. In that respect, the SEM results indicate the limiting seastate for damage survivability on the route on which the ferry operates. This in turn provides a rational basis for decision making with respect to risk considerations in safe operational management . Failure to meet SOLAS 90 standards should not disqualify a vessel from a particular route if it can be demonstrated that operations meeting the imperatives of the route conditions can be successfully performed. The SEM method can make a positive contribution to that endeavour.

STORYBOARD

6. Risk Analysis Criteria

6.1 Overview

Risk = Probability of occurrence of an event x severity of its consequences.

In the context of ferry safety, overall risk can be built up from a variety of components, such as the following,

- Probability of occurrence of a collision (traffic density)
- Severity of a collision (structural damage)
- Severity of the outcome. (loss of life)

Inherent in the consideration of risk is the application of probability, which makes it possible to differentiate between the specific operational conditions prevailing on the respective ferry routes and related considerations.

6.2 Approach

Internationally, safety criteria are moving away from deterministic standards and into the realm of probabilities. In terms of ship design, mention has already been made of the IMO probabilistic basis of damage stability evaluation - Resolution A.265. This has recently been modified to provide a safety ratio that compares the ship's actual index of survivability with its best notional index based on optimum sustainable damage. This ratio, referred to as A/Amax, is used by IMO to priorise the upgrading of non-compliant ships. This process forms the backbone around which the Canadian Risk Analysis Method has been built.

6.3 Process

The following main steps in the Risk Analysis process apply to the Canadian domestic ferry routes where the vessel is non-compliant with the prevailing deterministic damaged stability standards.

1. Determine the vessel's safety ratio (A/Amax) in accordance with the method set out in IMO MSC/Circ 574, June 1991.
2. Compare the above result with the compliance schedule set out in Chapter II Regulation 8-2 of the SOLAS construction rules for Ro-Ro passenger ships. If the vessel cannot comply with that schedule proceed to step 3 below.
3. Recalculate the A/Amax ratio in which any partial-compliant compartmental condition is subjected to an SEM analysis for the route sea state regime to restore its survival index to unity and thereby increase the overall A value.
4. Re-enter the SOLAS schedule for appropriate compliance and acceptance.
5. Adjust the result to take account of the collision probability associated with the route.

STORYBOARD

7. Statistical Sources

7.1 Scope

These are assumed to cover at least wave climate, traffic density and loading pattern applicable to the route operations all on a calendar basis. [Other statistics may be required as determined by theprocess]

7.2 Wave Climate

Main source will be the various wave atlases available for the sea areas of the world. In the Canadian scene a set of four wave climate atlases is available from the federal government DFO/TC covering the East Coast, Gulf of St. Lawrence, Great Lakes and the West Coast

7.3 Traffic Density

The principal sources of these statistics are the

- local marine traffic control organisations

- ferry route operators

7.4 Loading Patterns

The ferry operators are the principal sources of these statistics,

- route loading records by trip and season

- actual embarcation weights during loading.

STORYBOARD

8. Route Example.

8.1 General

The steps involved in using the SEM method to arrive at the critical wave height for a ferry design have already been outlined. The next step is now taken to apply that information to a fictitious route where the ferry does not fully meet all the route conditions. Two important conditions are the effect of loading and the effect of sea state.

8.2 Effect of Loading

In this case there are two loading considerations, namely,

-probability of exceedance of the critical wave height
- probability of exceedance of each wave height.

[See **Attachment 3** for a typical diagram based on
Fig 6.8 in TP 13394E Phase IV report]

This shows that the survivable wave height increases rapidly in part load cases.
At full load , the critical wave height is 0.4m (over 0.8 probability of exceedance)
At half load, the critical wave height increases to 3.1m (less than 0.05 exceedance)

8.3 Effect of Wave Height

This presents the consideration from a different operational perspective

[see **Attachment 3** for a typical diagram based on Fig 7.1 in TP 13394E Phase IV report]

At full load, the critical wave height will be encountered in every month of the year. At half load, there is less than a 0.1 probability of meeting the critical wave height in all months except November and December.

