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DAMAGE SURVIVABILITY OF RO-RO FERRIES

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SUMMARY

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Two comprehensive model test programs were devised to systematically examine the capsize phenomenon in sea states up to 7 metres significant wave height, using models which replicate the design characteristics and proportions of large, Canadian flag ferries. The vertical centre of gravity of the models were variable over a range of test conditions near SOLAS 90 damage stability criteria.

The first phase test results were analysed to identify patterns of repeatable behaviour. Initial conclusions drawn with respect to stability parameters, residual freeboard after damage, water behaviour on the RO-RO deck, freeing port area and presence of a centreline casing will be verified and/or expanded in the ongoing program. Areas for further work are identified for Phase II, and for additional efforts beyond.

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DAMAGE SURVIVABILITY OF RO-RO FERRIES

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ABSTRACT

The survival capability of damaged ships under dynamic sea conditions has been the subject of technical investigations since the early 1960's. Building upon this base of knowledge, a research program was initiated in Canada in 1991 to investigate the prime factors affecting the survival of RO-RO passenger ferries when flooded symmetrically after damage at midship.

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1. OVERVIEW

The survival capability of damaged ships under dynamic sea conditions has been the subject of technical investigations since the early 1960s (Comstock, 1961; Wendel, 1968; Middleton,1970; Bird, 1973). The loss of 192 lives in the capsize of the Roll-On/Roll-Off (RO-RO) passenger ferry *Herald of Free Enterprise* in 1987 highlighted the safety risks and brought forth the need to develop a better understanding of the matter along with a need to develop capsize safety design criteria. As a result of this accident, the Department of Transportation in the United Kingdom initiated several studies into the damage stability of these ship types [Dand, 1988; Pucill, 1990; Graham, 1990].

These studies encompassed model tests, full scale tests, and mathematical modelling to investigate the hydrodynamics of flooding after damage. Subsequent research efforts were broader in scope, involving risk analysis, collision resistance, hull form and superstructure effects, and assessment of internal arrangements and devices.

Building upon this knowledge base, an investigation was undertaken in Canada with a view to identifying the prime factors affecting the survivability of RO-RO passenger ferries when flooded symmetrically about amidships.

Polar Design Associates Ltd. (PDA) and the National Research Council Institute for Marine Dynamics (IMD) undertook the investigation in 1993-96 with a view to identifying the prime factors affecting the survivability of RO-RO passenger ferries when flooded symmetrically

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about amidships. The work was sponsored by the Transportation Development Centre and the Marine Regulatory Directorate (formerly Canadian Coast Guard, Ship Safety Branch) of Transport Canada. The conclusions of the research contributed to the position of Canada at international meetings of the International Maritime Organization (IMO) and its associated committees and panels. One of the most significant of these was the "Panel of Experts" which was formed to consider and improve constructional and operational aspects of RO-RO safety, and make recommendations for amendments to the 1990 Safety of Life at Sea (SOLAS 90) Convention.

1.1 Phase I

A comprehensive model test program was formulated to systematically investigate the effect on capsize of variations in residual freeboard, freeing ports and the presence (or absence) of the centreline casing on the vehicle deck, in waves up to 7 m significant height. This investigation formed the first phase of an effort to develop criteria for assessing RO-RO capsize safety after damage in dynamic sea conditions [Stubbs *et al.*, 1994; Molyneux, 1994].

A model replicating the design characteristics and proportions of large, Canadian-flag ferries was designed and used as the basis for conducting the study in SOLAS compliant loading conditions. The test program took place in the clear water towing tank at IMD.

Several interesting and important conclusions were drawn from this effort with respect to the capsize phenomenon, the effectiveness for freeing ports, the impact of a centreline casing, and the variables which seem to have some correlation with capsize survival. These included the observations that:

- capsize is the result of the accumulation of a "critical volume" of water on deck;
- accumulation of the water depends on relative motion at the damage opening;
- capsize occurs hydrostatically once the critical volume is reached; and,
- freeing ports and centreline casing have an impact on the accumulation.

