TP 13216E

Flooding Protection of RO-RO Ferries
Phase III

Prepared for
Transportation Development Centre
Safety and Security
Transport Canada

March 1998

Prepared by:

Andrew Kendrick, P. Eng.
Fleet Technology Limited
800 René Lévesque Blvd West, Suite 450
Montréal, Québec
H3B 1X9

In Association with:

Operational Dynamics
PO Box 1
Hudson Heights, QC
J0P 1J0

and

Science and Technology Corporation
9650 Santiago Road, Suite 2
Columbia, MD
USA 21045

This report reflects the views of Fleet Technology Limited and not necessarily those of the Transportation Development Centre.

PROJECT TEAM

FLEET TECHNOLOGY LIMITED
Andrew Kendrick, Manager
Terry Halliday, Project Engineer
Cody Lyster, Project Engineer

SCIENCE & TECHNOLOGY LIMITED
Maciej Pawlowski

OPERATIONAL DYNAMICS
Tom Peirce

Un sommaire français se trouve avant la table des matières.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 13216E	2. Project No. 9315	3. Recipient's Catalogue No.
4. Title and Subtitle Flooding Protection of Ro-Ro Ferries, Phase III		5. Publication Date March 1998
		6. Performing Organization Document No.
7. Author(s) A. Kendrick, M. Pawlowski, and T.H. Peirce		8. Transport Canada File No. ZCD1460-328-2
9. Performing Organization Name and Address Fleet Technology Limited 311 Legget Drive Kanata, Ontario K2K 1Z8		10. PWGSC File No. XSD92-00242-(651)
		11. PWGSC or Transport Canada Contract No. T8200-2-2557/01-XSD
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 800 René Lévesque Blvd. West 6th Floor Montreal, Quebec H3B 1X9		13. Type of Publication and Period Covered Final
		14. Project Officer A. Taschereau

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Co-sponsored by TC Marine Safety Directorate

16. Abstract

This report consolidates the work undertaken in the three phases of the project. Phases I and II included extensive model testing and analysis. Phase III utilized this work in testing and extending the proposed Static Equivalency Method (SEM) for predicting survivability in the flooded condition. It was demonstrated that the SEM can predict capsize wave conditions over a wide range of ship conditions, and that where its predictions are least accurate, they are conservative. Approaches were identified for further development of the model to cover freeing port effects, and recommendations were made for its use as an alternative or supplementary standard to the current SOLAS criteria.

17. Key Words	18. Distribution Statement
Ferries, damage, stability, model testing, freeing ports, SOLAS, safety, capsize	Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication)	20. Security Classification (of this page)	21. Declassification (date)	22. No. of Pages	23. Price
Unclassified	Unclassified	—	xvi, 40, app.	—

CDT/TDC 79-005
Rev. 96

Canadä

Transports Canada | Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada TP 13216E	2. N° de l'étude 9315	3. N° de catalogue du destinataire
4. Titre et sous-titre Flooding Protection of Ro-Ro Ferries, Phase III		5. Date de la publication Mars 1998 6. N° de document de l'organisme exécutant
7. Auteur(s) A. Kendrick, M. Pawlowski et T.H. Peirce		8. N° de dossier - Transports Canada ZCD1460-328-2
9. Nom et adresse de l'organisme exécutant Fleet Technology Limited 311 Legget Drive Kanata, Ontario K2K 1Z8		10. N° de dossier - TPSGC XSD92-00242-(651) 11. N° de contrat - TPSGC ou Transports Canada T8200-2-2557/01-XSD
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest 6e étage Montréal (Québec) H3B 1X9		13. Genre de publication et période visée Final 14. Agent de projet A. Taschereau

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Projet coparrainé par la Direction générale de la sécurité maritime, Transports Canada

16. Résumé

Ce rapport fait la synthèse des travaux réalisés au cours des trois phases du projet. Les phases I et II comportaient des essais sur maquettes et des analyses. La phase III a consisté à utiliser les données colligées au cours des deux premières phases pour valider et perfectionner la «méthode du système équivalent quasi-statique» (méthode SEM, de l'anglais *Static Equivalency Method*) proposée pour déterminer la survivabilité après envahissement. Il a été démontré que la SEM peut prédire l'état de mer menant au chavirement d'un navire, pour une large gamme de conditions de chargement, et que dans les cas où ses prédictions sont le moins précises, elle offre une bonne marge de sécurité. Des améliorations à la méthode ont été proposées, pour qu'elle prenne en compte l'effet des sabords de décharge. Des recommandations ont été également été formulées en vue de son utilisation en remplacement ou en complément des critères SOLAS en vigueur.

17. Mots clés Traversiers, avarie, stabilité, essais sur maquette, sabords de décharge, SOLAS, sécurité, chavirement	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	xvi, 40, ann.	—

ACKNOWLEDGEMENTS

The Project Team wishes to acknowledge the major contributions made to this report by Dr. Maciej Pawlowski of Gdansk University and Dr. David Molyneux of the Institute for Marine Dynamics. We would also like to thank André Taschereau and Jacques Laframboise of the Transportation Development Centre (TDC), and Marius Koniecki of Transport Canada, for their suggestions and comments throughout the project.

EXECUTIVE SUMMARY

In parallel with and in support of international efforts to develop new safety standards in the aftermath of several maritime disasters, Transport Canada has sponsored a multi-year, multi-phase program to investigate flooding protection of Ro-Ro ferries. This report summarizes the work of the program as a whole, and provides new insights into the damaged capsize phenomenon for such ships and ways of predicting its occurrence.

Phases I and II of the research involved major experimental programs at the Institute of Marine Dynamics (IMD) in St. John's, data analysis by the contractor, Polar Design Associates, and efforts at numerical modelling. A simplified model of a large West Coast ferry was used in the test series for Phase I, and a more ship-shaped version of a smaller Eastern Canadian ferry in Phase II. The test series included a range of ship configurations with different vessel centres of gravity and damaged freeboards, as well as with and without casings, bilge keels, and freeing ports. The wave heights needed to cause capsize were determined. All tests incorporated the damage extent specified by SOLAS 90, and all of the model conditions complied with one or more of the SOLAS 90 damaged stability criteria.

Test program findings indicated that the removal of the centre casing increased survivability under certain conditions, and that the use of flapped freeing ports was increasingly beneficial as their total area increased. Most importantly, however, it was found that the survivability of the models did not correlate very well with any of the SOLAS criteria, none of which is linked directly to the capsize phenomenon. The most important was determined to be the accumulation of water on the vehicle deck. Once a critical volume builds up, the ship will capsize relatively rapidly. Partial recognition of this effect is included in the SOLAS “90+50” criteria, which have now been adopted by certain countries as a more stringent standard; the “+50” refers to the need to meet the basic criteria with an assumed accumulation of 50 cm of water on the deck. The Canadian tests and other work have noted that the 50 cm level is not a rational standard for all vessels, and Canada continues to be part of the majority of countries that have retained the original SOLAS standards.

Phases I and II of the project were not able to identify an approach that could be used to predict survivability across a range of conditions, so Phase III was undertaken with this objective. Rather than attempting to develop a new approach, the initial portion of the work consisted of a review of other proposed methods to identify any that seemed particularly promising, and to test and validate them against the Canadian test data. It was soon decided that the Static Equivalency Method (SEM), developed by researchers at Strathclyde University, offered the greatest potential.

The SEM assumes that capsize in the damaged condition is a quasi-static phenomenon (as noted in the Phase I and II tests) and that the critical volume of water on deck can be calculated simply from the damaged hydrostatic properties of the hull. The accumulation of water on deck, meanwhile, can be predicted from the significant wave height, using a simple

relationship. Therefore, for a given service, with a known wave climate, it can be predicted whether a vessel with SOLAS (or other) damage extent will survive such damage all or some of the time. The SEM was initially developed and tested with the aid of extensive numerical simulations of capsize, with some additional physical model testing for validation.

In the Phase III work, the SEM predictions were checked against the results from Phases I and II, paying particular attention to certain features that were considered potential weak points in the method. It was necessary to re-analyse a subset of the original data to generate the "measured" values against which some of the predictions could be compared. This work was undertaken by IMD; one of the Strathclyde researchers was a member of the project team and provided valuable guidance.

The SEM's ability to predict capsize wave height proved extremely good over a wide range of ship configurations. The known tendency of the method to under-predict survivability for very stable ships was confirmed, and it was also determined that the presence or absence of a casing can make a significant difference in these cases: conditions without casing survive better. A few "anomalous" results were found in conditions of unlikely practical significance, and in all such cases the SEM again gave conservative predictions.

An effort was made to extend the basic SEM to predict freeing port effects. So far, this provides the expected trends but not the accuracy needed for a usable tool. It was recommended that more work be done to provide a better physical understanding of the mechanisms of water accumulation inside the ship. However, it was concluded that the SEM is sufficiently mature to be used to assess the survivability of existing vessels and new designs in a more rational manner than either the basic SOLAS 90 or the extended SOLAS 90+50 criteria.

Since the method is inherently probabilistic, its use in either a pseudo-deterministic or probabilistic manner will require further thought and calibration. The report suggests both short-term and long-term means of achieving this.

SOMMAIRE

En marge des efforts déployés à l'échelle mondiale visant l'élaboration de nouvelles normes de sécurité, dont les catastrophes maritimes récentes ne font qu'accentuer l'urgence, Transports Canada a parrainé un programme de recherche de longue haleine sur la tenue au chavirement de traversiers rouliers après envahissement par l'eau. Le présent rapport fait le point sur l'ensemble du programme et jette un regard neuf sur le phénomène du chavirement de ces types de navires après avarie et sur les façons de prédire un tel événement.

Les phases I et II ont comporté de vastes programmes d'essais à l'Institut de dynamique marine (IDM) de St. John's, l'étude des résultats de ces essais par le contractant, Polar Design Associates, ainsi que l'amorce de travaux de modélisation numérique. Une maquette simplifiée d'un gros traversier de la côte ouest a servi aux essais de la phase I, tandis qu'une version plus carénée d'un petit traversier utilisé dans les Maritimes a été retenue pour la phase II. Les essais ont porté sur diverses configurations de navires, qui variaient par la position de leur centre de gravité et la hauteur de leur franc-bord résiduel. De plus, ces navires étaient avec ou sans encaissement, quilles de roulis et sabords de décharge. L'essai consistait à déterminer la hauteur de houle menant au chavirement. Tous les essais restituaient les dimensions d'avarie prises en compte par la norme SOLAS 90 et tous les paramètres de la maquette étaient conformes à au moins un des critères de stabilité après avarie énoncés dans cette même norme.

Les essais ont permis de conclure que l'absence d'encaissement central améliorait la tenue au chavirement de certaines configurations, et que l'utilisation des sabords de décharge munis de panneaux articulés était d'autant plus profitable que l'aire totale de ces ouvertures était grande. Mais, plus intéressant encore, les essais ont révélé une faible corrélation entre la survivabilité des maquettes et l'un ou l'autre des critères SOLAS : aucun lien direct n'a pu être établi entre ces critères et le phénomène du chavirement. La variable qui produit l'effet le plus notable sur le chavirement est l'accumulation d'eau sur le pont-garage. Une fois atteint le volume d'eau critique, le chavirement est relativement rapide. Le critère SOLAS «90+50», un critère plus sévère déjà adopté par certains pays, prend partiellement en compte cet effet : le «+50» signifie que le critère de base doit être respecté en présence d'une accumulation hypothétique de 50 cm d'eau sur le pont. Les essais réalisés au Canada et ailleurs ont montré que ce niveau d'eau de 50 cm ne peut s'appliquer à tous les navires, et le Canada continue, comme la majorité des pays, à appliquer le critère SOLAS initial.

Les phases I et II du projet n'ayant pas débouché sur une méthode fiable de détermination de la survivabilité d'un navire dans une gamme étendue de conditions, la phase III a été entreprise dans le but précis d'élaborer une telle méthode. Plutôt que de partir de zéro, il a été décidé, dans un premier temps, d'examiner diverses méthodes existantes proposées, en vue de retenir la plus prometteuse, et de mettre à l'essai et valider ces méthodes à l'aide des données d'essais colligées au Canada. La «méthode du système équivalent quasi-statique» (SEM, de l'anglais *Static Equivalency Method*), mise au point par des chercheurs de l'Université Strathclyde, est rapidement ressortie comme celle qui offrait le potentiel le plus intéressant.

La SEM pose comme hypothèse que le chavirement après avarie est un phénomène quasi-statique (comme l'ont montré les essais des phases I et II) et que le volume d'eau critique sur le pont peut être calculé simplement à partir des propriétés hydrostatiques de la coque. Parallèlement, il est possible de prédire l'accumulation d'eau sur le pont à partir de la hauteur de houle significative, en établissant une relation simple. Il est donc possible, pour un parcours donné, dans un régime de vagues connu, de prédire la probabilité de survie d'un navire présentant des dimensions d'avarie répondant aux critères SOLAS (ou à d'autres critères). La SEM a d'abord été mise à l'essai et validée au moyen de simulations numériques de chavirement, complétées de quelques essais sur maquettes.

La phase III a consisté à vérifier les prédictions de la SEM à la lumière des résultats des phases I et II, en portant une attention particulière à certaines failles potentielles de la méthode. Pour cela, il a fallu reprendre l'analyse d'un sous-ensemble de données initiales, afin de générer des valeurs «mesurées», avec lesquelles comparer certaines des prédictions. Ces travaux ont été réalisés à l'IDM par une équipe de projet dont faisait partie un des chercheurs de l'Université Strathclyde, co-auteur de la méthode, qui a prodigué de précieux conseils.

La SEM s'est révélée un excellent outil pour prédire la hauteur de houle menant au chavirement, pour une large gamme de configurations de navires. Sa tendance à sous-estimer la survivabilité des navires très stables s'est confirmée, comme s'est confirmé l'effet puissant de la présence ou de l'absence d'un encaissement : pour ces types de navires, l'absence d'encaissement favorise la survie. Quelques résultats «anormaux» ont été obtenus pour des configurations qui présentent toutefois peu d'intérêt pratique : dans tous ces cas, les prédictions issues de la SEM comportaient encore une fois une bonne marge de sécurité.

Les chercheurs ont ensuite appliqué la SEM à l'étude de l'effet des sabords de décharge. À ce jour, les résultats confirment les attentes, mais le degré de précision obtenu est trop faible pour que la méthode soit utilisable à cette fin. Un complément de recherche a été recommandé, qui permettrait de mieux comprendre les phénomènes physiques qui régissent l'accumulation d'eau à l'intérieur du navire. On peut malgré tout conclure que la SEM a atteint une maturité suffisante pour servir à apprécier la survivabilité des navires existants et des nouveaux modèles de navires, de manière plus rationnelle que le critère SOLAS 90, ou le critère amélioré SOLAS 90+50.

Comme la SEM est une méthode essentiellement probabiliste, sa mise en oeuvre selon le concept pseudo-déterministe ou probabiliste nécessitera une réflexion plus approfondie ainsi que d'autres travaux d'étalonnage. Le rapport propose à cette fin des moyens à court et à long terme.

CONTENTS

LIST OF FIGURES

GLOSSARY

ACRONYMS:

IMD	Institute for Marine Dynamics
IMO	International Maritime Organization
JONSWAP	Joint North Sea Wave Project
LL	Load Line
MSC	Marine Safety Committee of the IMO
SLF	Stability and Load Lines, and Safety of Fishing Vessels, Sub-Committee of the MSC
RO-RO	Roll On-Roll Off
SEM	Static Equivalency Method
SNAME	Society of Naval Architects and Marine Engineers
SOLAS	Safety of Life at Sea
SSB	Ship Safety Branch
TDC	Transportation Development Centre
U.K.	United Kingdom

GLOSSARY (continued)

TERMINOLOGY

∇	Displaced Volume of the ship
A/b	Ratio of freeing port area, A, to damage opening width, b
A_{WL}	Area of the waterline
B	Centre of Buoyancy
C_{el}	Centre of gravity
ζ	Damaged opening
D	Displacement (weight) of the ship
δT	Sinkage of the ship
F_{ad}	Centroid of the undamaged waterplane
F_{WLD}	Centre of flotation of the damaged waterline
G	Centre of gravity
GM	Metacentric Height
GMf	Metacentric Height (fluid)
GMn	Metacentric Height (non-dimensional)
GZ	Righting arm calculated by constant displacement method
h	Elevation of water on deck above the mean damaged waterline after sinkage, WL
h'	Elevation of water on deck above the static waterline, WL_o
H_S	Significant wave height
H_{SR}	Modified significant wave height (Significant height of relative motion)
l_{ad}	Heeling lever due to the total water on deck
l_{el}	Heeling lever due to elevated water on deck
M	Righting moment
p_{ad}	Total weight of additional water on deck
p_{el}	Weight of water elevated above mean sea level
q_{in}	Non-dimensional inflow rate
q_{out}	Non-dimensional outflow rate
Q_{fp}	Outflow rate through freeing ports
Q_{in}	Mean inflow rates of water through the damaged opening
Q_{out}	Mean outflow rates of water through the damaged opening
θ	Heel Angle
$\theta_{\mathbf{max}}$, $\theta_{\mathbf{crit}}$	Heel Angle associated with maximum GZ
v_{ad}	Volume of additional water on deck above the waterline WL_o
v_{el}	Volume of water elevated above sea level
Vn	Volume (non-dimensional)
WL_o	Static damaged waterline (before sinkage)
WL	Mean damaged waterline (after sinkage)

1. INTRODUCTION

The capsize of the U.K.-registered roll on/roll off (RO-RO) passenger ferry, *Herald of Free Enterprise* in March 1987, accelerated action within the International Maritime Organisation (IMO) to provide more stringent damaged stability regulations for these vessels. The new requirements were issued as SOLAS 90 under the IMO Safety of Life at Sea Convention.

Prompted by these international initiatives, Transport Canada (Transportation Development Centre (TDC) and Ship Safety Branch (SSB)) initiated a multi-phase program of research in 1993 entitled "Flooding Protection of RO-RO Ferries". The objective of the program was to examine the survivability of monohull RO-RO ferries, fitted with freeing ports, under various conditions of ferry loading, residual freeboard after collision damage amidships and the prevailing sea state. Phase I of the program was completed in March 1995 and the report Ref [1(a)], with supporting data in Ref [1(b)], which confirmed the benefits of freeing ports, was provided to IMO.

Following the development of the original Work Statement for Phase I, many significant events took place. The most prominent was the capsize of the passenger ferry *Estonia* in September 1994 with heavy loss of life. The basic reason was similar to that of the *Herald of Free Enterprise* accident - intact condition with water on the bulkhead (RO-RO) deck. Similarly, the loss of the *Estonia* triggered another strong push at IMO to introduce additional stability criteria.

This action started at Marine Safety Committee (MSC) 64 in October 1994, where the Secretary-General's proposal to establish a panel of experts was accepted and mandated to consider and improve all constructional and operational aspects of RO-RO safety. The recommendation of the panel in the form of amendments to the SOLAS Convention were deliberated by MSC 65 in May 1995 and passed to the SOLAS Conference for final approval Ref [2].

The conference took place in October 1995. However, regarding Chapter II-1 (stability), consensus was reached only on the concept of regional application of the proposed amendments but without incorporating them in the text of the convention. The recommendations of the panel, although not implemented by the conference, sought a significant increase in the residual stability parameters over the SOLAS criteria and included the impact of water on the RO-RO deck and freeing arrangements. Additional Canadian research into these latter matters was conducted as a Supplement to Phase I and the report Ref [3(a)], supporting data in Ref [3(b)] provided to IMO for the above conference.

The outcome of IMO's deliberations was that the SOLAS 90 standard remained unchanged, despite the fact that it was recognized that it was potentially deficient in predicting performance when water is present on the bulkhead (vehicle) deck. This particular capsize configuration was addressed in one of the panel's proposed amendments.