8.4 Safety Index

The SEM method provides the means of arriving at a Safety Index for a ship/route.

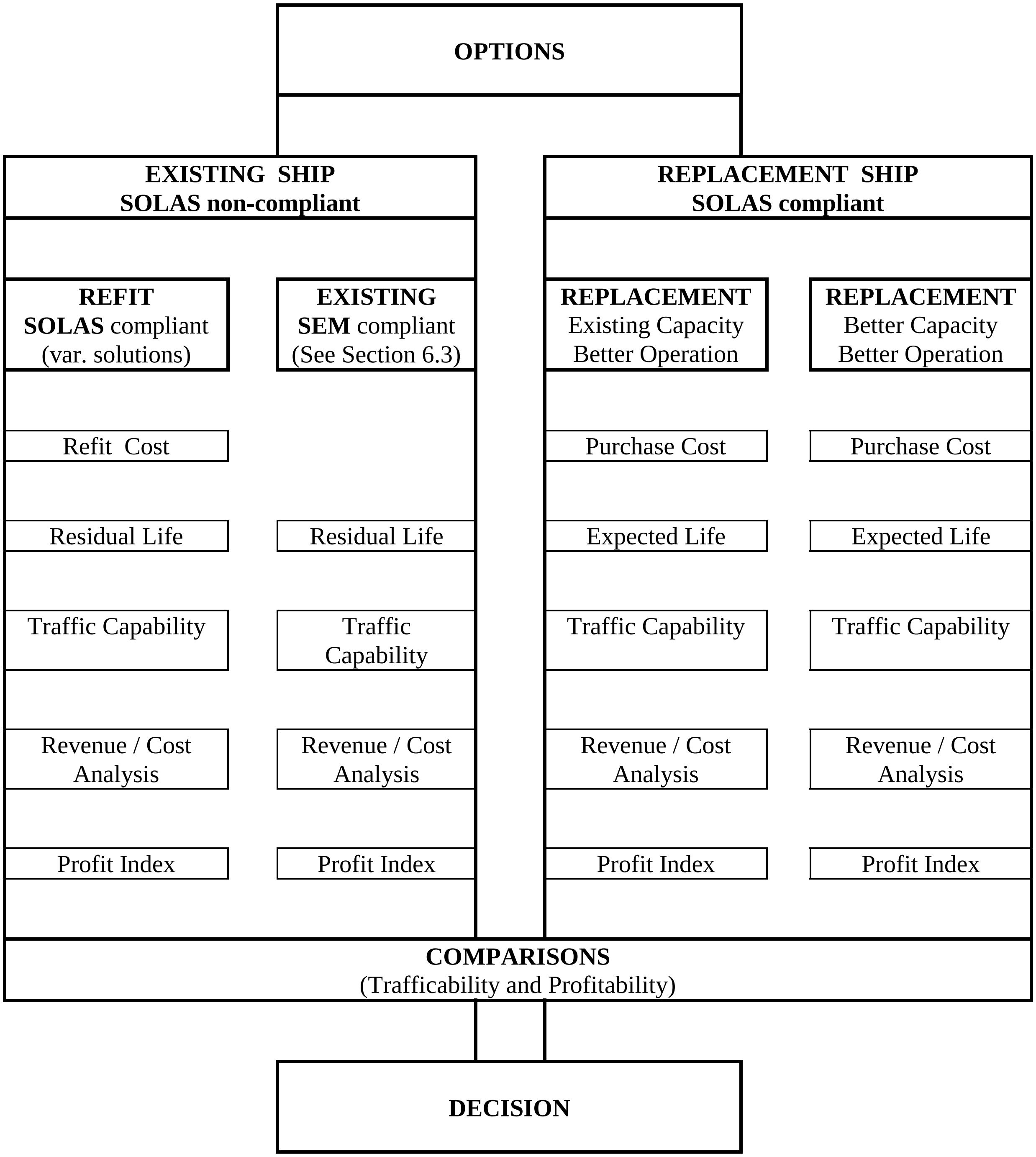
Safety Index, Si = 1 - (ph . pc . pl)
where ph = probability of exceeding critical wave height at a given loading condition.
pc = probability of capsize (0.5)
pl = probability of that loading condition.