1.2 Phase I - Extension

The above research was based on a model with a fully enclosed superstructure over the vehicle deck. However, many RO-RO ferries currently in operation have partially or completely open vehicle decks, and no data were available from model tests to evaluate their capsize safety. Given the need for such data, Transport Canada directed further study into this area by the performers of the previous research. [Rousseau, 1995; Molyneux & Sullivan, 1995]

This extension of the Canadian research effort was aimed at specific investigations related to enclosed, semi-enclosed and open shelterdeck configurations, and at the use of flaps on the freeing ports for vehicle deck drainage. These devices act as "non-return" enclosures on the vehicle deck, and it was desired to determine the impact (if any) on water build-up on the deck.

The most important result derived from the Phase I Extension was the demonstration that permanently open freeing ports give no survivability benefit to a damaged RO-RO vessel in waves. The conclusions were presented to the Intersessional Working Group on RO-RO Ferry Safety at the International Maritime Organization in London in mid-October 1995.

1.3 Phase II

The analyses presented in Phase I revealed the impact of some key parameters which may be useful as indicators of capsize safety:

a) GM and GZ in damaged condition as parameters related to the magnitude of restoring moment and consequently to the amount of water which can accumulate on the bulkhead deck before capsizing occurs;
b) Relative freeboard at the damage opening corresponding to a likelihood of bulkhead deck flooding due to vessel relative motion in waves;
c) Presence of flapped freeing ports on the RO-RO deck; and,
d) Presence of a centreline casing on the RO-RO deck.

It was considered logical to investigate these parameters further and use them in formulating the relationships reflecting the physics of capsizing. Planning therefore began for the Phase II investigations which would involve a different RO-RO vessel model.

In this stage of the research, an additional objective will be to validate the findings of Phase I by demonstrating that the same parameters and data trends governed the capsize of the new vessel model, and hence can be applied widely. If different parameters are identified (e.g. maximum GZ rather than GM), re-analysis of the Phase I data will be carried out.

Beyond this, the goal of Phase II is to develop a concrete understanding of the effect of GM and/or GZ, residual freeboard, wave period and wave height on RO-RO survivability, and contribute to IMO efforts to ensure safety of lives at sea.

2. RECENT RESEARCH

Despite considerable research and intergovernmental negotiations, the regulatory recommendations of the IMO Panel of Experts on RO-RO Safety were not adopted in 1995. The international community had managed to reach a consensus only on the concept of regional application of proposed amendments but without incorporating them in the text of the Convention. As a result, the current stability standard for damaged RO-RO vessels remained SOLAS 90.

However, it is noteworthy that there was little comprehensive scientific support for the SOLAS 90 standard as written, especially as it had been formulated on the basis of a RO-RO capsizing in the intact condition due to ingress of water on the bulkhead deck. The only well-documented case of capsizing of a RO-RO ferry in a damaged condition as the result of a collision is the sinking of the "European Gateway" in December 1982. [Spouge, 1985]

The early experiments conducted by H. Bird and R. Browne [Bird & Browne, 1973] are still considered to be comprehensive and reliable validation data for any theoretical approach. The collation of model test results published prior to 1993 was presented by J. Spouge. [Spouge, 1994]

A number of more recent model tests were conducted internationally to evaluate proposed amendments to the SOLAS 90 damage stability standard:

- The Italian model tests done at Hamburg Ship Model Basin showed that a RO-RO ferry complying with SOLAS 90 survives the sea state corresponding to the significant wave height of 4 m when trimmed forward in damaged condition. [Blume, 1995]
- The model tests conducted at DMI, Denmark and at Marintek, Norway [RO-RO/ISWG 1/3/20 1995] confirmed the improvement in survivability with higher residual freeboard and GM. Similar conclusions were presented by the Marine Safety Agency (MSA) of UK [SOLAS/CONF.3/INF.3, 1995].
- The research at the Ship Research Institute of Japan also indicated a clear dependency of capsizing on GM at a single residual freeboard. [RO-RO/ISWG 1/3/15 1995]
- The experiments conducted by Canal de Experiencias Hidrodinamicas de El Pardo of Spain also provided supporting evidence for the above conclusions [SOLAS/CONF.3/INF.5, 1995].
- In addition, theoretical work by D. Vassalos [Vassalos, 1994] identified residual freeboard and GM as key survivability parameters. This work also highlighted the importance of the "tuning" of the damaged vessel to the seas, i.e. the ratio of wave modal period to the natural roll period of the ship.