Phase II of the Transport Canada program was undertaken to evaluate the adequacy of SOLAS 90 in protecting RO-RO ferries in the damaged condition against capsize in waves, including the effect of water on deck, with or without the benefit of freeing ports. Using the findings of Phase I and other available publications on RO-RO ferry capsize, Phase II investigated the relationships which describe the capsize phenomenon. The results of this work are provided in Ref [4] (supporting data in Ref [5]), which was also provided to IMO. It noted that parameters other than those contained in the SOLAS 90 criteria appeared to provide better insight into safety than the SOLAS standards themselves.

Although the results of Phase II provided much additional valuable information on ship capsize, no firm conclusions were reached on how designers and regulators could readily incorporate these findings into simple assessments of vessel safety. Meanwhile, other international work has resulted in the development of a number of methods and hypotheses which aim to offer capsize prediction tools; and a number of nations have agreed to tighten SOLAS 90 for their own domestic and international vessels. Although Canada has decided to remain with the standard SOLAS 90 approach for the time being, it was recognized that this is also an imperfect predictor of safety.

Therefore, Phase III of this project was initiated with the objective of reviewing the results of the earlier phases and the other methods on offer, and selecting the most promising of these for further analysis and development. The work was conducted in two parts - an initial scoping study followed by a detailed re-analysis and interpretation of the earlier data. No new tests were conducted.

This report describes the approach in detail. It presents the results, and the conclusions that the authors feel can be drawn from these. In order that it can also act as a summary of the program as a whole, the following section provides a more detailed review of the earlier phases and their key findings.

2. SUMMARY OF PREVIOUS WORK

2.1 Program Overview

The Canadian research program was launched in 1993 with the objective of developing a means of evaluating the survivability of a damaged RO-RO ferry in a seaway. The ferries targeted for this evaluation were typical Canadian designs complying with the damaged stability standards of SOLAS 90. The program was aimed at obtaining a quantitative understanding of the survivability limits of SOLAS 90 both with and without the effect of water on the car deck taking into account the sensitivity to residual freeboard, the installation of freeing ports and the presence of a centreline casing.

It was originally planned that the focus of the research would be on the development of a numerical model by means of which specific ferry designs could be evaluated as to their damaged survivability limits. In the early part of the first phase of the study it was decided to de-emphasize the numerical approach and embark on a more comprehensive model testing program in order to create a strong physical database which could be used to prepare credible technical submissions to the MSC/SLF Committees at IMO who were continuing their deliberations on damaged stability standards. These deliberations were accelerated by the Estonia disaster which focused attention to the effect of water on the car deck and brought into consideration the type of superstructure involved, enclosed, semi-enclosed with open ends, and open car decks surrounded only by bulwarks. The Canadian research made a contribution to IMO with respect to these superstructure options and related freeing port arrangements.

Thereafter, our research turned again to the evaluation by model testing of another Canadian ferry design, complying with SOLAS 90, but of a smaller size of vessel than the one previously tested. The whole of this program comprised two main phases extending over a four-year period from 1993 to 1997. Briefly, the events covered were as follows.

Phase I In this phase, an extensive tank testing program was undertaken to examine the survivability of a simplified model of a large (160 m, 11650 t displacement) Canadian ferry with midships damage. The tests were carried out in sea states up to 7 m irregular waves, at three residual freeboards with and without the presence of a centreline casing on the car deck and the use of flapped freeing ports to counteract the ingress of water onto the car deck. A total of 280 tests were performed (Refs [1(a),(b)]).

Phase I Extension This extension was undertaken to provide quantitative test data to the IMO Panel of Experts set up following the *Estonia* tragedy. The same model was used but modified to permit the superstructure to be readily exchanged between enclosed, semi-enclosed and open concepts. Each of these options was again tank tested covering a similar set of variables used in Phase I but with open freeing ports. A total of 160 tests were performed Refs [3(a),(b)].

Phase II In this phase, a second model was tank tested again covering a similar set of variables used in Phase I. In this case, however, the model used was of a smaller ferry (85 m, 4450 t displacement) and its form more closely approximated to the shape of the parent ship. To visualize the impact of size, the results were combined with those of Phase I for a more complete understanding of the main survival criteria. A total of 160 tests were performed Refs [4], [5].

The range of SOLAS 90 compliant loading conditions covered by these two phases is as shown in **Figure 2.1** below, taken from Ref.[4]:

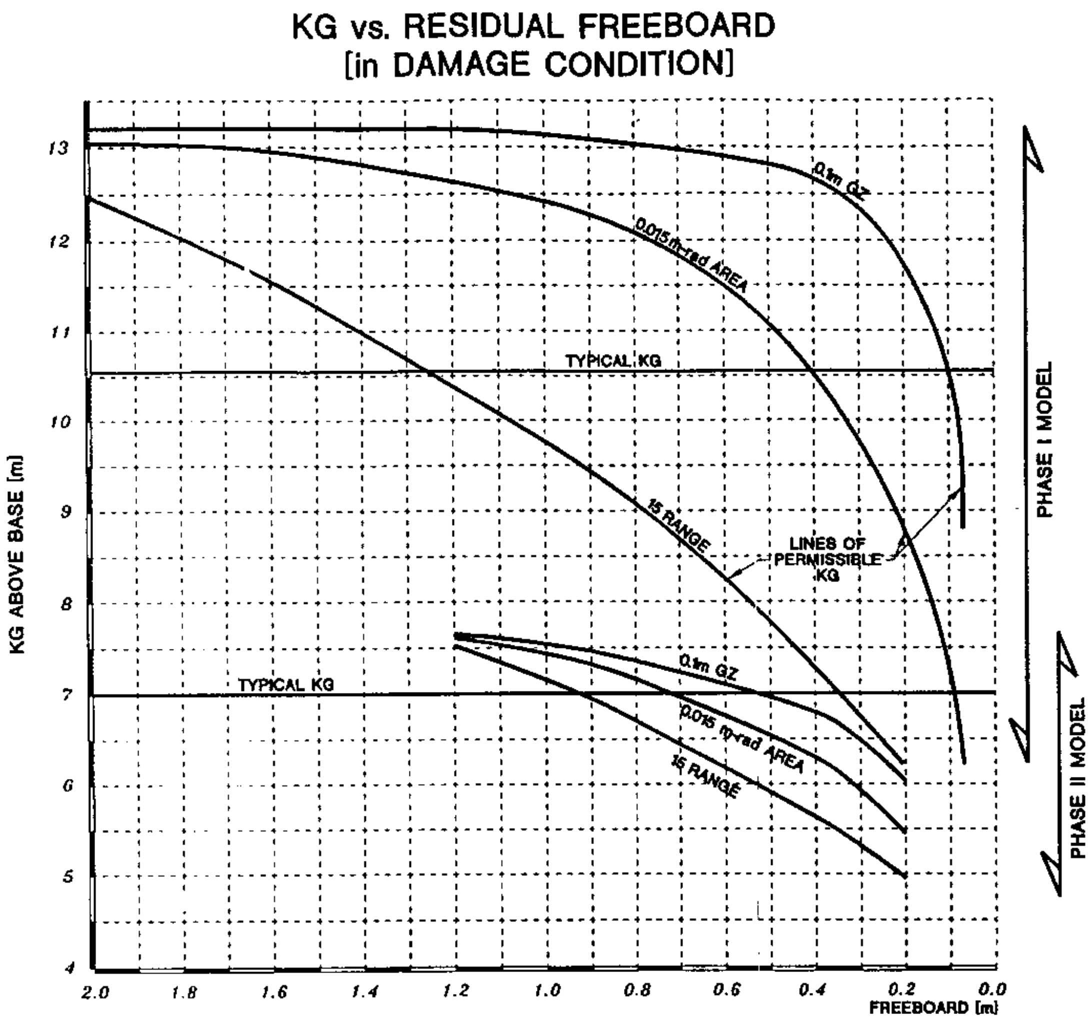


Figure 2.1: Comparison of Phase I and II limiting KG distributions

The principal parameters that were under consideration in the two-phase program were as follows:

- Residual freeboard after damage
- Effect of freeing ports
- Influence of centreline casing
- Effect of water on deck

Each of these considerations produced some informative and, in some cases, unexpected results which combined to provide valuable insight into the capsize phenomenon and these are summarized in the following sections.

2.2 Effect of Residual Freeboard

The Phase I model was tested at three residual freeboards (1.5 m, 1.0 m, 0.5 m compared with the intact loaded freeboard of 3.0 m). The highest upright and the lowest capsize wave heights are plotted as bands of survivability for each of the three residual freeboards against baselines of GZ area and flooded GM. The relevant **Figures 2.2** and **2.3** taken from Ref. [1(a)] are given below.

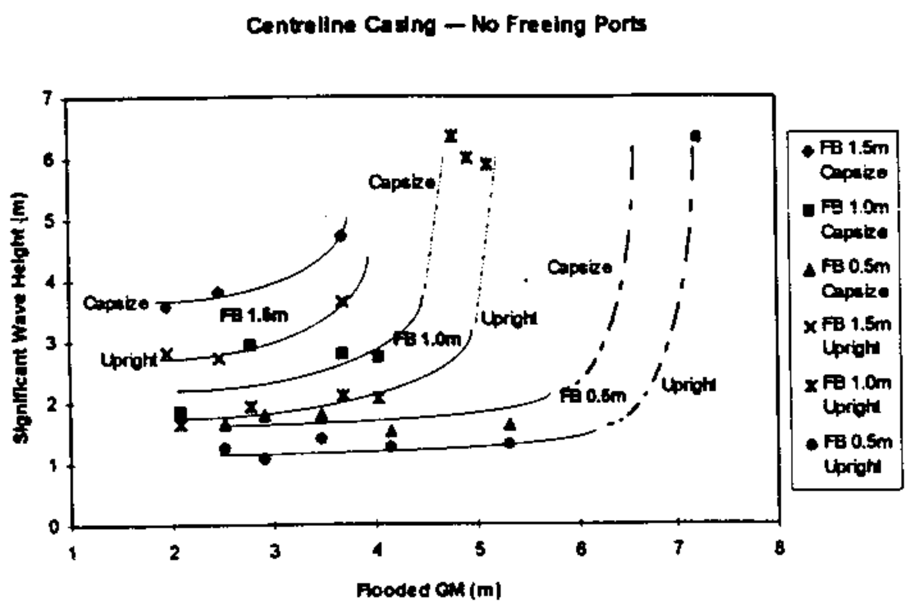


Figure 2.2: Significant wave height as a function of flooded GM for different freeboards

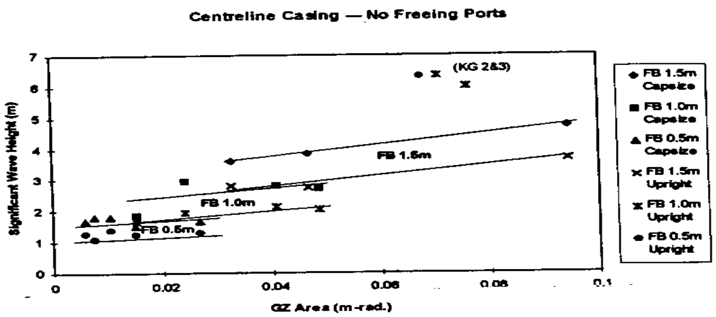


Figure 2.3: Significant wave height as a function of GZ area for different freeboards

In both cases it can be seen that freeboard has a noticeable influence on survivability which is to be expected. The unexpected characteristic of both figures is that the baseline plotting parameter makes only a very modest contribution to survivability over a large range of values. This raises a fundamental point for concern when it is remembered that the damaged stability design standards prescribed in SOLAS 90 are based on meeting certain minimum requirements for the GZ diagram. It was also found in plotting other test results that GZa was less useful as a baseline parameter than GMf. In the case of the Phase II model, tested at four residual freeboards (1.2 m, 0.8 m, 0.4 m, 0.2 m, compared with the intact loaded freeboard of 1.75 m), the equivalent plotting showed only GMf as a suitable baseline, as can be seen below in **Figure 2.4** taken from Ref. [4]:

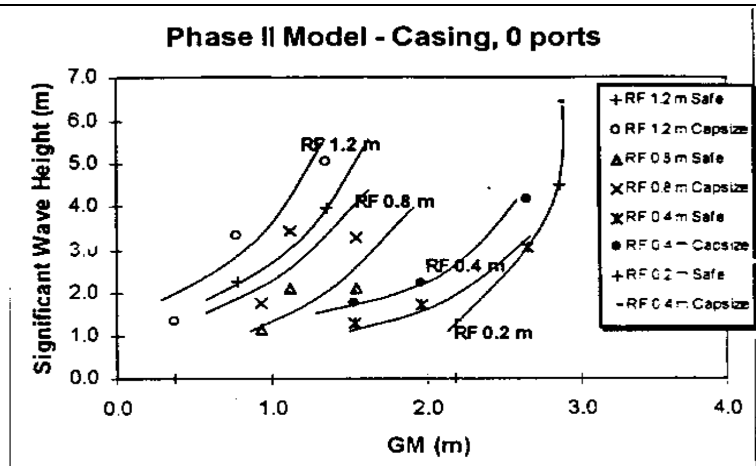


Figure 2.4: Significant wave height bands with casing and no ports

In this case, survivability is more influenced by the GMf value than the residual freeboard although both play a noteworthy role. The difference in the influence of these baseline parameters between the two sizes of models needs further investigation.

2.3 Effect of Freeing Ports

The models constructed for Phases I and II were outfitted with flapped freeing ports fitted along each side of the superstructure at the car deck. Tests were conducted with ports active in four progressive levels, namely, zero, Loadline, twice LL and four times LL. In the case of both models, it was found that the freeing port area had a significant effect on survivability, an example of which is given in the following **Figure 2.5** taken from Ref. [1(a)]:

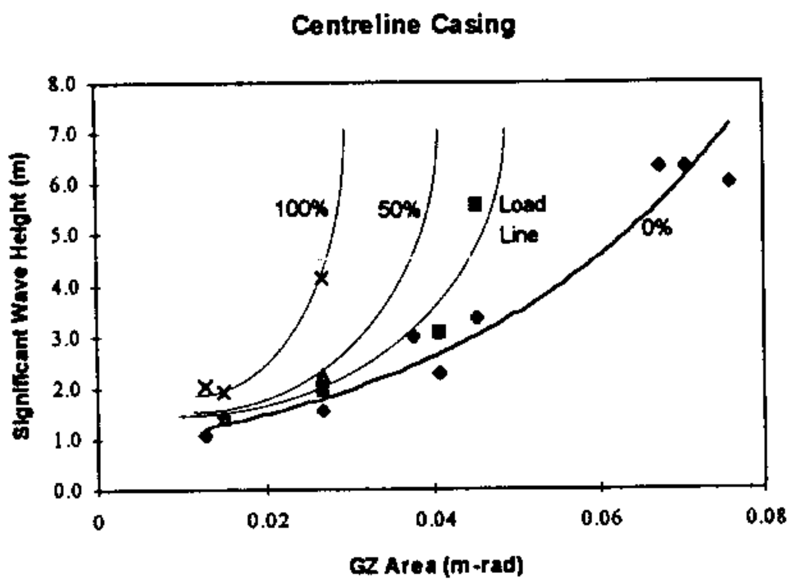


Figure 2.5: Effect of freeing port area by GZ area
(from Ref. [1(a)])

Note in the above figure, however, that the effect of freeing port area does not become noticeable until the GZa are multiples of the SOLAS 90 minimum requirement of 0.015 mr. This seems not too difficult to achieve when the design is also complying with the 15 degree minimum range requirement. Other plots based on GMf and distinguishing between residual freeboards also showed dramatic improvements, in fact one of the conclusions of the program is that a certain minimum residual freeboard is needed to ensure that the freeing ports can effectively drain water overboard from the deck.

2.4 Effect of Centreline Casing

Tests were carried out in both phases with and without the centreline casing being fitted to the models. The results from both sets of tests are shown combined in the following two **Figures 2.6** and **2.7** taken from Ref [4], where the axes have been non-dimensionalized for plotting.

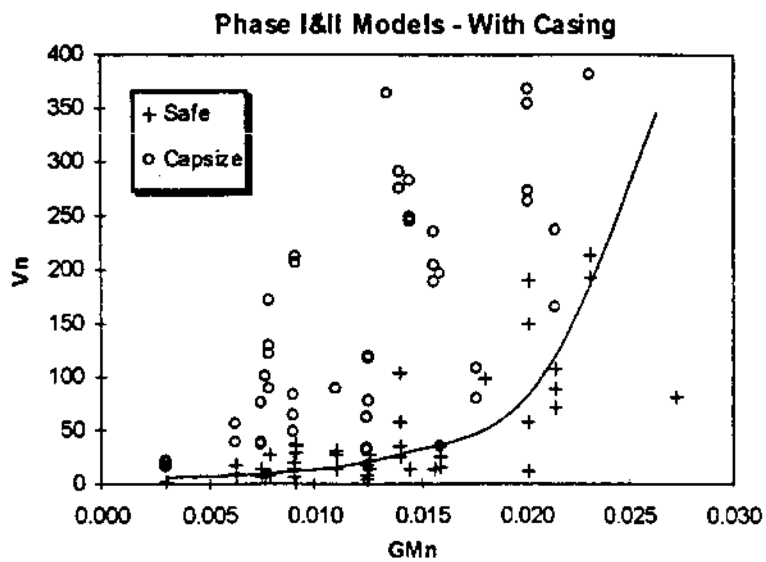


Figure 2.6: Water on deck Vn vs GMn - Phase I and II with casing (from Ref [4])

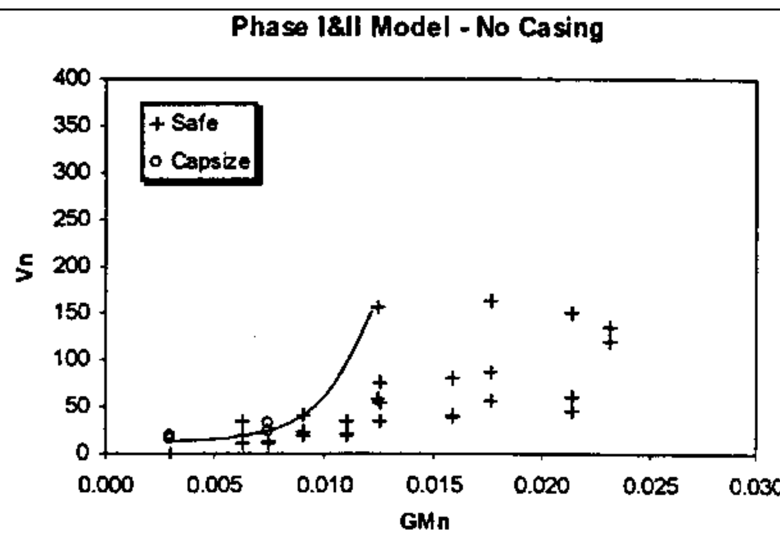


Figure 2.7: Water on deck Vn vs GMn - Phase I and II no casing (from Ref [4])

It was generally concluded that the removal of the casing tends to enhance the safety of the vessel by not restricting the build-up of water to one side, which would seem to have a more destabilizing effect than the free-surface effect of a wide deck. Moreover, it was found in Phase I that removal of the centreline casing with freeing ports active produced some significant increases in survivability.

2.5 Effect of Water on Deck

As a fundamental and important conclusion to this research program, the build-up of water on the car deck was carefully investigated in order to gain valuable insight into the capsize phenomenon. In both phases, it was found that there was a clear demarcation between upright and capsize dictated by the volume of the water accumulated on the deck. This is well illustrated by the following **Figure 2.8** derived in Phase I.