Safety Index is I.0 for a ferry that does not exceed the critical wave height on the route.

STORYBOARD

9. Decision Structure

Logic Diagram illustrating the techno-economic decision process to be followed in the event that a particular design only partially meets the route safety demands with respect to damaged survivability in a seaway.



STORYBOARD

10. Conclusions

10.1 Recap

Synopsis of the main points covered in the video.

10.2 Highlight

Emphasise the main strengths of the SEM methodology

10.3 Content

Content variation for different audiences is provided in **Attachment 4**

10.3 Acknowledgements

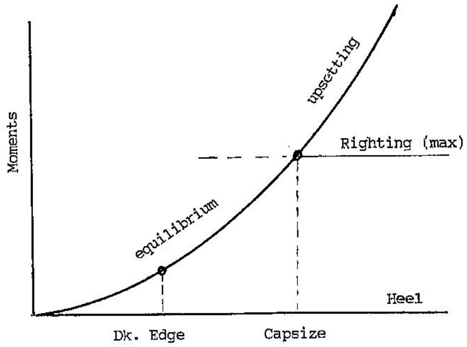
Originators
Sponsors
Producers
Participants
Performers.

Attachment 1

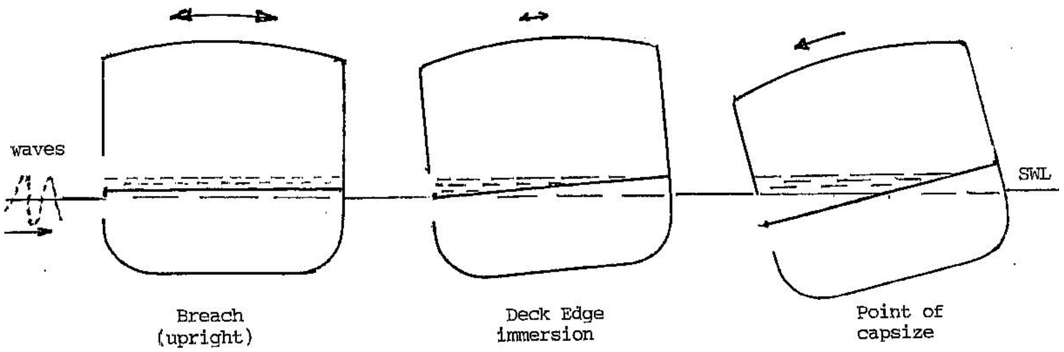
Add to Section 4.2 (where indicated)

Destabilising effect of deck flooding

Sea water flooding onto the car deck due to waves entering through a breach in the hull will cause the vessel to heel. Equilibrium heel occurs where the upsetting moment due to the water on deck is balanced by the vessel's righting moment. The righting moment is dictated by the vessel's damaged stability diagram where GZ reaches a maximum at a defined angle of heel. Thereafter, upsetting exceeds righting and a capsize results. These interrelationships are shown diagrammatically below.



The angle of deck-edge immersion is also shown on the above diagram because it has a special significance in connection with the calculation of the upsetting moment. Up to that angle, the upsetting moment is dictated by the weight of the total wedge of water on the car deck. Thereafter, in connection with the Static Equivalency Method, it is only the weight of the head of deck water above the still water level (SWL) that causes upsetting. These progressions are shown in the following animation where rolling motion decays as the heeling angle increases - no rolling at the point of capsize.