As well as pointing to the relevant variables involved, the Canadian Phase I research highlighted a need to examine a model which more truly represented a ship hull form rather than a prismatic body. This was reinforced by comments on the experimental results by representatives at IMO conferences. In addition, it was felt that new efforts should focus on lower values of residual freeboard after damage, to correspond more closely to RO-RO ships in international fleets.

As more research is done, and further analysis is undertaken of the results to date, the use of GM as an exclusice predictor of survivability has begun to lose favour among some researchers. The most recent works, including those of Vassalos [Vassalos, 1995] and Pawlowski [Pawlowski, 1995], attribute more of a predictive nature to the location of maximum GZ, and its link to water on deck. Such works lead to the definition of a "critical volume", which is the amount of water which causes the vessel to reach equilibrium with a heel angle at the location of maximum GZ. This may be described as a "point of no return" in survivability terms. This concept is to be an important part of the Phase II analysis, as the experiments attempt to validate, or contribute to modification of, the calculation method.

Additional efforts in mathematical simulation, such as Hutchison [Hutchison, 1995], will eventually lead to a more thorough understanding of the mechanics of the capsize phenomenon. Unfortunately, such programs are still at the stage where broad assumptions are made to simplify the analyses and hence limit the applicability of the results (e.g. stationary ships, prismatic hull forms, etc.). Such was also the case with the Phase I experiments, where the numerical modeling effort was not deemed successful.

The goal of Phase II is to carry on the investigations into the capsize phenomenon, both in terms of applying similar testing methods to a different ship and using newer analysis techniques to examine the data from all phases. In addition, the data collection effort is planned around using the information recorded to be able to set up numerical simulations to evaluate new formulations. This will provide the possibility of faster validation (or elimination) of these methods by using available model test data, hence avoiding the need to continuously plan and set up test programs for each new theory.

In a more general sense, applying knowledge of the factors involved to a model which represents a more realistic ship form will result in a comprehensive and systematic test program which will enable definition of the degree to which key variables impact upon the capsize phenomenon for typical RO-RO vessels. Conclusions may be reached as to the merits of SOLAS 90 compliance in the damage condition, and the required criteria which RO-RO ferries must meet in terms of geometry, arrangement and stability in order to be considered "safe".

A recent Nordic SLF submission (40/4/5) introduces a probabilistic method, and includes such elements as flooding of the RO-RO deck, loss of stability, heeling moments (e.g. cargo shifts) and downflooding. While it contains some questionable elements, it is significant in that it attempts to address criteria from a scientific basis. While a proposal such as SLF 40/4/5 would take several (4-5) years of discussion while working its way through the SLF/MSC/IMO regulatory procedures, it is a good start to eventual harmonization of the regulations. IMO working groups have already begun to make concrete efforts to analyze the proposal, including the acquisition of computer hardware and software for the purpose. Important concepts contained in the document will be addressed where possible in the course of Phase II, to contribute to the Canadian analysis effort and also to allow informed comment on the proposals.

3. MODEL DESIGN AND FEATURES

3.1 Common Design

Both of the models were constructed and outfitted in the following manner:

a) Robust construction in consideration of the loads placed on the model by repeated flooding and capsize;
b) Foam buoyancy on top of the superstructure to avoid the stresses resulting from complete capsize;
c) Submersible pumps within the hull for fast water evacuation between tests;
d) An eyebolts/pulley system to facilitate righting the model after capsize;
e) Light restraining ropes to facilitate towing of the model back to the start position between tests;
f) A Lexan superstructure top* to allow visual examination of the model interior from above;
g) Watertight housing to allow a camera to be fitted in the car deck space;
h) Soft moorings to allow the model to be towed back up the tank for a new test run, but which were let slack to allow the model to drift freely during the tests;
i) Ability to vary the vertical centre of gravity (KG) to simulate loading conditions conforming to SOLAS 90 residual damage stability criteria;
j) A damage opening complying with SOLAS damage stability criteria;
k) A car deck extending the full length of the model, with a simplified superstructure to constrain water on the car deck after damage and hence obtain realistic water build-up;

* The term "superstructure" denotes the vessel sides above the RO-RO deck.