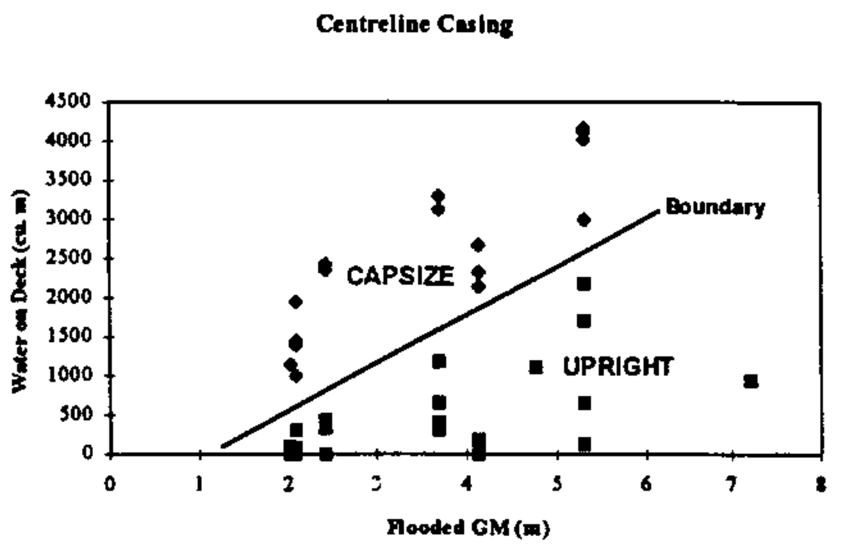


Figure 2.8: Volume of Water on Deck vs Flooded GM
(from Ref [1])

Closer examination of this water build-up process revealed that before the capsize volume was reached there was a critical volume which so changed the vessel's motion characteristics that further accumulation was inevitable and capsize was unavoidable. This is depicted in the following **Figure 2.9** taken from Ref [6]:

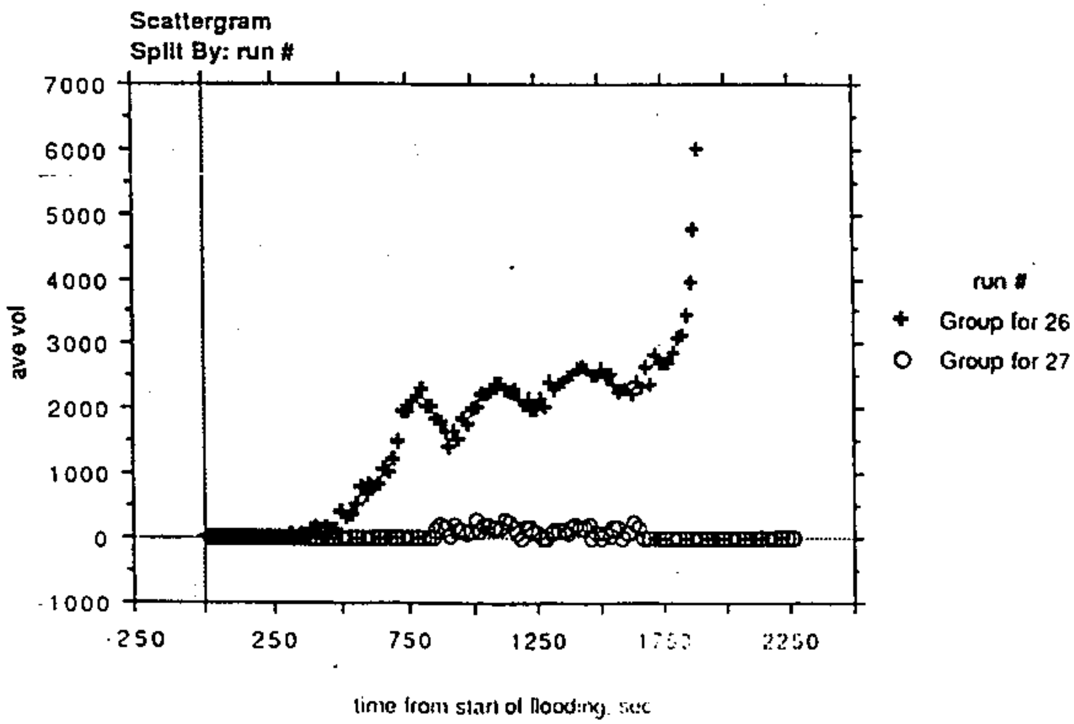


Figure 2.9: Average Volume of Water on Deck (cu m) Against Time (secs)
(from Ref [6])

In this figure, the accumulation process moves from an initial build-up into an oscillatory phase and then reaches a critical value after which the build-up becomes exceedingly rapid and catastrophic. This critical value is also linked to the volume which, in static conditions, would heel the vessel to the angle at which GZ is maximum.

2.6 Summary of Findings

The results of the extensive model test programs carried out in the first two phases of this research endeavour to demonstrate the degree to which a damaged RO-RO ferry can survive in a seaway. The influence of a centreline casing and the use of flapped freeing ports were also been demonstrated. More fundamentally, however, the findings also confirmed the capsize phenomenon essentially as being a hydrostatic one taking place at a certain definable point in the sequence of ship/wave dynamics. A number of specific conclusions were reached in this program; the main ones are set down below:

- Capsize is a hydrostatic phenomenon, occurring once sufficient water is accumulated on the vehicle deck. A sudden "cliff-edge" capsize event occurs once a critical flooding condition is reached.

- Dynamic stability as expressed by GZ area is important in terms of ability to withstand vehicle deck flood water but was not found to be very useful in the prediction of overall capsize safety.

- The analyses showed the importance and benefits that increased residual freeboard provides in enhancing capsize safety.

- Freeing port tests (with flaps) demonstrated that the ability to drain water from the deck greatly enhances capsize safety. In that connection, larger areas of freeing ports (than are currently provided for in the Loadline Regulations) are needed.

- Freeing ports (open without flaps) proved to be of no benefit to the survivability of the vessel and may actually have a detrimental impact.

- The presence of a centreline casing seems to have a detrimental effect on safety. Removal of the casing, when coupled with the use of freeing ports, has shown dramatic increases in survivability.

Unfortunately, it was not possible in the earlier phases to combine all of these results into a methodology capable of providing a reasonable prediction of capsize behaviour. In order to bring the overall program to a conclusion, it was decided to conduct a further survey of methods proposed by other researchers to identify one or more which offered the potential to provide such a prediction capability, and to use the results of the experimental work to test, and, it was hoped, to validate one of these methods.

3. BACKGROUND TO ANALYSES

3.1 Review of Alternative Methods and Hypotheses

The basic SOLAS 90 approach sets criteria for damaged stability following damage of a specified extent for location, penetration distance, and vertical extent. The earlier phases of the project demonstrated (as have other studies) that none of the criteria is a good predictor of capsize for all ship configurations.

The Stockholm Agreement among a number of European nations applies identical criteria to a ship assumed flooded to a depth of 50 cm of water on the vehicle deck. It has been argued by many (including the SNAME ad-hoc panel [7]), that a single number for depth of water is inappropriate, given the range of damaged freeboards which different ships may have, and the range of sea conditions which they may encounter. As an alternative, owners of existing vessels are allowed to demonstrate safety by model testing the worst damaged condition in a representative sea state. Since compliance with the water on deck standard is very onerous for many vessels, testing has proven a popular alternative. However, it is somewhat expensive and time-consuming, and there are often concerns about the repeatability and accuracy of the outputs.

The work of Spouge [8] and Hutchison [9] was discussed in the Phase II report, and was reviewed again in this Phase. Spouge attempts to find a limiting KG (or GM) value for the damaged ship, using empirical fits to experimental data. While some of the Canadian data shows a reasonable fit to his equations, the approach does not offer the potential to treat all the factors found important during the tests. Hutchison's models predict the final level of water on deck for ships of different initial freeboards and at various wave heights. They provide important insights into one of the key mechanisms involved in capsize, but do not offer a comprehensive description of the phenomenon.

During Phase I of the project (as noted in Section 2), efforts were made at IMD to develop a mathematical model of capsize [6], but these were unsuccessful. It was decided to revisit this unpublished work to see if it could be restarted using the knowledge gained since its termination. On review, it was agreed with Transport Canada that there was limited potential to achieve useful results.

One other method reviewed was the Static Equivalency Method developed by researchers at Strathclyde University as part of a major European project on RO-RO safety. Phase II had examined earlier reports on this method [10], but a reading of more recent publications [11] suggested that a further attempt to check its predictions with the Phase I and II data was warranted. Accordingly, it was agreed that this would be the initial focus for the next efforts under Phase III. The project was able to benefit from the availability of one of the method's originators in North America during its most critical time period. Therefore, Professor Pawlowski of Gdansk University was brought into the project team to assist in the interpretation of the experimental and analytical data.

3.2 The Static Equivalency Method

3.2.1 Basic Premises

The Static Equivalency Method (SEM) is based on a number of insights and hypotheses, some of which are common to other investigations of capsize, including the earlier phases of this project.

It is presumed that it is the accumulation of water on the vehicle deck that causes the ship to capsize, rather than the basic damaged stability in the flooded condition as measured by the SOLAS criteria.

The required capsize volume (or weight) of water on deck is assumed to be that which would cause the ship to loll to its angle of maximum GZ in the flooded condition. Any additional heel with this volume on deck, or any additional volume at the same heel angle, will create a larger overturning moment. This will be resisted by a smaller restoring moment. Thus, the ship will inevitably capsize.

The depth of water on deck at the critical condition corresponds to an elevation above the mean external sea level, and this elevation can, in turn, be correlated with the significant wave height. Kinetic wave energy is, in effect, transformed into potential energy.

The process can be treated quasi-statically, as the time frames associated with capsize are significantly longer than the wave or ship roll periods. Dynamic effects do need to be accounted for both in the stability calculation approach and in the correlation of water elevation and wave height.

The stability calculations needed to predict capsize water volume can be undertaken in several ways which should yield essentially identical results. Some are relatively easy to understand but difficult to apply, while others are simple to use but more conceptually challenging. Two alternatives are explained below in an attempt to provide maximum clarity.

3.2.2 Stability Calculation Process

3.2.2.1 Critical volume

The elevation of water above sea level at the critical point for capsize can be easily visualized as a function of heel angle θ, using the lost buoyancy or constant displacement method. As can be seen from **Figure 3.1**, the righting moment is produced by two pure couples. The first one is created by weight of the ship, passing through its center of gravity *G*, balanced by buoyancy force D which passes through the center of buoyancy *B*.

The other couple is created by weight of the elevated water on deck p_{el}, passing through its center of gravity C_{el}. This is balanced by a change in buoyancy due to sinkage of the ship dT, which is applied at the center of flotation of the damaged waterline F_{WLD} (the centroid of the waterplane without the part occupied by the flooded water). Hence, the righting moment is given as follows:

$$DGZ - p_{el}\, l_{el} = M, \text{ righting moment} \qquad (3.1)$$

Where:

D – displacement (weight) of the ship

∇ – volume displacement of the ship.

GZ – righting arm calculated by the constant displacement method, allowing for free flooding of the vehicle deck;

p_{el} – weight of water elevated above sea level = gv_{el};

l_{el} – heeling lever due to elevated water on deck, equal to the horizontal distance between the center of flotation F_{WLD} and center of gravity C_{el} of elevated water.

The additional amount of water on deck, elevated above sea level (shading in Figure 3.1) is such that the resultant righting moment $M = 0$ at each heel angle. Dividing Eq. 3.1 throughout by the density of sea water, the following is obtained:

$$v_{el}\, l_{el} = \nabla GZ \qquad (3.2)$$

where v_{el} is volume of water elevated above sea level;

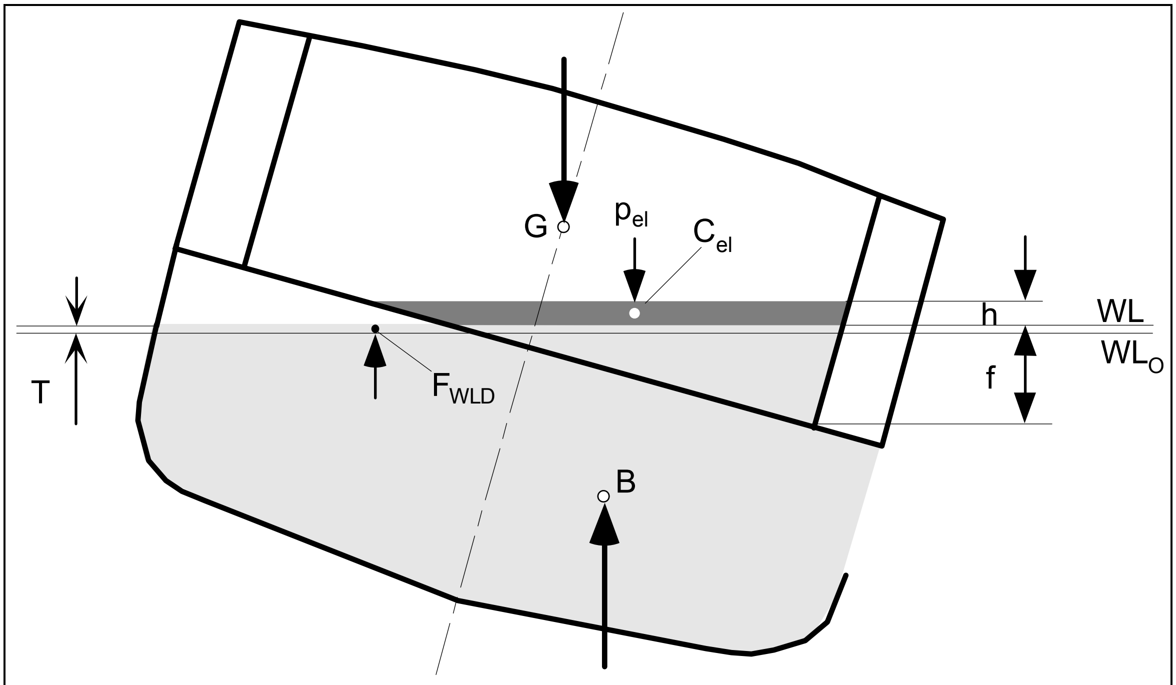


Figure 3.1: Stability of a Damaged Ship with Water Accumulated on Deck

Certain of the quantities required to apply this approach are not readily available from standard stability calculation packages. The calculation procedure is simplified if the additional amount of water on deck above the waterline WL_o (before sinkage) is taken into account. The heeling moment is created then by weight of the additional water on deck p_{ad}, passing through its center of gravity C_{ad}, balanced by a change in buoyancy due to sinkage of the ship δT, that is applied at the centroid F_{ad} of the undamaged layer (including the part occupied by the flooded water on deck but without the damaged part below the deck) cut off by waterlines WL and WL_o. As the sinkage δT is always very small, the centroid F_{ad} effectively coincides with the center of flotation F_{WL} of the two waterlines, treated as undamaged above the car deck. This feature allows, in turn, for an easy visualization of the problem, shown in **Figure 3.2**, as the centroid F_{WL} of the waterline WL_o lies close to a point of intersection between WL_o and the centerline, with some shift towards the opening in Figure 3.2.

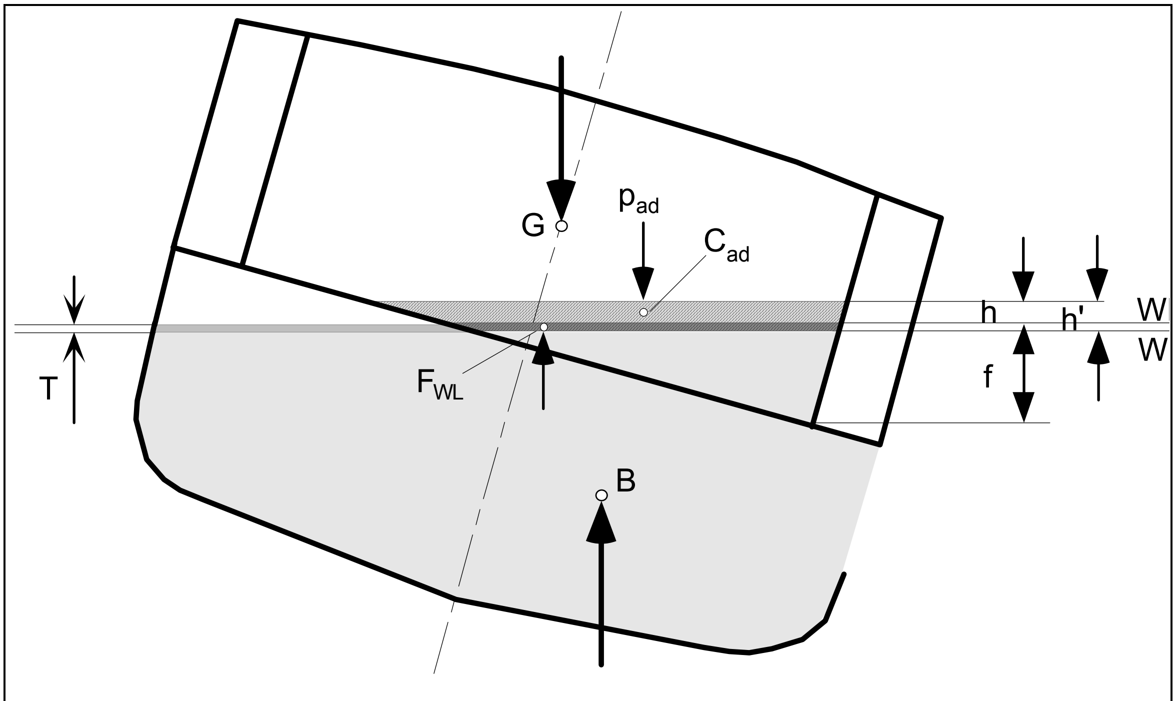


Figure 3.2: Alternative Representation of Stability Calculations

It is clear that p_{ad} is larger than p_{el} by the amount of water contained between the two waterlines, that their centers of gravity C_{ad} and C_{el} are not the same, and that the locations of the centers of flotation F_{WL} and F_{WLD} differ even more. Nevertheless, the sinkage of the ship δT and the heeling moment are exactly the same for both methods. These statements should be taken as self-explanatory. Hence, Eq. 3.2 can also take the form:

$$v_{ad}\, l_{ad} = \nabla GZ \qquad (3.3)$$

where

v_{ad} – volume of additional water on deck above the waterline WL_o;

l_{ad} – heeling lever due to the additional water on deck, equal to the horizontal distance between the center of flotation F_{WL} of the waterplane WL_o (undamaged above the car deck) and the center of gravity C_{ad} of the additional water on deck.

The solution of Eq. 3.3 poses much less difficulty. For a given heel angle, θ_{crit}, the right-hand side of Eq. 3.3 —∇GZ can be readily determined, as can other characteristics of the vessel at this condition. Meanwhile, the left-hand side of Eq. 3.3 —$v_{ad}\, l_{ad}$ is a function of h' — the elevation of water on deck above the static waterline WL_o. The desired water elevation h' is determined when Eq. 3.3 is satisfied, and that can be easily found numerically. l_{ad} can also be found, noting that the centre of flotation should consider the waterplane to be undamaged.

Finally, the water elevation with respect to sea level h, of prime importance for the damaged safety, can be found from the simple relation:

$$h = h' - \delta T$$

where the sinkage of the ship is defined by

$$\delta T = v_{ad} / A_{WL}$$

where A_{WL} is the area of the waterline WL_o for the ship undamaged above the vehicle deck, and v_{ad} is the known function of h'.

Only water elevated above sea level (due to the dynamic action of waves) can truly be called "water accumulated on deck", as distinct from the water which may be present on deck when the ship is heeled statically to an angle beyond vehicle deck immersion in calm water (or at mean water surface). The static waterplane, denoted by WL_o in Figure 3.1 and Figure 3.2, lies in a distance δT below the actual (quasi-dynamic) waterplane WL, with water accumulated on deck.

3.2.2.2 Limiting wave height

In order to provide a prediction of the capsize condition, it is necessary to relate the elevation of the internal water surface in terms of the sea state which will generate this.

In the SEM, no explicit numerical relationship defines this relationship. Instead, the elevation above mean sea level has been expressed using a regression on simulation results, as explained in [11]. The resulting equation takes the form:

$$h = 0.085 H_S^{1.3}, \text{ or alternatively} \quad (3.4)$$

$$h = 0.085 H_{SR}$$

where H_S is the significant wave height, and H_{SR}, designated as the "modified significant wave height" or as "significant height of relative motion". This is believed to account for heave and roll effects in adding to the instantaneous elevation of the outside water surface above the deck level. The value of 0.085 can be considered as a coefficient of proportionality.