Attachment 2

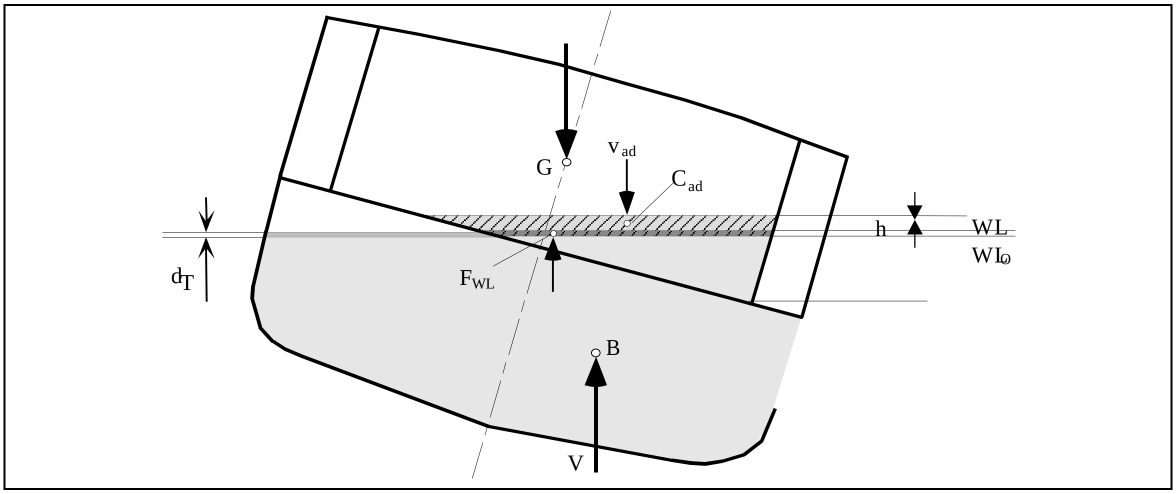
Add to Section 4.2 (where indicated)

The basic stability equation to be satisfied is as follows:

$$v_{ad}.l_{ad} = V.GZ$$

where

v_{ad} = volume of head of water on deck above the still waterline WL_o
l_{ad} = heeling lever due to head of water on deck , equal to the horizontal distance between the centre of flotation F_{wl} of the waterplane WL_o (undamaged above the car deck) and the centre of gravity C_{ad} of the head of water on deck
V = volume displacement of the ship
GZ = righting arm calculated by the constant displacement method, allowing for free flooding of the vehicle deck



SEM Calculation Principles

Solution of the above equation leads to calculation of h', the head of water on deck above the static waterline WL_o.. This, in turn, allows h to be calculated by allowing for the effect *d*T of sinkage due to the added head of water v_{ad} on deck (i.e., h = h' - dT).

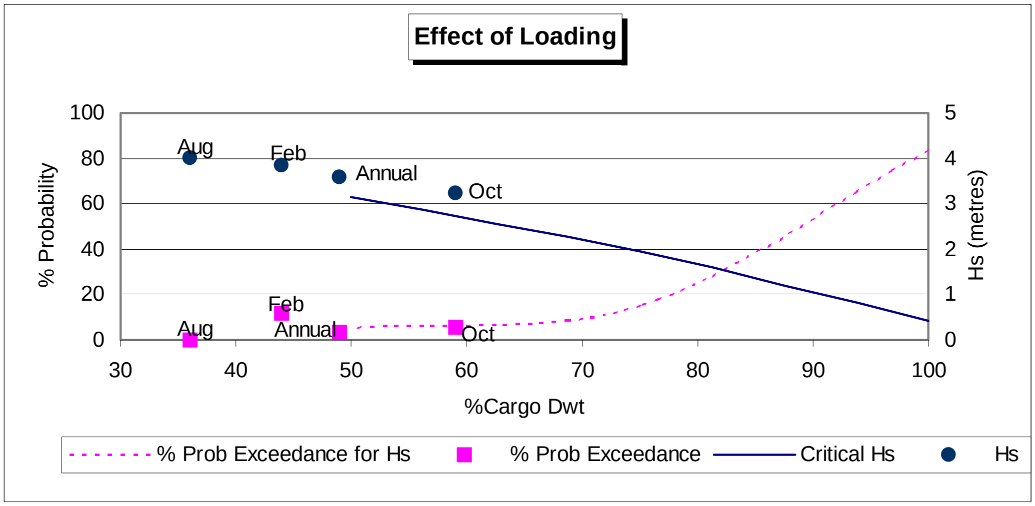
In order to provide a prediction of the capsize condition, it is necessary to relate the elevation of the internal water surface above mean sea level in terms of the sea state that will generate this. The SEM provides a connecting equation of the following form:

$$h = C.H_s^x$$

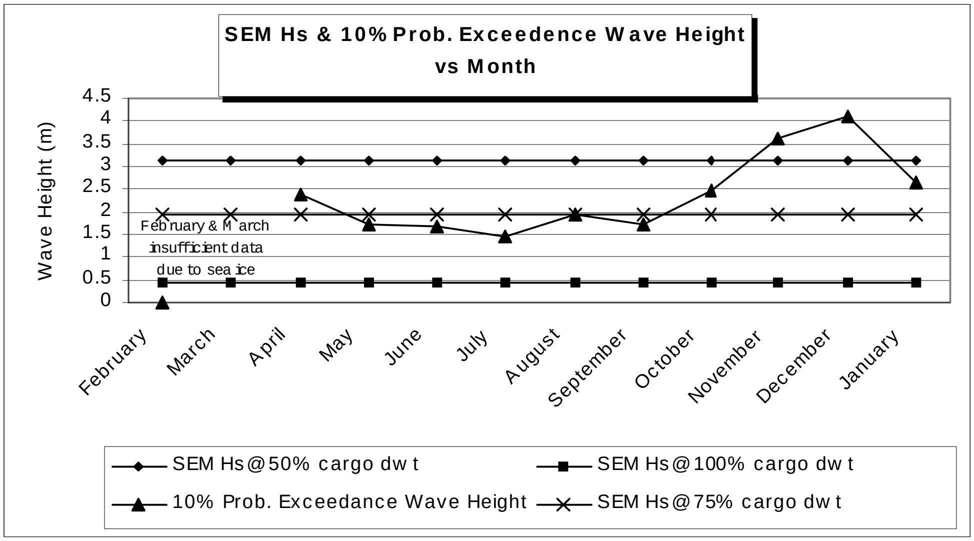
where C is a coefficient (determined experimentally at 0.085) and H_s is the significant wave height which is raised by the exponent x (determined experimentally at 1.3. The critical significant wave height at which h equals the value required for capsize is taken as representing a 50% capsize probability, when the results are interpreted probabilistically.

Attachment 3

Add to Section 8.2 (where indicated)



Add to Section 8.3 (where indicated)



Attachment 4

Ro-Ro 5 Video

Selective Content

1st level audience - Domestic; TC regulation, CFOA operators.
2nd level audience - International: IMO, IACS, Research Insts, etc
3rd level audience - Academic: Universities, Colleges, Marine Insts.

Storyboard Section	**Audiences**		
or sub-section	**1st level**	**2nd level**	**3rd level**
1. Introduction (1.1 - 1.5)	Yes	Yes	Yes
2. Design Criteria (2.1 - 2.3)	Yes	Yes	Yes
3. Water on Deck (3.1 - 3.2)	Yes	Yes	Yes
4. Static Equivalency (4.1 - 4.3)	Yes	Yes	Yes
5. Applications (5.1 - 5.3)	Yes	Yes	Yes
6. Risk Analysis Criteria (6.1 - 6.3)	Yes	No	No
7. Statistical Sources (7.1 - 7.5)	Yes	Yes	No
8. Route Example (8.1 - 8.4)	Yes	Yes	No
9. Decision Structure (9.1 - ?)	Yes	No	No
10. Conclusions	Yes	Yes	Yes