The instrumentation outfit includes:

a) Stationary and moving wave probes;
b) Electro-mechanical gyro mounted on the superstructure centreline in a watertight casing, to measure pitch and roll angles;
c) Strapdown accelerometers mounted on the superstructure centreline in a watertight casing to provide relative accelerations in heave, surge and sway;
d) Water level probes mounted on double bottom to assess water volume;
e) A camera in the watertight housing on the car deck, to record relevant details of flooding and motions;
f) External cameras to observe the test from outside the model, one being located on a movable bracket directed at one end of the model (for the carriage operator) and another mounted on a fixed bracket looking down on the model;

The buoyancy of the shell and deck thickness are significant parameters that affect results in model scale. To properly take account of these and the buoyancy of the internal video camera in the hull, stability calculations provide for permeability of the flooded compartment, and representative side shell and deck thicknesses.

3.2 Configuration - First Model

In Phase I, an idealised constant cross section hull form was developed whose displacement and stability characteristics replicate those of the larger ferries in Canada. The result was a 1:20 scale model of a 160 m long, 26.6 m wide and 8 m deep RO-RO hull with an intact displacement of 11666 t at 5.0 m intact draft. An exploded view of the arrangement and assembly of the model is depicted in Figure 1.

In order to provide for the testing of the anticipated prime variables, the design of the model included the following features:

a. A constant cross-section to meet the requirements of a numerical modelling project conducted in parallel with the subject investigation (Pawlowski, 1994);
b. Adjustable buoyancy in the flooded compartment to flood the model symmetrically at 0.5, 1.0, 1.5 and 2.0 metres residual freeboard after damage;
c. Water freeing ports just above the vehicle deck, fitted with hinged flaps which could be locked in the closed or open position to achieve varying total area;
d. Removable centreline casing extending over the midship 2/3 length.

3.3 Configuration - Second Model

The model to be used in the Phase II tests is based on a RO-RO ferry in Canadian service, with 94.56 m length on the waterline, 17.83 m waterline beam and an intact displacement of approximately 4400 t in the fully loaded departure condition. The scale is 1:16, a value chosen to ensure that the model is large enough in cross-section to fit all of the required equipment into the hull, while at the same time being small enough to allow the waves to be generated in scale and to enable the existing model swing to be used.

The model was to designed to possess two planes of symmetry: centreline and midship (the bow and stern are identical, and thus yield a double-ended configuration). This is to allow later numerical analysis efforts to model the hull without too much difficulty. Over a portion of the model length near midship, the cross-section is constant (i.e. parallel midbody) to facilitate the operation of a sliding damage door.

The initial hull form was based on the bow of the parent hull, mirrored about midship and modified to possess the parallel midbody. Since this procedure had modified the hydrostatic properties, the double ended hull form was further modified to fill out the lines and more closely reflect original hydrostatics. The geometry of the revised double ended model is depicted in Figure 2.

In order to provide for successful investigation of the main capsize parameters, the design of the model includes the following features:

a) Adjustable compartment size to flood the model symmetrically to the required residual freeboards of 0.2, 0.4, 0.8 and 1.2 metres after damage;
b) Water freeing ports just above the vehicle deck, fitted with hinged flaps which can be locked in the closed position to achieve total areas corresponding to the Load Line Convention requirement and the former IMO recommendation of 0.3L per side;
c) A removable centreline casing of approximately 60% of the car deck length, centred on midship, and with a width similar to that fitted in the parent hull;
d) Removable bilge keels over 30% of the waterline length, placed at the turn of the bilge, constructed as flat plates 550 mm in span; and,

Additional sensors are to be used:

a) No.1 pressure transducer mounted just above the car deck facing the incident waves;
b) No. 2 pressure transducer mounted just above the car deck facing inboard at roughly the same location as No.1;

These will gather data on the pressure exerted by the incident waves on the superstructure side, and the sloshing water on the RO-RO deck.