3.2.3 Issues Associated with the SEM

The method as described above was developed using numerical simulations of capsize, supported (to a limited extent) by experimental investigations on a model of one of the two vessels simulated [11]. The limited range of variables which were included in the simulations and tests left a number of issues to be explored in the validation of the static equivalency method in this project, including:

i) the influence of relative motions (including GM, bilge keel, and other effects) over the range of vessel "stiffnesses";
ii) the comparative critical volumes of water on deck measured and calculated;
iii) the influence (if any) of sea spectrum;
iv) the influence of ship size and configuration;
v) the ability of the method to represent adequately centre and side casing influences; and,
vi) the potential for treating freeing port effects in the method.

Points (i), (iii), and (iv) reflected concern that the regression equation (3.4) would only be valid for the restricted range of configurations and conditions used in the initial development of the method. Point (ii) would test the basic validity of the assumption of quasi-static behaviour. Point (v) is an issue where the Phase I and II results appeared to find differences between ships with and without centre casings which would not be predicted by the SEM. Point (vi) was investigated exhaustively in the earlier project phases, where the SEM as previously presented offered no guidance on how freeing port effects might be included.

4. ANALYTICAL APPROACH

4.1 Review of Database

The earlier phases of this project included considerable processing of the data traces to establish values for a number of parameters whose influences were explored in the earlier work. In several cases, these were very similar parameters to those used in the SEM. However, they were not necessarily calculated in the same manner, or presented in an immediately useful format. IMD, therefore, agreed to reprocess a set of results to produce numbers which should be aligned as closely as possible to the predictions of the method for critical volumes, heel angles, and relative motions at the damage opening. These values were replotted over periods of interest prior to final capsize, and mean values over (sometimes parts of) the time intervals were calculated.

The data sets obtained during the Phase I [1(b)], I extension [3(b)], and II [5] experimental programs were reviewed to identify conditions expected to be most relevant to the testing of the static equivalency hypotheses as described in 4.2.2 below. This was done both qualitatively (through the characteristics of the data traces) and quantitatively (through comparisons with the numerical analyses). FTL and IMD personnel initially undertook this independently, searching on a variety of criteria. The resulting lists were then collated to produce an agreed set, which was confined to cases which the SEM has been developed to handle, i.e., fully-enclosed car decks, rather than those with bulwarks or open ends.

It was not considered necessary to reprocess many non-capsize runs, as the previous data analysis was expected to have provided representative mean values for the volume, heel, and motion parameters under safe conditions. However, some "marginally safe" runs were re-examined, particularly where closely related capsize runs showed unexpected characteristics.

Rapid capsizes were also excluded from reprocessing, due to the difficulty of identifying any specific critical point in the process.

The Phase I data sets were not reviewed in any detail, due to a drawback of the instrumentation system for that work. The water depth probes did not extend all the way to the deck, and thus the results for small water depths are considered suspect. However, the lowest capsize/highest safe wave heights are as accurate as the data from the other phases, and have thus been included in the overall analysis.

4.2 Initial Analyses

4.2.1 Stability Calculations

The predicted volumes of water associated with capsize were calculated as described at 3.2.2 above. The desired value of θ_{GZm} was first been found from analysis of the damaged hulls from Phases I and II of the project. The "equilibrium" weight/volume of water on the car deck has then been established for this (imposed) heel angle. Sinkage, deck edge immersion, and internal water level are supplementary outputs.

The well-known GHS program was been used for all calculations, and the basic hydrostatic calculations were checked against those from the Phase I and II projects to ensure that all input data was consistent with that used in earlier analyses. In general, results were identical or differed only in the 3rd or 4th significant figure, i.e., most were within 0.1% of previous numbers. For the Phase II analyses, this was expected, as the identical data deck and program were used in both cases.

Since the SEM provides (sets of) predictions for any unique ship condition, numerical results were generated for all combinations of ship freeboard and KG which were tested in the experimental program. This data is provided in Appendix 1 for all the conditions examined.

4.2.2 Experimental Data

The SEM predicts that marginally unsafe conditions are unlikely to capsize without a period of "hesitation". As also noted in the work of Hutchison [9], the build-up of water on deck will take some time, and the rate of growth will slow as it approaches its equilibrium value. If this value is close to the stability limit, then the latter stages of the process may be quite protracted. The data review showed that a significant portion of the capsize runs, usually those with the lowest capsize wave height, show a prolonged hesitation period of this sort. Therefore, it was decided to reanalyze the averaged values of heel, water on deck, etc., over this interval and to compare the derived values with the numerical predictions. In principle, the desired values might be regarded as unique points on the heel or volume curves, representing points of inflexion in their progress towards capsize. However, the nature of the traces makes any such points impossible to identify with any precision, requiring the use of such averages.

Initially, the reprocessing was done only for the cases without freeing ports (as the basic SEM does not handle ports) and with all other influences, casing location, bilge keels, sea spectra, etc., lumped into one data set. The method either did not predict the effect of such influences, or did predict that any effects would be unnoticeable.

Selection of the appropriate time period for the averaging was done in two steps, first using the relatively small-scale traces from the original Phases I and II reports to identify the relevant run segments; and second (in some cases only) to use expanded traces for these segments to select the critical intervals with more precision. In both steps the procedure was subjective, in that the judgement of the individuals involved was used rather than any automated analytical process. However, in most cases, the traces are relatively unambiguous, and it is not felt that significantly different results would have been produced by any other method (or individual). Appendix B contains a sample of the original and expanded traces; full sets of the originals are included in the earlier reports [1b], 3b], [5].

4.3 Extended Analyses

The initial data set was reprocessed and compared with the predictions of the method. This had been set as a breakpoint for the project, and if the comparisons had been poor, then another approach would have been taken to bring the project to its conclusion. However, since the comparisons proved to be generally remarkably good (see Section 5.1), the work was extended in three directions. The first of these was to reprocess results for conditions with freeing ports. Coupled with this, additional numerical analyses were undertaken in order to derive an extension to the SEM capable of handling their effects. Finally, the whole data set was used in examining the effect of casings, bilge keels, and other factors on the results.

5. RESULTS OF ANALYSES

5.1 Capsize Prediction

5.1.1 Water on Deck

As explained in Section 3, the Static Equivalency Method predicts capsize wave height by relating this to the build-up of water on deck, and assuming that the required volume on deck corresponds to the predictions of static stability calculations. Thus, the initial verification of the method considered its ability to predict the critical volume of water on deck and capsize wave height, and, second, heel angles and relative motions just prior to capsize.

Comparisons of predicted and actual volumes of water in capsize conditions for the Phase I (Phase I extension data only) and Phase II models are shown in **Figures 5.1** and **5.2**, respectively. Tabulations of the experimental data and equivalent calculated values are provided in Appendix B.

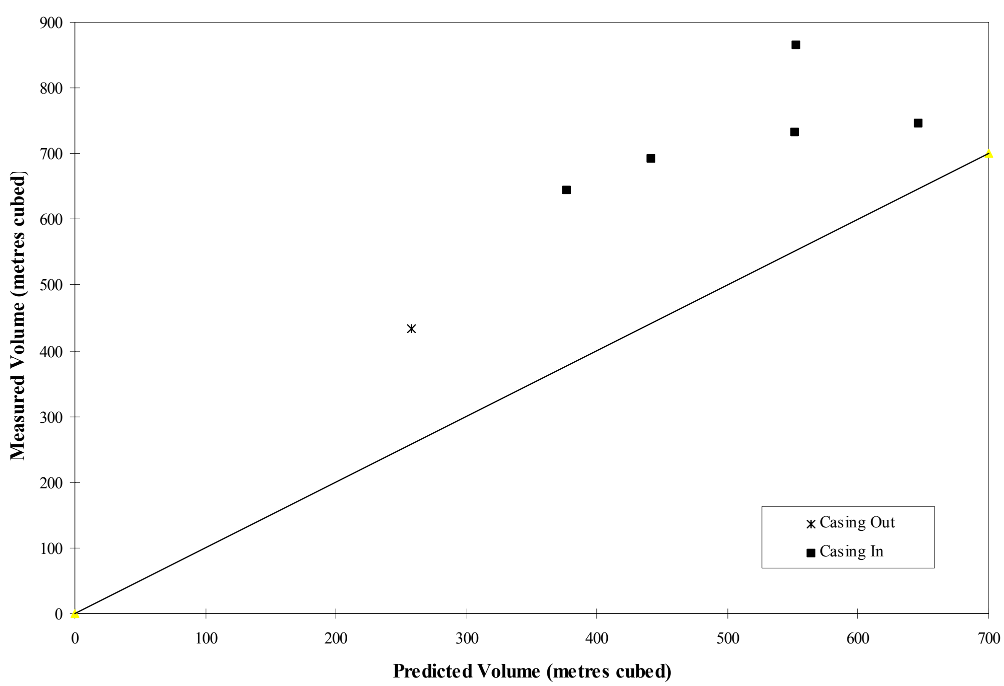


Figure 5.1: Phase I Extension Volume Comparisons

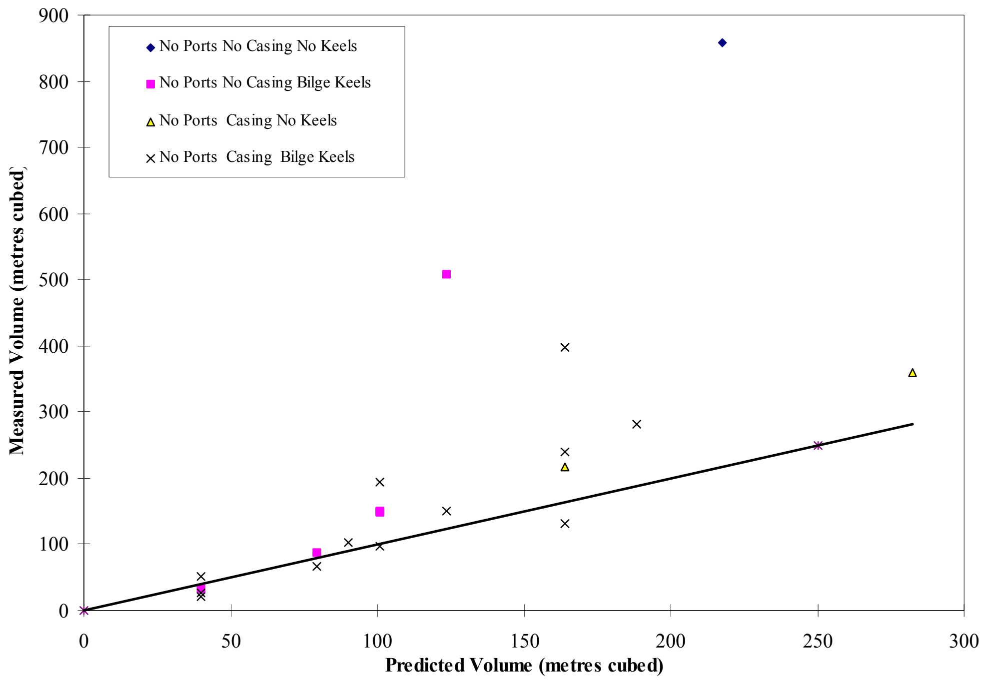


Figure 5.2: Phase II Volume Comparsions

As can be seen, the critical volume data shows some scatter about the expected lines, with a tendency to underpredict the volumes at the higher values. Neither the scatter nor this underprediction was unexpected. As explained in Refs [10] and [11], the capsize process is itself random in nature, and any model tests have some lack of precision. A degree of scatter is expected, therefore, and that in the IMD data, was actually significantly less than was found in tests of a single model in different tanks during the initial validation of the SEM. This earlier work also observed an underprediction of survivability under conditions where the damaged ship has high residual stability. **Figure 5.3** (reproduced from [11]) shows the divergence between the "exact" simulation results and the simplified SEM. The differences were assigned to the increasingly dynamic behaviour under these circumstances, which the motion correction factor in the SEM only partly captures. It can also be noted that the effects are more dramatic for cases without a casing present, a trend which is discussed in more detail at Section 5.4.3.

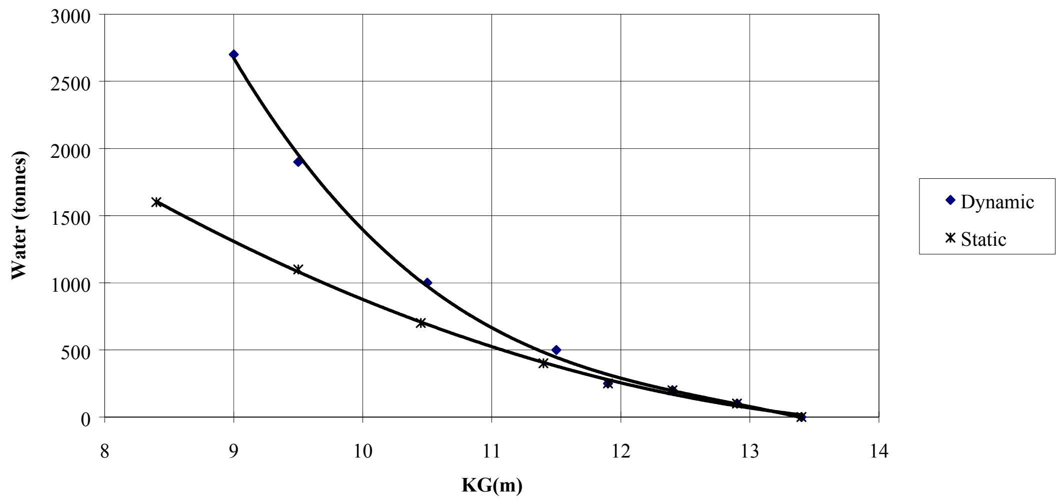
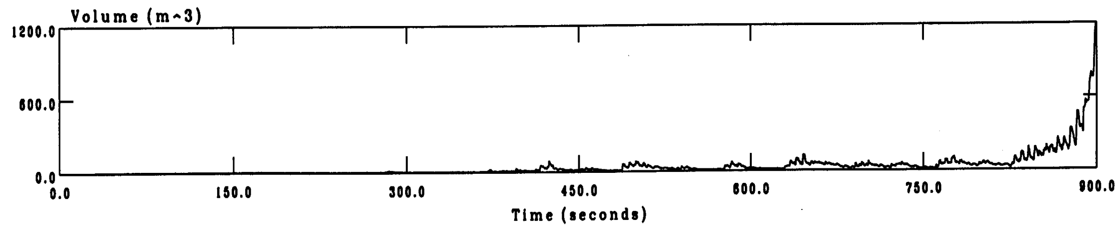
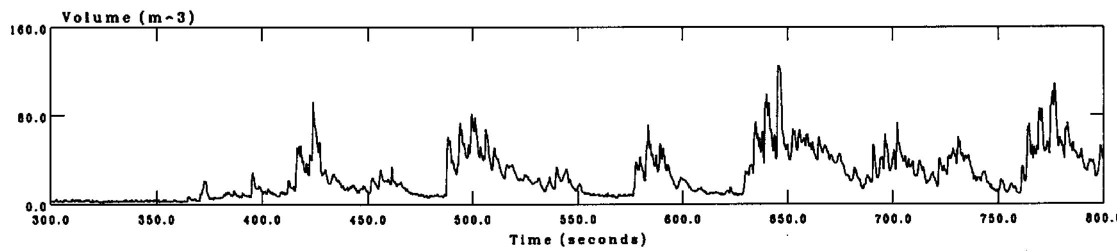


Figure 5.3: Divergence from Dynamic Analysis - 1.5 m Freeboard (from [11])

Where the predicted and actual volumes of water are small, the technique used in the data reprocessing tended to underestimate the volume associated with the actual initiation of capsize due to the nature of the averaging process. This can be seen clearly in the volume trace shown as **Figure 5.4**. in its initial and reprocessed form. The time interval selected for reprocessing appeared from the small-scale trace to represent an average, but, on expansion, can be seen as a succession of more or less discrete events in which water floods the deck, then rapidly wholly or partly drains away. Capsize occurs when a combination of factors combine to maintain the critical conditions for long enough to allow the quasi-static response to take over. In this particular case a smaller time slice at the end of the trace shown was processed again to give a more representative value of volume and heel, but for most others this was left undone and the resulting inaccuracy accepted. In practical terms, the conditions associated with the low volumes are unlikely to be acceptable under any stability criteria.



Original Time History



Expanded Time History

Figure 5.4: Original and Expanded Volume Traces

Although the volume traces proved easy to interpret, the heel/roll angle traces were more ambiguous. In general, the experimental tests had larger roll amplitudes than had been calculated in the simulations, even when the models were fitted with bilge keels. The overall issue of vessel motions is discussed in more detail in Section 5.2. However, although no systematic plotting of heel angle averages has been undertaken it can be seen in examining the traces that the moment of joint occurrence of predicted critical (mean) heel angle and critical volume is generally just prior to the change of response behaviour into the final capsize portion of the run (see **Figure 5.5** as an example of this). No examples of this were found in the highest non-capsize runs, with the exception of a few runs whose generally anomalous nature is discussed at Section 5.4.3.

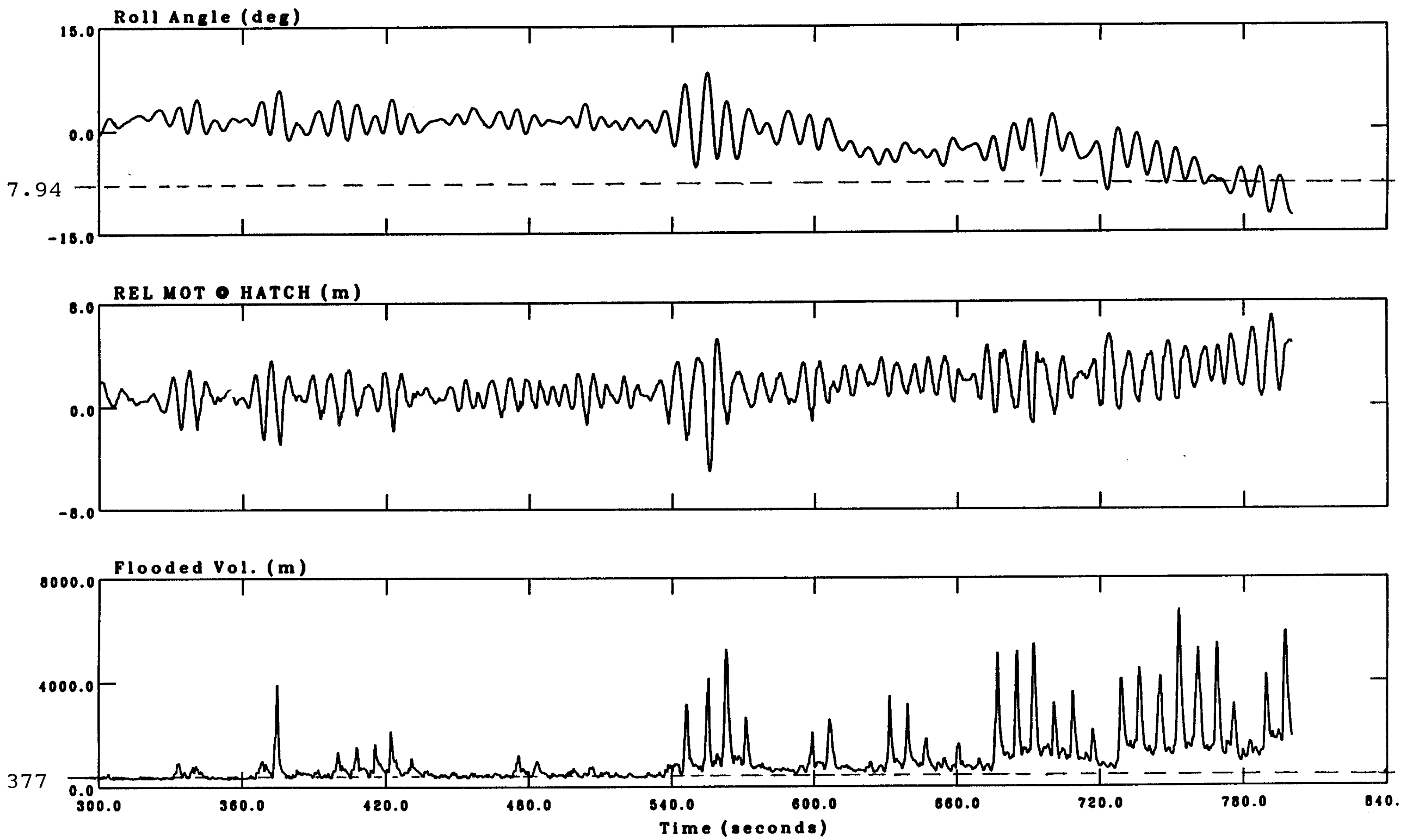


Figure 5.5: Progress to Capsize, Showing Predicted Angle, Volume

5.1.2 Capsize Wave Height

Comparisons of measured and predicted volumes are an indication of the validity of the general methodology, but the most important question is, obviously, whether the method can accurately predict the sea conditions under which capsize can be expected to occur.