3.4 Freeing Ports

Freeing ports were incorporated into the models to assess their ability to reduce accumulations of water on the car deck. The freeing ports were fitted with hinged covers, or "flaps", which allowed water on the RO-RO deck to drain but limited the ingress of further water through the openings (Rousseau, 1995).* This is illustrated in Figure 3. The flaps may be locked shut to prevent water transmission; the Phase I flaps could also be locked open to eliminate the

* At this stage of research, the implications of the freeing ports on intact stability of the vessel were not considered, as the principal goal in evaluating the ports was to determine the usefulness of water drainage. Designs for angled freeing ports and/or other drainage devices which may address the intact stability issue are outside the scope of this paper.

flow bias introduced by the covers.

Multiple freeing port conditions were established for testing, ranging from the 1966 International Load Line Convention requirement up to an area of approximately 30% of the vessel length, i.e. 0.3 L. Each opening represents a 2.0 m x 0.6 m freeing port on the full scale vessel.**

3.5 Centreline Casing

Also incorporated in the models were removable centreline casings extending symmetrically over the midship location of the model. Since the casing do not cover the entire length of the model, water is free to move across the car deck around the forward and aft ends of the casing, replicating the actual situation aboard a ship.

The main body of testing was performed with the casing present, with additional tests performed for several conditions without the casing.

4. SCOPE OF INVESTIGATION

4.1 SOLAS Criteria

The purpose of the test programs were to establish the capsize safety limits in conditions compliant with the limiting SOLAS 90 criteria at the selected residual freeboards.

The SOLAS requirements mandate a minimum 0.1 m GZ value, a minimum 0.015 m-radian dynamic stability requirement and a positive GZ range of at least 15 degrees. Extensive damage stability calculations were performed to calculate the KG condition compliant with SOLAS criteria at each of the pre-selected residual freeboards. The results of these extensive calculations were used to construct the overall test matrices serving to test current SOLAS criteria in waves.

Depicted in Figure 4 are the calculated limiting KG values for both full scale vessels corresponding to the SOLAS criteria at the respective predetermined residual freeboards. This representation of "limiting KG" lines is used to determine KG values (i.e. test data points) for the test plans, in order to evaluate the capsize safety associated with meeting the SOLAS criteria.

As can be seen in the figure, the second model represents a vessel with a considerably reduced range of KG values, and lower residual freeboards after damage (the first model was only tested down to 0.5 metres freeboard). This was an intentional component of the selection of this ship, as it was felt to more closely reflect typical ferry parameters. In addition, the reduced range of KG means that testing can be carried out for a configuration which nearly exactly meets the SOLAS criteria, which allows examination of these regulations to a certain extent.

4.2 Sea States

Canadian Coast Guard, Ship Safety provided sea state specifications compiled from wave data for Canadian waters where ferry operations are routinely conducted. Based on these coastal

** It should be noted that, throughout this paper, an "open" freeing port denotes an unlocked flap, which is free to open and close as the vessel rolls.

observations, a profile of representative wave conditions was developed for model testing.

The resulting irregular wave patterns were characterised by the Jonswap spectrum, with significant wave heights of 0.5 to 7.0 metres (or modal periods of 5.0 to 9.0 seconds).

5. TEST METHODOLOGY

Each test began with the 8 m long model transversely across the 12 m wide towing tank at IMD. The model was tested in beam sea conditions using both regular and irregular waves. Testing progressed as follows:

a. Systematic tests in progressively larger sea states were conducted to determine the maximum upright and minimum capsize sea states at each of the residual freeboards in the freeing ports closed condition;
b. Building on the established baseline capsize characteristics, the effect of freeing port area was subsequently investigated systematically; and,
c. Also assessed was the effect of removing the centreline casing.

At each of the test condition KG values, tests were conducted as follows:

a. The model was ballasted to one of the calculated KGs to a tolerance of ±0.1 m full scale, verified by inclining experiment;
b. Roll decay tests were conducted in both intact and damage cases to determine damping coefficients and roll radius of gyration; and,
c. The model was systematically tested in irregular waves, with freeing ports closed, in increasingly severe sea states until it either capsized or the maximum 7 m full scale wave height was successfully tested. Individual test runs were stopped after a capsize or after approximately 40 minutes of elapsed survival time after damage; whichever occurred first.