The predicted and measured capsize wave heights are compared in **Figures 5.6** and **5.7**, with all the Phase I data shown in 5.6. In the experimental program, there was always a significant spread between the lowest capsize and highest safe wave heights, due to the difficulty of providing a precise sea state. Therefore, the "measured" capsize wave height is shown as the band joining the two test points (where both exist, no "safe" sea states were found for some experimental conditions, and no capsize ones for others).

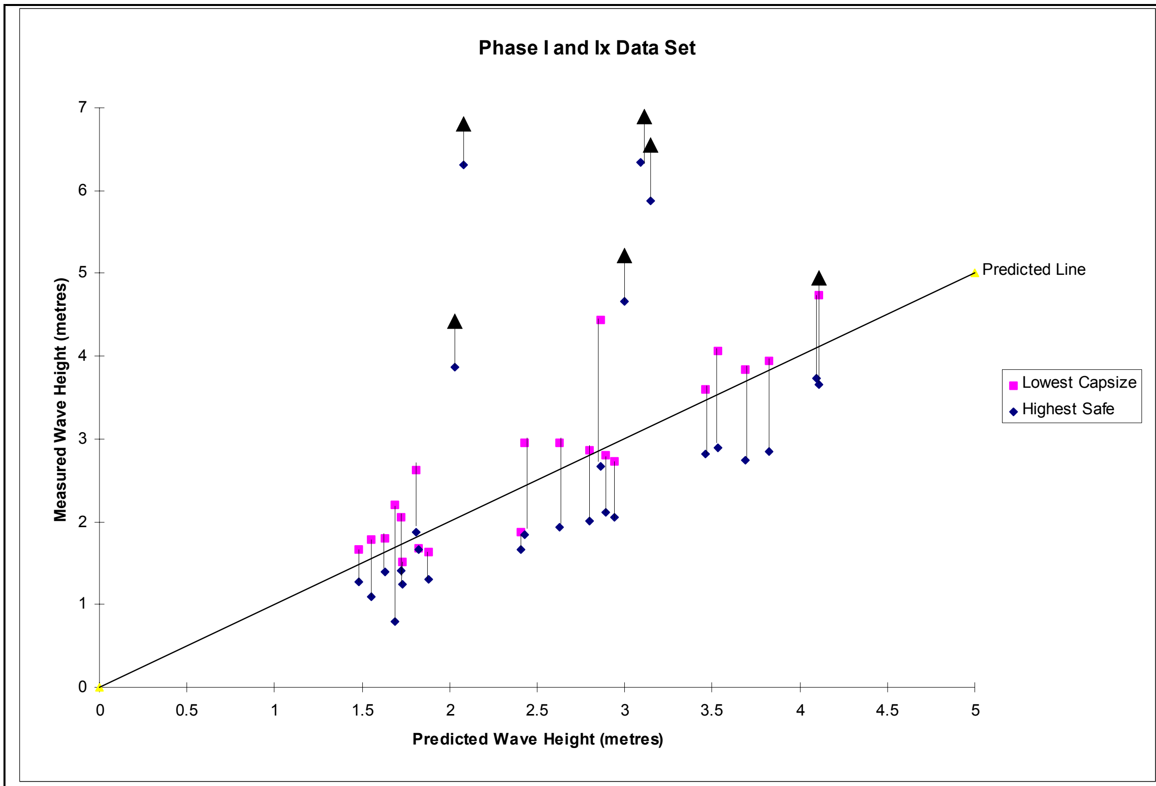


Figure 5.6: Predicted and Measured Capsize Wave Heights, All Phase I Data

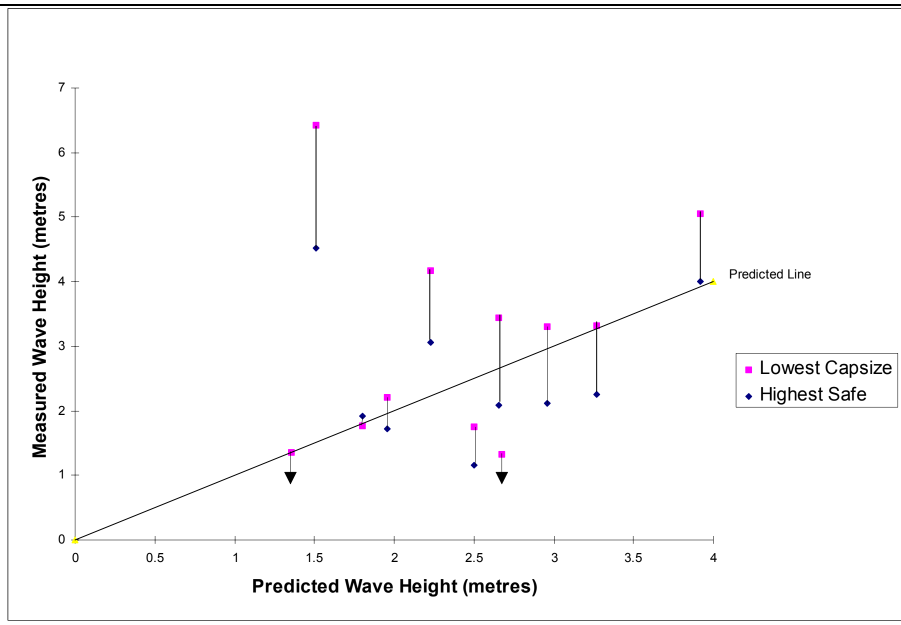


Figure 5.7: Predicted and Measured Capsize Wave Heights, Phase II

As can be seen, almost all the measurements bracket the predicted value for both the models tested. The few exceptions almost all fall into the category of "anomalies" noted earlier and discussed in more detail below. This excellent correspondence between prediction and measurement is the key result of the project, as it demonstrates the SEM's ability to account for a range of variables in a single, simple approach to capsize prediction. The data sets plotted here cover only cases with a centre casing; the set without casing is discussed at 5.4.3.

5.2 Ship Motions

Two of the major uncertainties in the SEM were the validity of the regression equation linking internal water elevation and wave height, and the physical meaning of the "H_{SR}" term in equation 3.4. The capsize prediction capability appears to provide a reasonable validation of the equation, but closer examination of the significant wave height and relative motion data has not provided much clarification of the mechanisms at work.

Figure 5.8 relates the Phase I motion data to the wave height, and shows that there is not a constant relationship between the two. Very similar results were observed in the original research that led to the development of the SEM, as shown in **Figure 5.9** [12]. However, the actual relationship of water on deck to wave height does not seem to track this more complex linkage between wave height and relative motion any more accurately than the simple regression equation does.

The factors modifying the influence of wave height thus remain somewhat unclear, and more extensive simulations and analyses of the phenomenon are likely to be needed to gain further insights. It is possible that the heave and roll components of the relative motion need to be considered separately, and there is a certain amount of evidence from the test series that changes in roll amplitude have relatively little effect on performance (see 5.4.2).

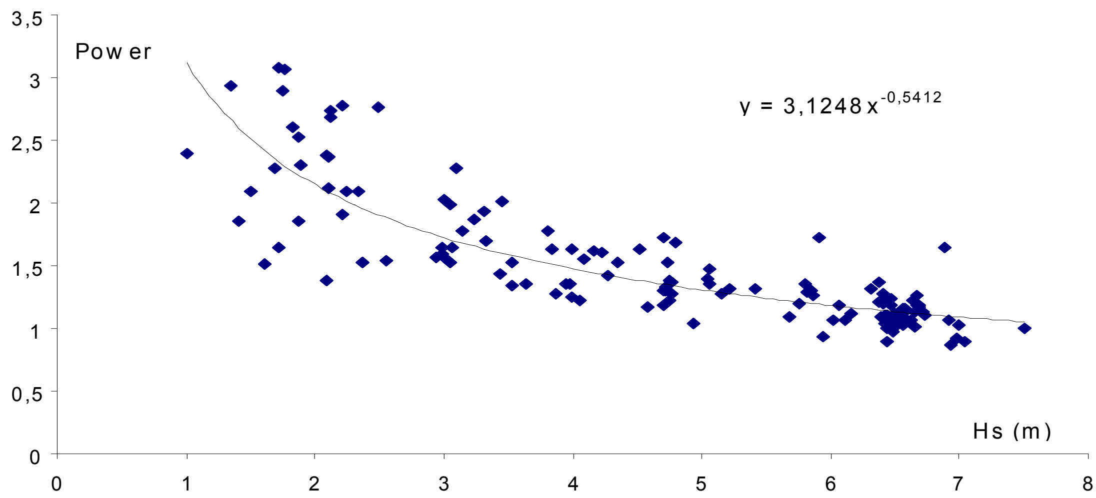


Figure 5.8: Regression on power p between significant height of relative motion $H_{sr} = H_s^{\,p}$ and significant wave height H_s for all data from Phase I. Average value of $p = 1.50$.

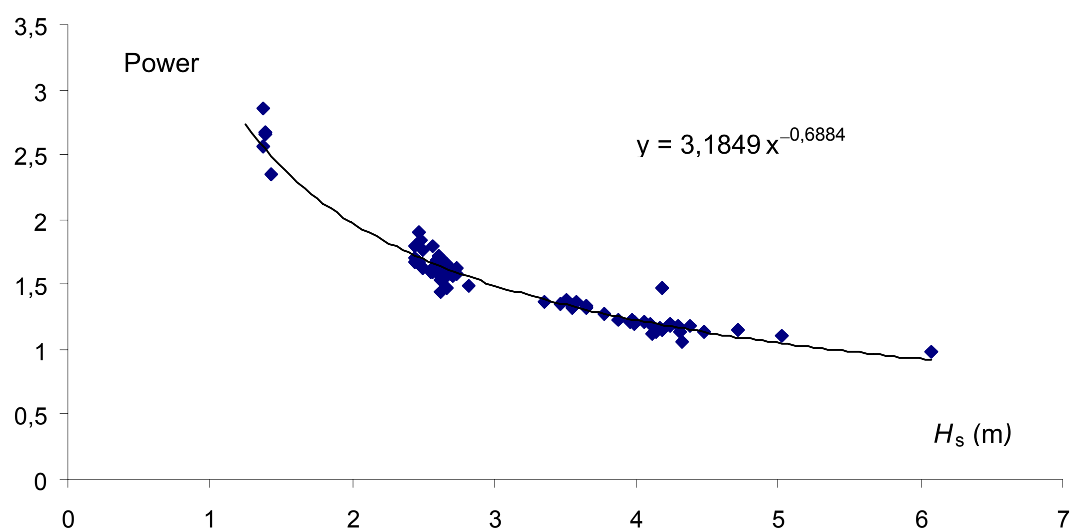


Figure 5.9: Regression on power p between significant height of relative motion $H_{sr} = H_s^{\,p}$ and significant wave height H_s for Strathclyde data. Average value of $p = 1.54$.

5.3 Freeing Port Effects

5.3.1 Experimental Analysis

A considerable amount of effort was made in the earlier phases of the program to investigate freeing port effectiveness in preventing capsize. Several different configurations were used, including both flapped and permanently open ports. The first of these allows more outflow for the same inflow, while the second produces both more inflow and more outflow. Flapped ports will thus generally give greater safety than permanent ports, although there are doubts about how reliable most designs would prove in actual service.

Re-analyses of both approaches were undertaken, with the main focus on flapped ports. The SEM was not originally intended to account for either option, though as discussed below it appeared probable that it could be modified relatively easily to investigate flapped ports.

The approach taken was as for the basic ship. Runs showing the characteristic hesitation before capsize were reanalyzed to find the volumes, etc., just prior to capsize. Expanded data traces were produced to help confirm that representative time intervals had been selected.

Summary data from the freeing ports conditions is provided in Appendix B and volume data is plotted in **Figures 5.10-5.11**, the former being for Phase I extension with (mainly) open ports, while the latter is for Phase II (all flapped). Comparing the results with those for the same basic ship conditions, the following observations can be made:

(a) the volumes of water associated with capsize are essentially the same as those for the basic condition (and show even less scatter from the predicted line);

(b) the wave heights at capsize for flapped freeing ports are much higher, while those for the permanent openings are more ambiguous to interpret.

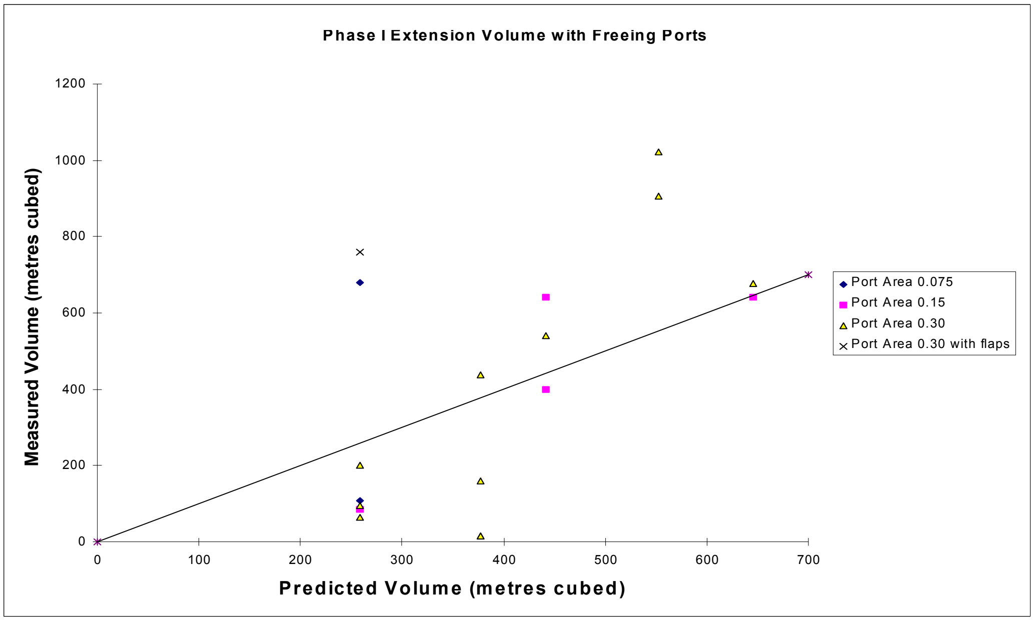


Figure 5.10: Phase I Extension Volume with Ports

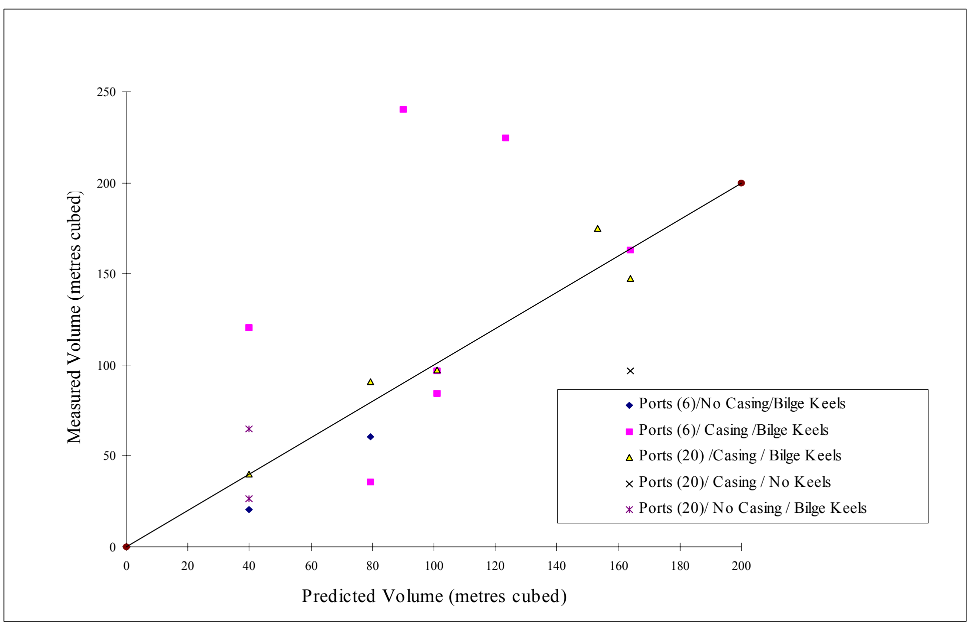


Figure 5.11: Phase II Volume with Ports

5.3.2 Theoretical Treatment

Given the observations noted above, the basic premise of the SEM should continue to hold; i.e., capsize is caused by an accumulation of water on deck that can be correlated to the statically sustainable volume. It can be assumed that the form of equation 3.4 will also be retained, i.e.:

$$h = CH_S^x \qquad (5.1)$$

For different freeing port areas, it can be expected that the coefficient of proportionality C will change. It may also be assumed that H_s to H_{sr} does not change, in which case $H_{sr} = H_s^{1.3}$ would remain the same.

Any changes in the relationship are difficult to quantify just from the experimental results, since the population for any condition is limited and the scatter is relatively large. Therefore, a simplified theoretical method has been developed to model the flow in both directions, using approaches similar to the simple Gaussian method described by Hutchison et al. [9, Appendix B]. A significant difference is that Hutchison's calculations assume a net positive freeboard throughout, whereas the SEM (and model tests) shows that at the critical point, the deck edge is generally immersed.

The model is described in some detail in Annex 1. It leads to the generation of reduction factors for the coefficient of proportionality which depends on the ratio of freeing port area, A, to damage opening width, b, and also to the significant wave height. From this, new (lower) values of water elevation, h, against significant wave height can be derived, as shown in **Figure 5.12**. It should be noted that the ratio A/b has dimension (metres) as it relates an area to a width.

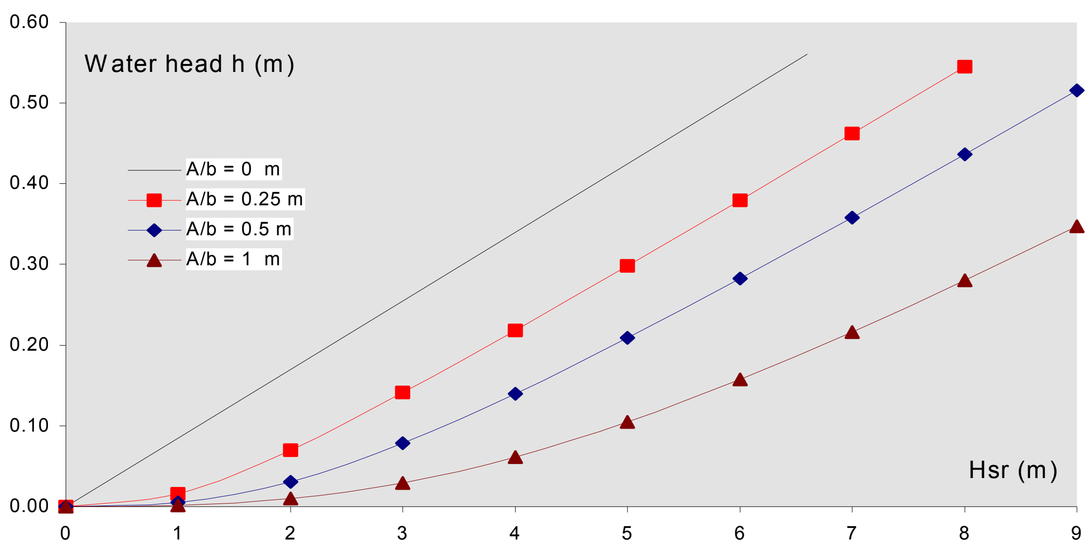


Figure 5.12: Effect of the Ratio *A*/*b* on the Reduction of Water Head

The method is only suited for the analysis of flapped (non-return) ports, which were tested fairly extensively in Phases I and II of the project. A few runs were also made in Phase I extension, but most of that series looked at permanently open ports. Unfortunately, as noted earlier, the detailed Phase II volume data is not reliable, and so it can only be used for capsize wave height comparisons.

5.3.3 Extent of Correlation

Using the approach described above and at Annex 1, it is possible to generate predictions for water on deck and for capsize wave height for experimental conditions with any configuration of freeing ports. The extent to which the predictions can be correlated against the experimental data is limited, but these comparisons do indicate that more work will be needed to provide adequately reliable results, although the results are qualitatively reasonable.

It appears that the theoretical model, so far, considerably overpredicts the effectiveness of freeing ports. Taking as an example, the Phase II runs with the smallest number of ports, the area ratio A/b is 1.32 m. For a typical h value of interest of 0.2 m this would require moving from an Hsr of just over 2 m without ports to one of well over 7 m with ports to produce the same depth on deck; i.e., a change in actual wave height of over 2.5 times. This magnitude of improvement was not observed in the tests.

There are a number of possible reasons for this, some of which are also noted in Annex 1. The simple port discharge calculation has assumed an orifice coefficient for the ports the same as the coefficient for the damage opening, which is unlikely to be accurate. There may also be a need to incorporate a constant head loss, as in Hutchison's method. Both of these effects will significantly reduce the outflow. It is also possible that not only the coefficient of proportionality but also the power law in Equation 3.4 need to be modified. Splitting the *ports* data from the *no ports* data in Figure 5.8 leads to two distinct lines as shown in **Figure 5.13**, the *no ports* case being essentially identical to the Strathclyde results (from Figure 5.9). Unfortunately, time has not permitted these, or other options, to be explored as a part of this work and so further work in this area forms part of the recommendations at Section 7.

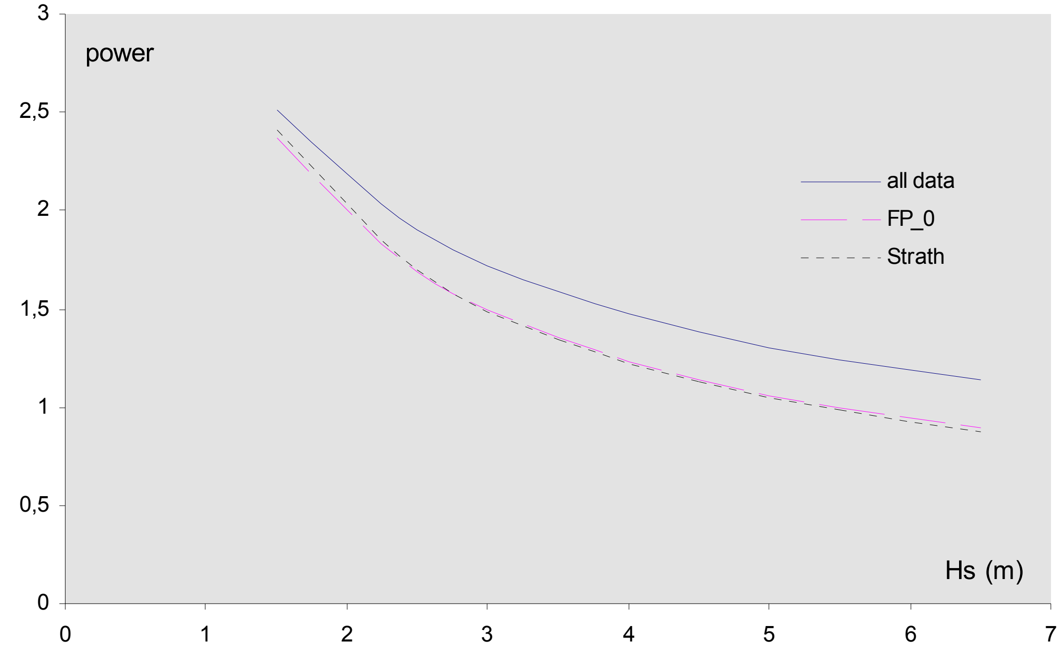


Figure 5.13: Comparison of different power relationship for data with/without freeing ports

5.4 Other Effects

Other variables investigated in the Phase I and II projects which were expected to have some influence on the capsize performance included casing location, presence/absence of bilge keels, and sea spectrum. Points associated with these conditions are identified in Figures 5.1 and 5.2 to illustrate the results discussed below.

5.4.1 Sea Spectrum

The number of runs with a spectrum other than JONSWAP was very limited (only examples were in Phase II), and only the most tentative of conclusions can be drawn from the data. In the two conditions tested with an ITTC spectrum, the model capsized at a higher wave height than with JONSWAP. Unfortunately, no otherwise identical runs were taken with the two spectra, but it appears from the results of the non-capsize runs that the volumes of water which built up were less for any given wave height for the ITTC spectrum.

This might be considered an expected result, as the energy distribution of the two spectra at a given wave height differs significantly, with JONSWAP's being higher at frequencies that produce relative motions of the ship.

As one of the underlying hypotheses of the SEM is that wave energy outside the ship transforms into potential energy raising the internal water level, the regression formula defining this would also be expected to change. However, there is insufficient data to attempt to construct a new relationship at this point. The JONSWAP spectrum is representative of coastal conditions, where most collision damage is likely to occur. Therefore the relationship used in the basic SEM, which is conservative, is considered to be appropriate for most applications.

5.4.2 Bilge Keels

Phase II treated bilge keels fitted as the standard condition for the tests, but included a small number of runs without keels. In the Phase I work, the bilge keels were never fitted. Here again, a small population of results does not allow any very definite conclusions.

There does not appear to be anything in the data to suggest that the build-up of water in the with/without bilge keel conditions followed different relationships, although there was some difference in relative motions (larger without) due to the increase in roll motion [5]. It appears from results of these and other analyses that the SEM is relatively insensitive to the roll component of motion, as is real risk of capsize.

5.4.3 Casings

The SEM does not predict differences in the behaviour of ships with side, centre, or no casings, except insofar as these may affect the damaged hydrostatics. The test programs did not consider side casings, but devoted considerable attention to the influence of centre casing versus no casing. In general, the previous reports indicated that no casing conditions had more survivability than conditions where the casing was present, but there were no obvious ways of quantifying the expected degree of performance improvement.

Figures 5.1 and 5.2 show the differences between casing and no casing results on the standard SEM volume plots. These appear to show that there is relatively little difference between the two configurations when critical volumes are small, but much greater divergences for larger volumes when dynamic effects become significant. The magnitudes of divergence found in the experimental program for “no casings” cases were significantly larger than from the numerical simulations. The reason for this is unclear, though it may be that the treatment of internal waves in the simulation needs further refinement. This “sloshing” is a complex phenomenon, aspects of whose treatment are discussed in [13].

When dynamic effects become important, it is logical that they will be more beneficial when the flow of water across the deck is unobstructed than when the casing retains it on one side. **Figure 5.14** shows the casing effects on capsize wave height (Phase II model only; the Phase I data shows similar trends but is less complete), plotted against changing KG for each of the freeboards. In the conditions with casing present, it can be seen that the SEM and measured data only diverge significantly in some of the highest stability cases (c.f. Fig.5.3). However, when the casing is out, only some of the lowest stability cases behave as expected.

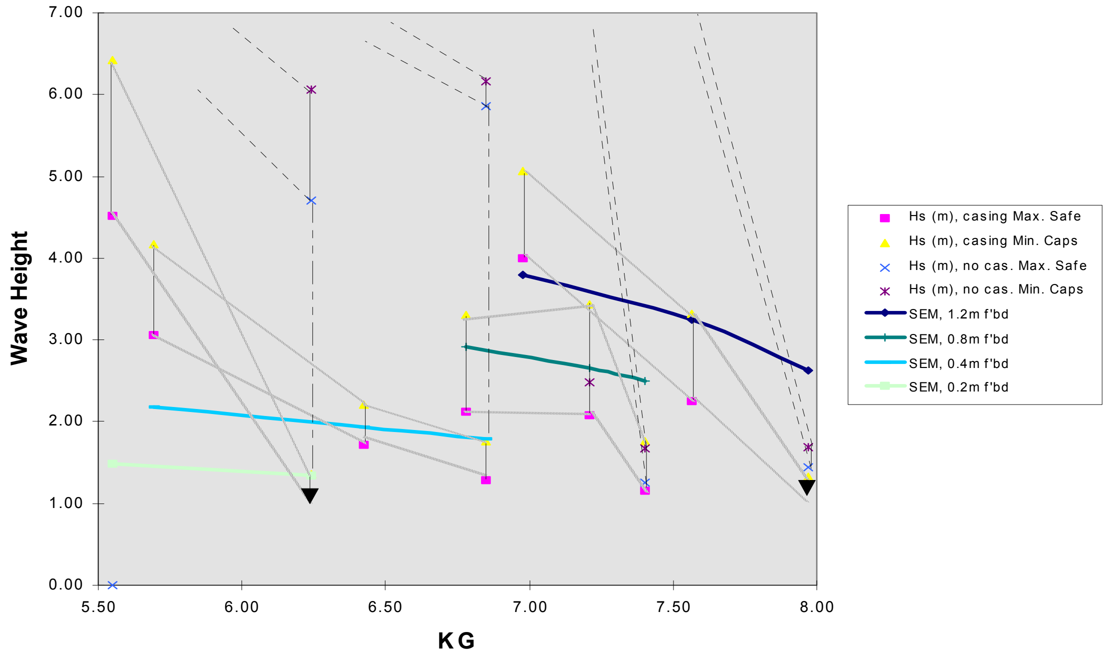


Figure 5.14: Comparisons of behaviour with/without casing (Phase II)

It is questionable whether this type of behaviour would actually have practical meaning, as the flow of water in a real damage event is likely to be restricted by vehicles on deck, etc. This would make it more likely that the response can be treated as quasi-static, and the potential for dynamic enhancements of stability can thus be substantially discounted. In other words, it may be non-conservative to explore ways of accounting for improvements when the centre casing is not present. However, the effect certainly warrants further exploration.

5.5 "Anomalous" Results

Some non-capsize results from all three experimental test series proved impossible to explain convincingly in terms of the SEM theory. In each of Phase I, I ext, and II, several tests with casing present did not capsize despite the presence of water volumes up to four and five times those predicted by the method. These "anomalous" results show up in Figures 5.6 and 5.7 as measured wave heights significantly above the predicted capsize line.

Possibly the most extreme examples are run 51 Phase I, June 1993, [1]), where the average volume on deck was close to 3000 m^3, and run 166 from Phase II [5] where the volume was 930 m^3 . In both cases this volume exceeded the total reserve buoyancy available to the vessels at the initial residual freeboards, and they should therefore have sunk rather than (or in addition to!) capsizing. Including casing and side shell buoyancies in the hydrostatic calculations does not completely explain this behaviour, but it appears from examination of the data traces that the models rapidly flood to a condition where the car deck is completely awash, and then behave as semi-submersibles. Increasing the wave height in these conditions does in some cases eventually produce capsize, presumably due to the more dynamic behaviour of the water on the opening side.

These conditions generally had extremely low values of KG, often well below the car deck, and it is considered improbable that a practical ferry would display similar characteristics. Therefore, no further efforts have been made to fully explain the mechanisms at work in these cases. Their results have been shown in the figures in order to provide a complete picture of the data set, but it would be recommended that they be excluded from any future manipulations of the data in order to avoid skewing the outcomes.

6. RECOMMENDATIONS AND CONCLUSIONS

6.1 Overview of Static Equivalency Method

It is considered that the results of the two experimental phases of this program compare very well with the predictions of the Static Equivalency Method. This demonstration that the SEM works well over a range of ship forms and conditions means that it can provide a superior correlation with ship survivability over the current SOLAS criteria, and over any of the other simplified methods which have been published to date. Its immediate use in a deterministic framework and its potential future use in probabilistic stability analysis are discussed in Section 6.3.

6.2 Outstanding Issues and Concerns

The SEM has some shortcomings, the most significant of which are summarized below. None is considered to invalidate the overall conclusions reached above, but all warrant additional investigation to enhance the current version of the method.

The method does not take full account of dynamic effects, which appear to be of increasing importance when capsizing a ship with good inherent damaged stability and when no casing or other obstructions are present to restrict the flow of water across the deck. The method errs on the side of conservatism, and so the consequences may be acceptable from a regulatory or initial design standpoint. Since the detailed numerical simulations of capsize on which the simplified SEM is based do appear to track all model test data, either model tests or simulations could be used by designers and owners to justify a relaxation in the criteria where appropriate.

The correlation of h and H_s in the model at present is based entirely on a regression of the simulation data, and raises a number of concerns as a result. It is not clear what, if any, physical reality is being represented in the relationship and thus what limits to its validity might be expected. The Phase I and II data is insufficient in extent to justify proposing any alternative relationship, and the expense of repeated model tests makes this an unattractive way of exploring the issue in more detail. However, additional simulations of a range of ship configurations and sizes would be warranted to investigate this issue further; as would extensions to the numerical analyses to allow more direct calculation of the water surface elevation.

The published data on the SEM does not allow the degree of expected scatter in its results to be quantified with great confidence, although some feel for this scatter can be derived from the available experimental results, as discussed earlier. This is a concern for its use in a deterministic analysis of stability, where it is important that the criteria be set near the upper bound of potential capsize behaviour.

The effectiveness of freeing ports cannot yet be quantified using the SEM, although a promising line of approach to this has been identified. This could be carried forward analytically, though it is probable that additional numerical simulations would also be required to bring the work to a conclusion.

Some of the results of the test program have defied explanation by the SEM or by other hypotheses. The enormous volumes of water on deck survived by some low KG cases with casings would produce considerable quasi-static instability, and should in some cases have led to pure foundering due to lack of reserve buoyancy. The dynamic enhancement of stability noted above does not provide an explanation of the phenomenon in these "anomalous" cases. However, the cases in question are considered to have little practical significance (see Section 5.5), and so they are a minor concern for the general use of the SEM.

6.3 Current and Future Use of the Method

6.3.1 Immediate Stability Assessments

The SEM could be used immediately to provide an assessment of the damaged stability of any RO-RO vessel of conventional form and dimensions. Since it matches the vessel characteristics against capsize significant wave height, the wave climate for the route needs to be known, and an appropriate limiting value needs to be selected. This could be done using two approaches to ensure that an appropriate level of safety is achieved.

The first approach could be regarded as a "direct method", which would determine the appropriate height based on physical considerations. The predicted limiting wave height for capsize is a mean value, with considerable scatter around it. As discussed earlier, the level of scatter is difficult to quantify from the small number of data points available (and the experimental uncertainty involved in these). It is suggested that, based on the test data, a 25% reduction in allowable significant wave height would be an appropriate safety factor, if combined with a suitably conservative definition of expected wave height, as discussed below.

The definition of expected wave height must be done semi-probabilistically, in that higher wave heights are associated with longer return periods. Using a one-year return period would be expected to give a quite conservative result, given that the joint probability of a collision and a worst storm condition can be considered to be very low.

Thus, a direct criterion for the acceptability of a vessel on a given service could be to check that capsize is not predicted by the SEM under a significant wave height of 75% of the annual expected value.

Since it could be argued that several of the steps above are not fully justifiable without much additional analysis, the second approach would be to compare the predicted performance of a ship, presumably one having difficulties complying with the SOLAS 90, or SOLAS 90+50 criteria, against other vessels assessed as being satisfactory.

Here it would only be necessary to assess all the vessels against their operational wave climates. If, on average, the “successful” designs could withstand (say) 80% of the 20 year maximum wave height, then this could provide a basis for the evaluation of the questionable design. Obviously, this second approach requires the analysis of a range of ships using the SEM to establish an appropriate evaluation criterion.

It is recommended that Transport Canada undertake an analysis of this sort using a representative range of designs in operation around Canada. This would permit a rational assessment of the adequacy of any vessels hitherto classed as unsatisfactory or marginal, and would also assist in the calibration of future, more probabilistic criteria, as described below.

6.3.2 Future Safety Criteria

The general trend in ship safety assessment is to move towards more probabilistic methods, which can provide a more rationale overall assessment of performance than current deterministic approaches. For stability analysis, a fully probabilistic method would require calculation of the joint probabilities of collision and wave height, together with collision location and penetration extent. The probabilities of surviving each combination of circumstances would then be combined into an overall survivability index.

The SEM can provide a calculation engine for the assessment of stability under any damage condition where the vehicle deck may become flooded, irrespective of location along the hull - this is one of its great strengths. However, the other necessary components of a probabilistic method need to have a reasonable statistical basis and, fortunately, there are a very limited number of RO-RO vessel accidents to draw on. Therefore, it will likely be necessary to calibrate any proposals against what has traditionally been considered as good practice.

The analyses recommended in 6.3.1 will provide a step towards this, though much additional work (on an international basis) will be needed before a truly probabilistic approach can be taken. It is recommended that Transport Canada continue to support international efforts along these lines. The wide variety of ferry operations around our coasts makes a uniform (and quite crude) set of criteria, such as that offered by SOLAS, inappropriate to the need to ensure adequate and reasonably consistent levels of safety for the travelling public as a whole.

REFERENCES

[1a,b] "Flooding Protection of RO-RO Ferries, Phase I", (Volumes 1 and 2), TP 12310E, March 1995.

[2] "RO-RO Ferry Safety: Report of the Panel of Experts to the Steering Committee", IMO MSC 65/4, 31 March 1995.

[3a,b] "Flooding Protection of RO-RO Ferries, Phase I Extension", (Volumes 1 and 2), TP 12581E, October 1995.

[4] "Flooding Protection of RO-RO Ferries, Phase II" TP 12991E, March 1997.

[5] "RO-RO Ferry Passenger Vessel Capsize Safety Investigation: Physical Model Experiments, Phase II", W.D. Molyneux and D. Cumming, IMD TR-1997-01, April 1997.

[6] "Analysis of Experiments on RO-RO Damage Stability", Pavlowski et al., IMD TR-1994-27, October 1994.

[7] "Safety Initiatives from the SNAME Ad-Hoc RO-RO Safety Panel", B. Hutchison et al., RO-RO 96 Conference, Lubeck, May 1996.

[8] "A Technique to Predict the Capsize of a Damaged RO-RO Ferry", J. Spouge, Symposium on RO-RO Ships' Survivability, RINA, London, 1994.

[9] "Time Domain Simulation and Probability Domain Integrals for Water on Deck Accumulation"; Hutchison et al., Cybernautics 1995, SNAME.

[10] "Damage Survivability of Passenger Ships"; Vassalos; Trans SNAME, 1994.

[11] "Dynamic Stability Assessment of Damaged Passenger/RO-RO Ships and Proposal of Rational Stability Criteria"; Vassalos et al, Marine Technology, October 1997.

[12] Unpublished note by Dr. Pawlowski, Gdansk Technical University, March 1998.

[13] "Experimental Study on Wave Motion Inside a Damaged Ship Compartment", Z.J. Huang and C.C. Hsiung, Ocean Engineering International, 1997.

ANNEX 1 - FREEING PORT EFFECTS

When results with flapped freeing ports present are compared with those for the same basic ship conditions, the following observations can be made:

a) the volumes of water associated with capsize are essentially the same as those for the basic condition;
b) the wave heights for flapped freeing ports are much higher, while those for the permanent openings are more ambiguous to interpret.