The desired result for each KG condition was a pair of data points, one representing the highest wave height in which the model remained upright, and the other representing the lowest wave height at which capsize took place. These are referred to as the maximum upright and minimum capsize wave heights. Where capsize did not occur, the latter data point is indeterminate.

6. RESULTS THUS FAR

6.1 Capsize Mechanism

A vessel capsize may be summarized as follows:

a) In the build-up to a capsize event, there is a continuous and progressive increase in the mean angle of heel of the model as a function of time.
b) This progressive increase in angle of heel follows a corresponding increase in measured roll

relative motion at the damage opening. This implies that an increasing head of water flooding the vehicle deck is present.

c) Once a critical condition is reached, a sudden 'cliff-edge' capsize event occurs suddenly.

The principal difference between cases involving capsize and those where the vessel remains upright lies in the absence of the progressive build-ups of relative motion and angle of heel. In such cases, substantial water may be observed to accumulate on deck, but no capsize event occurs.

From the analysis of the data, it became apparent that a capsize occurs after a critical volume of water has built up on the deck. The amount of water flowing onto the deck is a function of the relative motion between the deck and the wave surface. The relative motion is in turn a function of the wave height and modal period, the residual freeboard and the dynamic characteristics of the hull. A third parameter in the capsize process is the ability of the deck to drain, which is a function of the freeboard, the freeing port area and the presence or absence of a centreline casing.

An interesting result is that the critical volume of water that capsizes the hull appears to be independent of all of the above factors except the metacentric height of the damaged hull. This would indicate that the actual capsize is a nearly hydrostatic phenomenon. This is significant, in that it implies that the capsize event is a repeatable phenomenon independent of the manner in which the water build-up takes place.

6.2 Metacentric Height Vs. Residual Freeboard

The first parameter assessed in the testing of the first model was the metacentric height after damage, i.e. $GM_{flooded}$. Data reduction and analysis revealed that strong correlations are evident between GM, sea state and residual freeboard. Sample data are presented in Figure 5.

Noteworthy is the clear effect that residual freeboard has on enhancing capsize safety. The first observations are the consistent relationships derived from both the maximum upright and minimum capsize test results. Both exhibit consistent trends; thus giving confidence in the quality of the results.

At each of the three residual freeboards tested, it is consistently evident that:

a) The capsize safety limit occurs at a near constant sea state despite substantial variations in GM;
b) There is a yet to be defined critical point where a radical change occurs; and,
c) In higher sea states, the relationship between the safe sea state and GM assumes an infinite (vertical) slope. This is particularly evident at lower residual freeboards.

6.3 Dynamic Stability Vs. Residual Freeboard

A natural extension of the GM analysis is consideration of dynamic stability (represented by area under the GZ curve) which takes into account the roll restoring energy available within the damaged hull.

Figure 6 indicates that while the derived relationships between wave height and GZ area exhibit the same "banded" characteristics as revealed by GM, the trend is more linear. A sensitivity to residual freeboard is distinguishable within the test results. An element of interest is the absence of the trend towards infinite slope as observed in the GM analysis and shown in Figure 5.

6.4 Effect of Freeing Ports

The investigations to this point have shown that significant improvements in capsize safety are obtained by allowing water to drain off the car deck through freeing ports. These devices always enhanced capsize safety; that is, the model could always withstand greater sea states without capsizing when freeing ports were present.

The tests did show, however, that the effect of permanently open freeing ports is not beneficial, as water may flow inward as well as outward. The survivability benefits only accrue from the presence of one-way or "biased flow" devices (e.g. flaps on the freeing ports).

It was also found that the effectiveness of the freeing ports is highly dependent on residual freeboard: lower freeboard cases did not receive the same degree of safety enhancement as demonstrated at higher freeboards. This was most likely due to the ability of the water to drain effectively though the flapped freeing ports for a greater time portion of each roll cycle.

6.5 Effect of Centreline Casing

Various test conditions were repeated with the centreline casing was removed. The general effect of removing the casing is to enhance survivability except at the lowest freeing port areas (including zero). Physical observations during testing of selected cases showed that the centreline casing serves to constrain water on deck in all test cases. This facilitates the build-up of water on the car deck leading to capsize.

Open ports at the side of the model opposite the damage become more effective when the centreline casing is removed. This increases the net outflow of water significantly and therefore improves the survivability of the model in higher sea states.

The net conclusion is that, when freeing ports are fitted, a centreline casing has a detrimental effect on capsize safety. The results without freeing ports were inconclusive, showing neither significant benefit or detriment.

7. VALIDATION OF RESULTS

The efforts discussed in this paper were summarised in a Canadian submission to IMO in January of 1995 (IMO SLF 39/INF.16, 1995). While presenting the important progress made thus far in assessing capsize safety of RO-RO vessels, the document also compared the numerical results of the model test program with data from earlier experiments.

Using a non-dimensionalising approach proposed by J.R. Spouge of DNV Technica (UK), the Canadian data were combined with information from tests on:

a) the Holyhead Ferry, Bird and Browne, 1974;
b) "Ship B", the Danish Maritime Institute, 1989, and;
c) "Ship A", BMT, 1989.

The graphical comparison is shown in Figure 7. The data are presented using the non-dimensional metacentric height, GMn, and non-dimensional wave height Hn. The definition of these quantities is as follows:

$$Hn = \frac{\omega^2 HBA}{4gF} \quad (1)$$

$$GMn = \frac{D(GM)}{1.025 L_{BP} B^3} \quad (2)$$

where ω = circular frequency in rad/s = $2\pi/T_m$
T_m = modal period, seconds
H = significant wave height to capsize, metres
L_{BP} = length between perpendiculars, metres
B = beam, metres
F = freeboard to car deck after damage, metres
GM = flooded metacentric height, metres
D = flooded displacement, tonnes
g = gravitational constant = 9.81 m/s^2
A = 1.0 for damage into waves, 0.5 for damage away from waves

The Canadian data fall within the GM range covered by the other ships, and exhibit comparable survivability in terms of survivable significant wave height.

This is an important result, as it helps to validate the entire model test program and results. Perhaps more importantly, it indicates that the eventual formulation of design criteria from further research into the areas identified in this paper will be applicable to vessel arrangements beyond the single model tested.

9. THE WAY AHEAD

The conclusions deduced thus far in this investigation may be summarised as follows:

- The model tests demonstrated the importance of residual freeboard in preventing a capsize, particularly in allowing water to drain from the car deck through freeing ports.
- Limiting safe sea states show a linear trend when plotted against dynamic stability (as represented by GZ area).
- Sea state vs. metacentric height (GM) in the flooded condition shows a marked sensitivity to residual freeboard.
- Freeing port tests demonstrated that the ability to drain water from the vehicle deck greatly enhances capsize safety with the provision of substantially larger freeing port areas than

dictated by current Load Line Regulations.

- With freeing ports and sufficient residual freeboard for water drainage from the car deck, removal of a centreline casing leads to a survivability benefit.
- Capsize is a hydrostatic phenomenon, occurring once sufficient water accumulates on the vehicle deck.

The results of this project provide information that will help to increase the understanding of the capsize phenomena of RO-RO vessels. Results are promising and relationships derived contribute to the prime objective of ultimately developing design criteria. The following areas of further work are being actively considered by the RO-RO Safety Steering Committee, which includes members from Transport Canada, the performing organizations, and RO-RO operators in Canada:

1. Although preliminary comparisons with other data show good agreement with the data published here, more work is required to define adequate capsize prediction equations related to ship and environment parameters. This includes the concept of "critical volume" of water on the RO-RO deck, and the investigation of other stability indicators besides GM and GZ area.
2. The effect of different vessel proportions should be included in further test programs to support formulation of capsize prevention criteria. In this respect, consideration also needs to be given to the sea state conditions against which capsize safety criteria will be formulated.
3. Side casings, bilge keels and other arrangement details, including the effect of asymmetrical flooding, need to be addressed.
4. The impact of vehicles on the RO-RO deck in terms of damping the motion of internal water should be considered, as should the effect of weight shifts as in the case of non-lashed vehicles.
5. Numerical modeling should be commissioned to further investigate all aspects of the inflow/outflow and dynamic phenomena associated with RO-RO motions and water build-up on deck.