Given the observations noted above, the most obvious change to the formulations in the SEM when flapped freeing ports are activated will be in the ratio h to H_{sr}. It can be assumed that H_s to H_{sr} does not change, in which case $H_{sr} = H_s^{1.3}$ remains the same.

For different freeing port areas, the coefficient of proportionality will change. The relationship is difficult to establish just from the experimental results, since the population for any condition is limited and the scatter is relatively large. Therefore, a simplified theoretical method has been developed to model the flow in both directions, using approaches similar to the simple Gaussian method described by Hutchison et.al. [9]. A significant difference is that Hutchison's calculations assume a net positive freeboard throughout, whereas the SEM (and model tests) shows that at the critical point the deck edge is generally immersed.

At the critical stability limit for the ship, the volume of water on deck would be constant, which means that the mean overall flow rate through all openings would then be zero. Hence, mean inflow and outflow of water from the deck are in balance for the ship at this limiting condition, and:

$$\overline{Q}_{in} = \overline{Q}_{out} + \overline{Q}_{fp} \qquad (A.1)$$

where the mean inflow and outflow rates denote flow rates through the damaged opening, and $\overline{Q}_{fp}$ is outflow rate through freeing ports. The two first quantities can be given by the following equations:

$$\overline{Q}_{in} = \tfrac{2}{3} c \sqrt{2g}\, b \sigma^{3/2}\, q_{in} \qquad (A.2)$$

$$\overline{Q}_{out} = \tfrac{2}{3} c \sqrt{2g}\, b \sigma^{3/2}\, q_{out} \qquad (A.3)$$

where: c = correction coefficient for non-stationary flow and resistance,
b = the width of the damage opening,
g = acceleration due to gravity, and
$\sigma = H_{sr}/4$ is the standard deviation (dispersion) of the modified significant wave height (relative motion) at the damage opening, ζ.

The non-dimensional inflow and outflow rate q_{in} and q_{out} are given by the equations:

$$q_{in} = \int_{t_1}^{\infty} \left(t - t_1\right)^{3/2} f(t)\,dt \qquad \text{(A.4)}$$

$$q_{out} = \int_{t_o}^{t_1} \left(t_1 - t\right)^{3/2} f(t)\,dt + \tau^{3/2} F\left(t = t_o\right) \qquad \text{(A.5)}$$

where: $f(t)$ and $F(t)$ are the standard normal density function and cumulative distribution of the nondimensional random variable $t = \zeta/\sigma$,

$t_o = f/\sigma$ is the nondimensional freeboard at opening,

$t_1 = h/\sigma$ is the nondimensional height of the level of water on deck above sea level (water head), and

$\tau = d/\sigma = t_1 - t_o$ is the nondimensional depth of water on deck at opening.

As can be seen from the form of the equations, $q_{in} = q_{in}(t_1)$ and $q_{out} = q_{out}(t_o, t_1)$ and all quantities have to be calculated numerically (in this case using the Gaussian model).

Equations A.2 and A.3 can be written in a abbreviated way:

$$\overline{Q}_{in} = Q_o\, q_{in} \qquad \text{(A2a \& A2b)}$$

$$\overline{Q}_{out} = Q_o\, q_{out}$$

where Q_o is a constant, given by

$$Q_o = \tfrac{2}{3} c \sqrt{2g}\; b \sigma^{3/2} \qquad \text{(A.6)}$$

corresponding to flow rate through a weir of breadth b and depth of water σ at the weir.

For non-return freeing ports, it has been assumed in this simplified analysis that they are entirely immersed at the critical position. In such a case, the flow through freeing ports occurs under water head h whose flow rate is given by

$$\overline{Q}_{fp} = c\, A \sqrt{2gh} \qquad \text{(A.7)}$$

where A is active area of freeing ports. With this assumption, Eq. A.1 when divided throughout by the constant Q_o becomes:

$$q_{in}\left(t_1\right) = q_{out}\left(t_o, t_1\right) + 6 \frac{A}{bH_{sr}} \sqrt{t_1} \qquad \text{(A.8)}$$

In the basic static equivalency method, for $A = 0$ (i.e., without freeing ports), t_1 (= h/σ) is 4*0.085 = 0.34. When t_1 = 0.34 then Eq. A.8 yields for τ (= d/σ) a value 0.6555. Assuming that the ratio t_1/τ, like the h/d ratio, is unaffected by freeing ports:

$$\tau = 1.928045\, t_1 \qquad \text{(A.9)}$$

With this assumption, Eq. A.8 yields values of t_1 (nondimensional water head $h/\sigma = 4h/H_{sr}$), which depend on the parameter A/bH_{sr} (freeing port area ratio). Knowing the asymptotic value of t_1 provides a relationship between water head and the modified significant wave height, as follows

$$h = t_1 \sigma = c_{red}\, 0.085 H_{sr} \qquad \text{(A.10)}$$

where: $c_{red} = t_1/0.34$ is a reduction factor for the coefficient of proportionality linking h and H_{sr},

Values for c_{red} derived from calculations are presented in **Table 1** and **Figure 1**. For use in further analyses, an approximation for this factor can be represented by a polynomial of the sixth degree, shown in the figure. It can be seen c_{red} initially reduces rapidly as the freeing port area ratio A/bH_{sr} increases, but beyond a value of about 0.25 little additional benefit is gained.

It should be noted that, in a more complete analysis, the area ratio should include only those freeing ports that will be effective. This may include those at the ends of the ship, for tapered forms; and if the method were used to investigate trimmed damage conditions, the trimmed internal waterline should be used to define those ports that are active.

As can be seen, the reduction factor c_{red} is itself a function of modified significant wave height, H_{sr}. Hence, Eq. A.10 is in fact a nonlinear function of H_{sr}, as shown in **Figure 2** and **Table 2**, influenced by the dimensional parameter A/b. The effect of the reduction factor can be considerable. Figure 2 illustrates the observed effect that freeing ports prevent a build-up of water on deck. Thus, to achieve the same water head on deck for the critical condition, a much higher sea state may be needed.

Table 1: Effect of freeing port area ratio on the reduction of water head

A/bH_{sr}	c_{red}
0	1
0.0625	0.6433
0.125	0.4107
0.25	0.1813
0.375	0.0943
0.5	0.0563
0.625	0.0370
0.75	0.0261
0.875	0.0193
1	0.0149

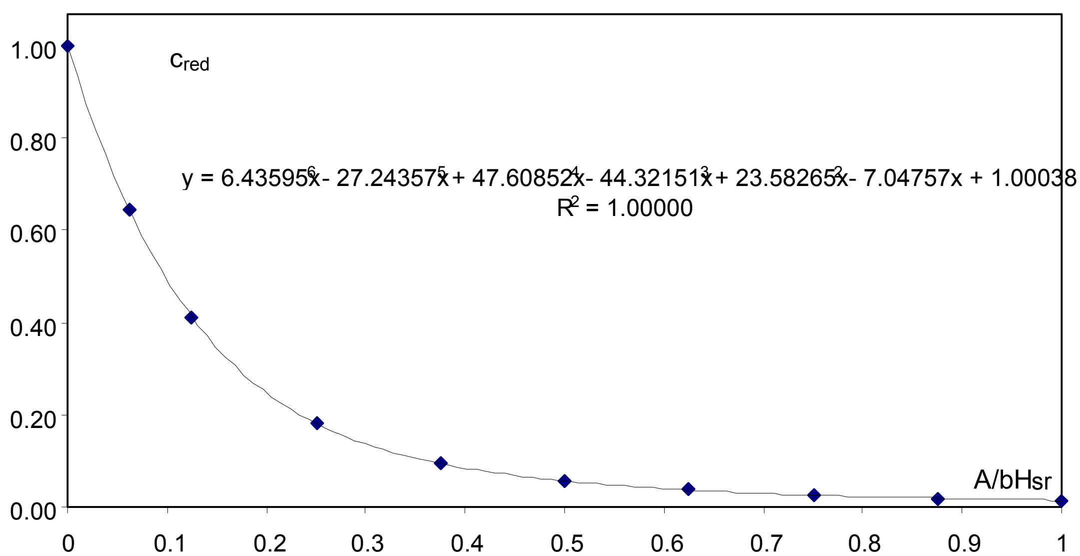


Figure 1: Effect of freeing port area ratio on the reduction of water head

Table 2: Effect of the ratio *A*/*b* on the reduction of water head.

	A/*b* =	1 m	2 m	0.5 m	0.25 m
H_{sr}	A/bH_{sr}	*h*	*h*	*h*	*h*
0		0	0	0	0
1	1	0.001	0.000	0.005	0.015
2	0.5	0.010	0.003	0.031	0.070
3	0.33333	0.029	0.008	0.079	0.141
4	0.25	0.061	0.019	0.140	0.218
5	0.2	0.105	0.036	0.209	0.298
6	0.16667	0.158	0.058	0.282	0.380
7	0.14286	0.217	0.087	0.358	0.462
8	0.125	0.280	0.123	0.436	0.545
9	0.11111	0.348	0.164	0.516	0.629

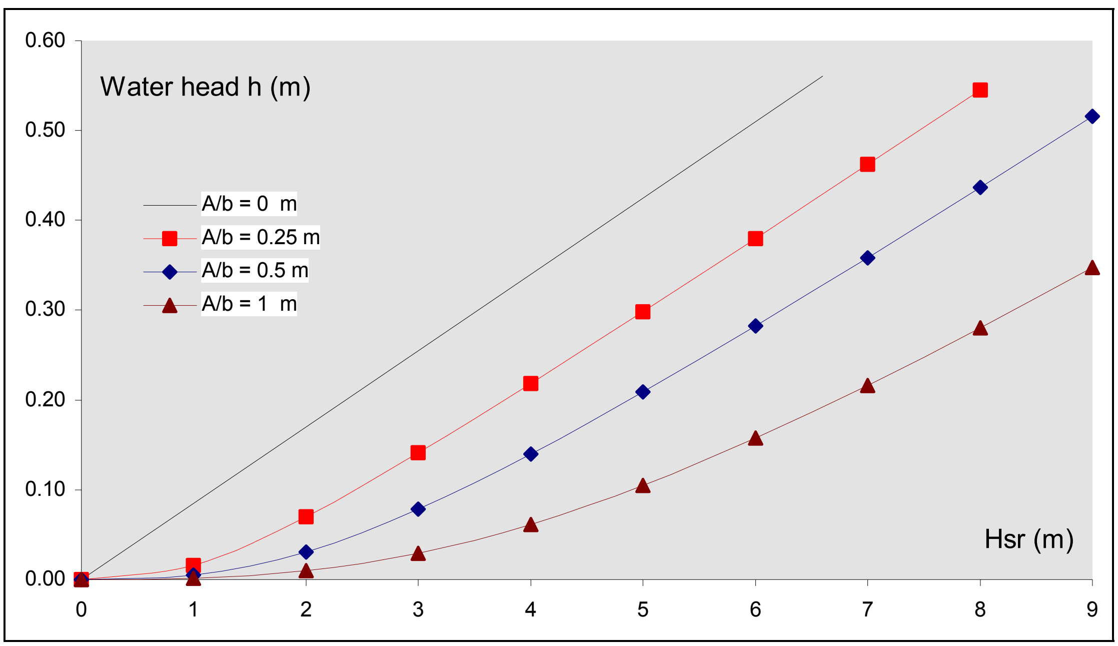


Figure 2: Effect of the ratio *A*/*b* on the reduction of water head

Notes:

Phase I - opening 7.8 m, fp 6.6, 13.2, 27.6, 51.6 m^2 gives A/b of 0.85, 1.69, 3.54, 6.62
Phase II - 5.44 m opening; 7.2 and 24 m^2 fp gives A/b of 1.32, 4.41

APPENDIX A - SEM STABILITY CALCULATION SUMMARY

GLOSSARY

KG actual	- Actual height of centre of gravity during test (m)
RF	- Residual freeboard (m)
Vanish Stability	- Angle of vanishing stability of main hull (below vehicle deck)
Deck Edge Immersion	- Angle of immersion of vehicle deck adge
GZ_{MAX}	- Maximum righting arm of main hull
$Theta_{GZmax}$	- Angle at which GZ is maximum (critical angle)
V_{CRIT}	- Critical volume of water on deck to cause capsize
Parallel sinkage	- Sinkage from initial damaged condition due to additional water
Weight of Water	- Critical weight of water on deck to cause capsize
Tank TCG	- Transverse centre of gravity of water on deck at critical angle
Tank VCG	- Vertical centre of gravity of water on deck at critical angle
Angle of loll	- Heel due to water on deck (cross check value)
f+h	- Total depth of water (at deck edge)
f	- Submergence of deck edge below mean sea level
h	- Elevation of water on deck above mean sea level
Hs	- Predicted capsize significant wave height (m)

Table A.1 - Phase I Model Summary

KG Actual (m)	RF (m)	Vanish Stability of Bare Hull	Angle of Dk Edge Immers	GZ_{MAX} of Bare Hull	$Theta_{GZMAX}$ of Bare Hull	V_{CRIT}	Parallel Sinkage (cm)	Weight of Water in Tank (tonnes)	Tank TCG (m)	Tank VCG (m)	Angle of Loll	f+h (m)	f (m)	h (m)	Hs (m)
7.809	0.50	15.06	2.19	0.422	4.86	1440.00	53.10	1476.0	8.315	8.416	4.86	1.238	1.018	0.220	2.078
11.189	0.50	6.69	2.19	0.191	3.27	386.34	18.90	396.0	10.115	8.177	3.27	0.528	0.360	0.168	1.689
10.890	0.50	7.12	2.19	0.208	3.36	437.07	21.40	448.0	9.963	8.190	3.36	0.569	0.396	0.173	1.727
11.409	0.50	6.41	2.19	0.179	3.21	352.20	17.20	361.0	10.227	8.167	3.21	0.499	0.336	0.163	1.650
9.720	0.50	9.17	2.19	0.281	3.78	690.73	33.70	708.0	9.357	8.254	3.78	0.759	0.566	0.193	1.879
10.306	0.50	8.06	2.19	0.243	3.56	551.22	26.90	565.0	9.668	8.220	3.56	0.658	0.474	0.184	1.811
12.122	0.50	5.56	2.19	0.140	3.00	253.66	12.40	260.0	10.588	8.137	3.00	0.410	0.260	0.150	1.548
11.553	0.50	6.22	2.19	0.171	3.17	329.76	16.10	338.0	10.305	8.161	3.17	0.480	0.320	0.160	1.627
12.509	0.50	5.14	2.19	0.121	2.90	204.88	10.00	210.0	10.811	8.121	2.90	0.363	0.222	0.141	1.476
9.602	1.00	15.50	4.49	0.467	6.74	961.95	42.60	986.0	9.815	8.401	6.74	1.186	0.813	0.373	3.119
9.755	1.00	15.04	4.49	0.449	6.64	904.39	40.10	927.0	9.893	8.386	6.64	1.141	0.773	0.368	3.087
10.031	1.00	14.18	4.49	0.418	6.46	806.83	35.80	827.0	10.033	8.359	6.46	1.064	0.704	0.360	3.035
12.431	1.00	8.70	4.49	0.174	5.30	244.88	11.00	251.0	11.274	8.179	5.30	0.533	0.267	0.266	2.405
12.463	1.00	8.64	4.49	0.171	5.28	239.22	10.80	245.2	11.293	8.177	5.28	0.526	0.260	0.266	2.405
10.980	1.00	11.64	4.49	0.315	5.88	525.85	23.50	539.0	10.518	8.277	5.88	0.822	0.489	0.333	2.859
10.832	1.00	12.00	4.49	0.331	5.95	561.95	25.10	576.0	10.445	8.288	5.95	0.854	0.516	0.338	2.892
10.952	1.00	11.71	4.49	0.318	5.89	532.68	23.80	546.0	10.503	8.279	5.89	0.828	0.493	0.335	2.872
11.746	1.00	10.00	4.49	0.239	5.59	364.88	16.50	374.0	10.905	8.225	5.59	0.669	0.371	0.298	2.625
9.411	1.00	16.23	4.49	0.489	6.86	1034.15	45.70	1060.0	9.721	8.419	6.86	1.239	0.861	0.378	3.152
10.499	1.00	12.85	4.49	0.366	6.16	657.56	29.30	674.0	10.271	8.317	6.16	0.938	0.592	0.346	2.944
11.621	1.50	14.07	6.87	0.319	8.11	452.68	18.80	464.0	11.087	8.302	8.11	0.887	0.426	0.461	3.671
12.008	1.50	13.00	6.87	0.266	7.91	360.00	14.90	369.0	11.292	8.266	7.91	0.782	0.351	0.431	3.486
11.573	1.50	14.20	6.87	0.326	8.14	465.37	19.30	477.0	11.062	8.307	8.14	0.900	0.436	0.464	3.690
10.355	1.50	18.11	6.87	0.507	9	853.66	34.90	875.0	10.446	8.437	9.00	1.279	0.746	0.533	4.105
12.080	1.50	12.82	6.87	0.256	7.86	342.93	14.20	351.5	11.332	8.259	7.86	0.762	0.335	0.427	3.461

Table A.2 - Phase I Extension Model Summary

KG Actual (m)	RF (m)	Vanish Stability of Bare Hull	Angle of Dk Edge Immers	GZ_{MAX} of Bare Hull	$Theta_{GZMAX}$ of Bare Hull	V_{CRIT}	Parallel Sinkage (cm)	Weight of Water in Tank (tonnes)	Tank TCG (m)	Tank VCG (m)	Angle of Loll	f+h (m)	f (m)	h (m)	Hs (m)
12.360	2	15.37	9.34	0.246	10.2	310	11.80	318.00	11.644	8.281	10.20	0.817	0.285	0.532	4.099
11.251	1.50	15.14	6.87	0.372	8.34	551	22.60	565.00	10.897	8.338	8.34	0.994	0.508	0.486	3.824
11.929	1.50	13.22	6.87	0.276	7.94	377	15.60	386.00	11.252	8.272	7.93	0.801	0.363	0.438	3.530
9.999	1.00	14.26	4.49	0.421	6.48	817	36.30	837.00	10.019	8.362	6.48	1.072	0.712	0.36	3.035
10.957	1.00	11.70	4.49	0.318	6.03	552	24.60	566.00	10.487	8.287	6.03	0.852	0.528	0.324	2.799
12.353	1.00	8.83	4.49	0.181	5.34	258	11.60	264.00	11.232	8.184	5.34	0.549	0.279	0.2696	2.430
7.773	0.5	15.23	2.22	0.425	5.2	1579	56.40	1618.00	8.256	8.450	5.20	1.340	1.127	0.213	2.027
9.969	0.5	8.67	2.22	0.264	3.75	646	31.80	662.00	9.475	8.245	3.75	0.730	0.544	0.186	1.826
10.869	0.5	7.15	2.22	0.21	3.37	441	21.50	452.00	9.953	8.192	3.37	0.573	0.4	0.173	1.727

Table A.3 - Phase II Model Summary

KG Actual (m)	RF (m)	Vanish Stability of Bare Hull	Angle of Dk Edge Immers	GZ_{MAX} of Bare Hull	$Theta_{GZMAX}$ of Bare Hull	V_{CRIT}	Parallel Sinkage (cm)	Weight of Water in Tank (tonnes)	Tank TCG (m)	Tank VCG (m)	Angle of Loll of Hull with S.S	f+h(m)	f (m)	h (m)	Hs (m)
5.55	0.2	10.12	1.3	0.128	3.26	217.6	17.60	223.0	5.042	6.897	3.26	0.618	0.475	0.143	1.492
5.694	0.2	9.23	1.3	0.12	3.1	192.2	15.70	197.0	5.172	6.882	3.10	0.569	0.430	0.139	1.460
6.241	0.2	6.75	1.3	0.093	2.62	123.4	10.60	126.5	5.623	6.837	2.62	0.426	0.301	0.125	1.341
5.694	0.40	15.02	2.53	0.193	5.43	282.4	27.60	289.5	5.470	6.990	5.43	0.917	0.682	0.235	2.186
6.426	0.40	10.46	2.53	0.137	4.47	153.2	15.70	157.0	6.084	6.900	4.47	0.629	0.428	0.201	1.939
6.85	0.40	8.24	2.53	0.101	3.98	101.0	10.30	103.5	6.476	6.856	4.00	0.490	0.309	0.181	1.789
6.78	0.80	14.90	5.05	0.177	7.43	163.9	16.10	168.0	6.636	6.970	7.43	0.851	0.509	0.342	2.918
7.21	0.80	12.24	5.05	0.124	6.75	101.0	9.90	103.5	7.032	6.908	6.75	0.653	0.351	0.302	2.652
7.40	0.80	11.17	5.05	0.102	6.53	79.3	7.80	81.3	7.217	6.884	6.53	0.578	0.299	0.279	2.495
6.98	1.2	19.85	7.6	0.226	10.43	188.3	17.40	193.0	6.856	7.046	10.43	1.079	0.598	0.481	3.793
7.57	1.2	15.18	7.6	0.125	9.34	90.2	8.40	92.5	7.415	6.937	9.35	0.738	0.346	0.392	3.241
7.97	1.2	12.33	7.6	0.062	8.67	40.0	3.70	41.0	7.905	6.861	8.69	0.499	0.200	0.299	2.631

APPENDIX B - PREDICTED AND MEASURED DATA SUMMARIES

GLOSSARY

Test Data

KG, KG act	-	Actual height of centre of gravity during test (m)
Freebd	-	Residual freeboard (m)
Hs	-	Significant wave height during test
T1, T2	-	Start and finish of averaging interval for reanalyses (see data traces)
Mean Roll	-	Mean heel (roll) over averaging interval (degrees)
Relmo SD	-	Mean relative motion at damage opening (m)
Mean Volume	-	Mean measured volume on deck over averaging interval (m^3)

Static Equivalency Method Predictions

Crit. Angle	-	Angle of GZ_{max} (degrees)
Crit. Vol.	-	Predicted volume to cause capsize (m^3)
SEM h	-	Elevation of water on deck above mean sea level (m)
SEM Hs	-	Predicted capsize significant wave height (m)

Table B.1 - Phase I Summary Results

Test Data											SEM Predictions			
Run_#	Date	KG_act	Freebd	casing	freeports	Hs_act	capsize	Volume (m^3)	RelMo (m)	Mean Roll	Crit. Angle	Crit. Vol	SEM h (m)	Hs (m)
18	jun	11.41	0.5	0	0	1.9	yes	*2326.45*	1.02	-11.84	3.21	352.20	0.16	1.65
21	jun	11.41	0.5	0	4	1.9	yes	*1902.06*	0.4875	-9.704	3.21	352.20	0.16	1.65
55	jun	10.83	1	1	3	4.8	no	*5274.09*	1.5372	-9.792	5.95	561.95	0.34	2.89
8	dec	10.89	0.5	1	0	1.5	yes	*1070.15*	0.749	-4.199	3.36	437.07	0.17	1.73
25	dec	9.72	0.5	1	0	1.9	yes	*2216.59*	1.000	-4.027	3.78	690.73	0.19	1.88
26	dec	9.72	0.5	1	0	1.6	yes	*2312.76*	0.735	-5.568	3.78	690.73	0.19	1.88
34	dec	9.72	0.5	1	3	2.8	yes	*3159.6*	1.287	-7.256	3.78	690.73	0.19	1.88
35	dec	9.72	0.5	1	3	1.9	no	*860.42*	1.14	-2.427	3.78	690.73	0.19	1.88
40	dec	9.72	0.5	1	2	1.9	yes	*2289.49*	0.944	-4.94	3.78	690.73	0.19	1.88
49	dec	10.83	1	1	0	2.8	yes	*2206.24*	1.202	-8.706	5.95	561.95	0.34	2.89
50	dec	10.83	1	1	0	2.1	no	*165.63*	0.677	-3.859	5.95	561.95	0.34	2.89
52	dec	10.83	1	1	4	4	no	*92.82*	1.351	-1.351	5.95	561.95	0.34	2.89
59	dec	10.83	1	1	2	3.7	yes	*2403.05*	1.223	-10.17	5.95	561.95	0.34	2.89
81	dec	12.43	1	1	0	1.9	yes	*924.53*	0.5887	-6.219	5.30	244.88	0.27	2.41
149	dec	12.01	1.5	1	0	4.5	yes	*618.872*	1.165	-6.218	7.91	360.00	0.43	3.49

Note: Volume data from Phase I is not accurate

Table B.2 - Phase I Ext Summary Results

Test Data																SEM Predictions			
Fig #	KG_ nominal	KG_ actual	GM_flood	Freebd	F.Port A	Covers	Casing	Hs	Result	Nominal_ Hs	T1	T2	MEAN ROLL	RELMO SD	MEAN VOL	**Crit. Angle**	**Crit. Vol**	**SEM h (m)**	**Hs (m)**
25	12.40	12.35	2.17	1.00	0.00	closed	out	2.56	capsize	3.00	370	650	-5.62	1.06	433	5.34	258	0.267	2.41
55	10.83	10.96	3.56	1.00	0.00	closed	in	2.86	capsize	3.00	600	1125	-3.80	1.44	866	6.03	552	0.324	2.80
69	11.00	10.87	4.16	0.50	0.00	closed	in	2.05	capsize	1.50	450	1250	-1.30	0.93	692	3.37	441	0.173	1.73
89	9.77	9.97	5.06	0.50	0.00	closed	in	1.69	capsize	2.00	240	540	-2.70	1.05	747	3.75	646	0.186	1.83
114	11.30	11.25	2.79	1.50	0.00	closed	in	3.94	capsize	4.00	650	800	-6.01	2.04	733	8.34	551	0.486	3.82
132	12.00	11.93	2.11	1.50	0.00	closed	in	4.06	capsize	4.00	300	600	1.31	1.21	645	7.94	377	0.438	3.53
Freeing Port series																			
3	12.4	12.35	2.17	1.00	0.075	open	in	2.69	capsize	3.00	250	390	3.56	1.16	681	5.34	258	0.267	2.41
4	12.4	12.35	2.17	1.00	0.075	open	in	1.91	capsize	2.00	1000	1125	-11.59	0.97	109	5.34	258	0.267	2.41
6	12.4	12.35	2.17	1.00	0.15	open	in	1.62	capsize	1.50	400	550	-6.00	0.92	84	5.34	258	0.267	2.41
78	11	10.87	4.16	0.50	0.15	open	in	1.92	capsize	1.50	240	500	-4.61	0.75	640	3.37	441	0.173	1.73
79	11	10.87	4.16	0.50	0.15	open	in	1.48	capsize	1.00	500	1500	-4.07	0.55	399	3.37	441	0.173	1.73
90	9.765	9.97	5.06	0.50	0.15	open	in	1.57	capsize	1.50	250	1550	-3.47	0.69	641	3.75	646	0.186	1.83
11	12.4	12.35	2.17	1.00	0.3	flap	in	4.58	capsize	5.00	300	860	-6.49	1.80	759	5.34	258	0.267	2.41
9	12.4	12.35	2.17	1.00	0.3	open	in	1.16	safe	1.50	220	260	-6.54	0.82	202	5.34	258	0.267	2.41
27	12.4	12.35	2.17	1.00	0.3	open	out	1.72	capsize	2.00	240	360	-7.10	0.91	94	5.34	258	0.267	2.41
28	12.4	12.35	2.17	1.00	0.3	open	out	1.53	capsize	1.50	500	600	-4.78	0.95	63	5.34	258	0.267	2.41
59	10.83	10.96	3.56	1.00	0.3	open	in	3.72	capsize	4.00	260	300	-4.82	1.93	1023	6.03	552	0.324	2.80
62	10.83	10.96	3.56	1.00	0.3	open	out	3.80	capsize	4.00	300	900	-8.12	1.55	905	6.03	552	0.324	2.80
71	11	10.87	4.16	0.50	0.3	open	in	1.36	capsize	1.00	350	1700	-5.77	0.55	542	3.37	441	0.173	1.73
93	9.765	9.97	5.06	0.50	0.3	open	in	1.43	capsize	1.50	200	1500	-3.89	0.63	677	3.75	646	0.186	1.83
138	12	11.93	2.11	1.50	0.3	open	in	1.85	capsize	2.00	400	600	-4.95	1.00	15	7.94	377	0.438	3.53
139	12	11.93	2.11	1.50	0.3	open	in	1.61	capsize	1.50	400	620	-4.52	0.91	16	7.94	377	0.438	3.53
144	12	11.93	2.11	1.50	0.3	open	out	3.50	capsize	4.00	100	260	-1.33	1.48	161	7.94	377	0.438	3.53
145	12	11.93	2.11	1.50	0.3	open	out	2.74	capsize	3.00	210	470	-4.22	1.61	439	7.94	377	0.438	3.53

Table B.3 - Phase II Summary Results

Test Data																		SEM Predictions			
Run #	Fig. #	KG_act	Freebd	GZ_area	GZ_max	GZ_range	#_FP	Casing	Bilge_keel	Hs	spectra	Outcome	T1_(s)	T2_(s)	MEAN_ROLL	RELMO_SD	MEAN_VOL	**Crit. Angle**	**Crit. Vol**	**SEM h (m)**	**Hs (m)**
R173	131	5.550	0.2	0.0143	0.128	10.13	0	none	no_keel	4.93	jonswap	capsize	400	960	7.546	1.4458	857.74	3.26	217.6	0.143	1.492
R39	26	7.210	0.8	0.0152	0.124	12.23	0	none	keel	2.49	jonswap	capsize	450	470	-5.304	1.204	150.04	6.75	101	0.302	2.652
R16	8	7.404	0.8	0.0112	0.102	11.18	0	none	keel	1.68	jonswap	capsize	430	475	-3.543	0.3288	86.64	6.53	79.3	0.279	2.495
R129	88	7.969	1.2	0.0071	0.062	12.34	0	none	keel	1.69	jonswap	capsize	430	480	-6.88	0.816	32.508	8.67	40	0.299	2.631
R151	109	6.850	0.4	0.0085	0.101	8.23	0	none	keel	6.16	jonswap	capsize	300	390	0.938	1.7236	147.88	3.98	101	0.181	1.789
R160	118	6.241	0.2	0.0069	0.093	6.73	0	none	keel	6.06	jonswap	capsize	325	500	4.571	1.7329	507.26	2.62	123.4	0.125	1.341
R68	45	6.779	0.8	0.0272	0.177	14.96	0	casing	no_keel	3.45	jonswap	capsize	650	920	-8.251	1.293	217.15	7.43	163.9	0.342	2.918
R197	151	5.694	0.4	0.0296	0.189	14.67	0	casing	no_keel	3.24	jonswap	capsize	440	760	-8.012	1.476	360.53	5.43	282.4	0.235	2.186
R94	57	6.976	1.2	0.0459	0.226	19.85	0	casing	keel	5.06	jonswap	capsize	420	520	-9.3	1.68	280.86	10.43	188.3	0.481	3.793
R102	65	7.566	1.2	0.0186	0.125	15.18	0	casing	keel	3.33	jonswap	capsize	400	625	-6.142	1.222	102.21	9.34	90.2	0.392	3.241
R112	74	7.969	1.2	0.0071	0.062	12.34	0	casing	keel	2.55	jonswap	capsize	380	450	-5.733	0.937	26.923	8.67	40	0.299	2.631
R113	75	7.969	1.2	0.0071	0.062	12.34	0	casing	keel	1.76	jonswap	capsize	500	900	-6.178	0.74	21.75	8.67	40	0.299	2.631
R114	76	7.969	1.2	0.0071	0.062	12.34	0	casing	keel	1.33	jonswap	capsize	875	975	-8.31	1.122	50.65	8.67	40	0.299	2.631
R60	44	6.779	0.8	0.0272	0.177	14.96	0	casing	keel	6.48	ittc	capsize	820	950	-13.54	1.028	398.04	7.43	163.9	0.342	2.918
R50	34	6.779	0.8	0.0272	0.177	14.96	0	casing	keel	4.28	jonswap	capsize	320	440	-5.831	2.104	239.3	7.43	163.9	0.342	2.918
R51	35	6.779	0.8	0.0272	0.177	14.96	0	casing	keel	3.31	jonswap	capsize	440	600	-5.438	1.029	130.39	7.43	163.9	0.342	2.918
R28	18	7.210	0.8	0.0152	0.124	12.23	0	casing	keel	3.43	jonswap	capsize	520	545	-12.185	0.742	97.7	6.75	101	0.302	2.652
R10	2	7.404	0.8	0.0112	0.102	11.18	0	casing	keel	1.76	jonswap	capsize	460	600	-4.516	1.154	66.98	6.53	79.3	0.279	2.495
R144	102	6.850	0.4	0.0085	0.101	8.23	0	casing	keel	1.76	jonswap	capsize	600	950	-5.791	0.7573	194.41	3.98	101	0.181	1.789
R155	113	6.241	0.2	0.0069	0.093	6.73	0	casing	keel	1.35	jonswap	capsize	400	900	-2.607	0.702	150.56	2.62	123.4	0.125	1.341
Freeing Port Cases																					
R23	14	7.404	0.8	0.0112	0.102	11.18	6	none	keel	6.05	jonswap	capsize	210	420	2.772	0.7278	60.43	6.53	79.3	0.279	2.495
R125	85	7.969	1.2	0.0071	0.062	12.34	6	none	keel	1.87	jonswap	capsize	450	920	-4.268	0.859	20.55	8.67	40	0.299	2.631
R103	66	7.566	1.2	0.0186	0.125	15.18	6	casing	keel	4.77	jonswap	capsize	420	490	-13.37	1.37	240.44	9.34	90.2	0.392	3.241
R54	38	6.779	0.8	0.0272	0.177	14.96	6	casing	keel	5.04	jonswap	capsize	374	630	-4.645	1.61	162.89	7.43	163.9	0.342	2.918
R115	77	7.969	1.2	0.0071	0.062	12.34	6	casing	keel	1.83	jonswap	capsize	570	1025	-3.767	0.782	120.15	8.67	40	0.299	2.631
R12	4	7.404	0.8	0.0112	0.102	11.18	6	casing	keel	2.34	jonswap	capsize	325	900	-3.093	0.8546	35.69	6.53	79.3	0.279	2.495
R30	20	7.210	0.8	0.0152	0.124	12.23	6	casing	keel	3.10	jonswap	capsize	525	750	-4.977	1.108	84.23	6.75	101	0.302	2.652
R146	104	6.850	0.4	0.0085	0.101	8.23	6	casing	keel	1.88	jonswap	capsize	450	900	-3.692	0.745	96.83	3.98	101	0.181	1.789
R156	114	6.241	0.2	0.0069	0.093	6.73	6	casing	keel	1.32	jonswap	capsize	625	1000	-3.749	0.7536	224.78	2.62	123.4	0.125	1.341
R136	94	6.426	0.4	0.0139	0.131	10.13	20	casing	keel	3.52	jonswap	capsize	400	750	-2.74	1.419	174.94	4.47	153.2	0.201	1.939
R118	80	7.969	1.2	0.0071	0.062	12.34	20	casing	keel	2.37	jonswap	capsize	400	450	-7.174	1.16	39.9	8.67	40	0.299	2.631
R15	7	7.404	0.8	0.0112	0.102	11.18	20	casing	keel	5.16	jonswap	capsize	275	600	-3.635	1.415	90.51	6.53	79.3	0.279	2.495
R35	24	7.210	0.8	0.0152	0.124	12.23	20	casing	keel	6.89	jonswap	capsize	400	1350	-1.571	2.012	97.28	6.75	101	0.302	2.652
R55	39	6.779	0.8	0.0272	0.177	14.96	20	casing	keel	6.68	jonswap	capsize	300	1350	-2.536	1.79	147.36	7.43	163.9	0.342	2.918
R70	47	6.779	0.8	0.0272	0.177	14.96	20	casing	no_keel	6.47	jonswap	capsize	500	1400	-2.214	1.778	96.92	7.43	163.9	0.342	2.918
R120	81	7.969	1.2	0.0071	0.062	12.34	20	none	keel	5.41	jonswap	capsize	210	310	-5.34	1.704	64.76	8.67	40	0.299	2.631
R121	82	7.969	1.2	0.0071	0.062	12.34	20	none	keel	3.24	jonswap	capsize	380	620	-4.824	1.288	26.25	8.67	40	0.299	2.631
R147	105	6.850	0.4	0.0085	0.101	8.23	6	casing	keel	1.22	jonswap	safe	500	950	-2.167	0.555	29.67	3.98	101	0.181	1.789
R149	107	6.850	0.4	0.0085	0.101	8.23	20	casing	keel	1.25	jonswap	safe	400	750	-1.636	0.4718	13.35	3.98	101	0.181	1.789
R152	110	6.850	0.4	0.0085	0.101	8.23	0	none	keel	4.70	jonswap	safe	375	950	8.517	1.641	415.33	3.98	101	0.181	1.789
R159	117	6.241	0.2	0.0069	0.093	6.73	0	none	keel	4.71	jonswap	safe	400	640	7.202	1.579	581.67	2.62	123.4	0.125	1.341

Table B.4 - Safe/Capsize Wave Heights

Cond. No	Freebd	KG	SEM Hs	Measured Hs (m)	
	(m)	(m)	(m)	Highest Safe	Lowest Capsize
	Phase 1				
22	1.50	12.08	3.46	2.82	3.60
20	1.50	11.57	3.69	2.75	3.83
21	1.50	10.36	4.11	3.66	4.73
6	1.00	12.43	2.41	1.66	1.87
17	1.00	11.75	2.63	1.94	2.95
8a	1.00	10.98	2.86	2.67	4.44
8b	1.00	10.83	2.89	2.12	2.80
19	1.00	10.50	2.94	2.05	2.73
3b	1.00	9.76	3.09	6.34	over limit
18	1.00	9.41	3.15	5.88	over limit
16	0.50	12.51	1.48	1.27	1.67
14	0.50	12.12	1.55	1.09	1.79
15	0.50	11.55	1.63	1.40	1.80
5a	0.50	11.19	1.69	0.80	2.21
5b	0.50	10.89	1.73	1.25	1.51
13	0.50	10.31	1.81	1.88	2.63
9	0.50	9.72	1.88	1.31	1.64
2	0.50	7.81	2.08	6.31	over limit
	Phase 1ext				
9	2.00	12.36	4.10	3.73	over limit
8	1.50	11.93	3.53	2.89	4.06
7	1.50	11.25	3.82	2.85	3.94
1	1.00	12.35	2.43	1.85	2.96
3	1.00	10.96	2.80	2.00	2.86
2	1.00	10.00	3.00	4.67	over limit
4	0.50	10.87	1.73	1.41	2.05
5	0.50	9.97	1.83	1.66	1.69
6	0.50	7.77	2.03	3.87	over limit

Table B.5 – Predicted and Measured Capsize Waveheights, Phase II Model

Cond. No	Freebd (m)	KG (m)	SEM Hs (m)	Measured Hs (m), casing		Measured Hs (m), no casing	
				Highest Safe	Lowest Capsize	Highest Safe	Lowest Capsize
A1	1.2	6.98	3.79	4.00	5.06	6.75	n/a
A2		7.57	3.24	2.25	3.33	6.65	n/a
A3		7.97	2.63	n/a	1.33	1.45	1.69
B1	0.8	6.78	2.92	2.12	3.31	6.55	n/a
B2		7.21	2.65	2.09	3.43	6.47	2.49
B3		7.40	2.50	1.16	1.76	1.26	1.68
C1	0.4	5.69	2.19	3.06	4.17	6.98	n/a
C2		6.43	1.94	1.72	2.21	6.65	n/a
C3		6.85	1.79	1.29	1.77	5.86	6.16
D2	0.2	5.55	1.49	4.52	6.42	not tested	n/a
D3		6.24	1.34	n/a	1.35	4.71	6.06