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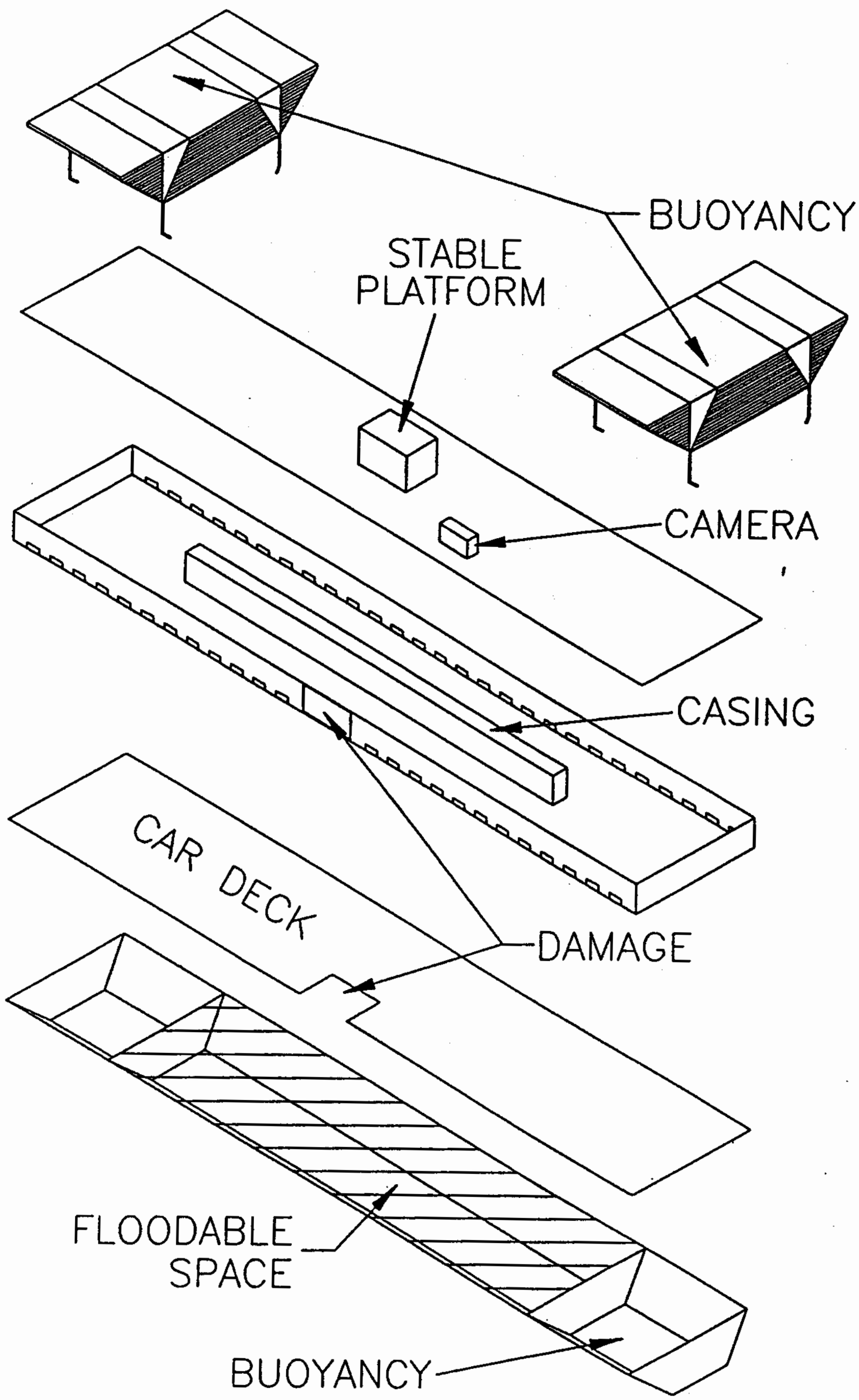

Figure 1 Exploded view of first model

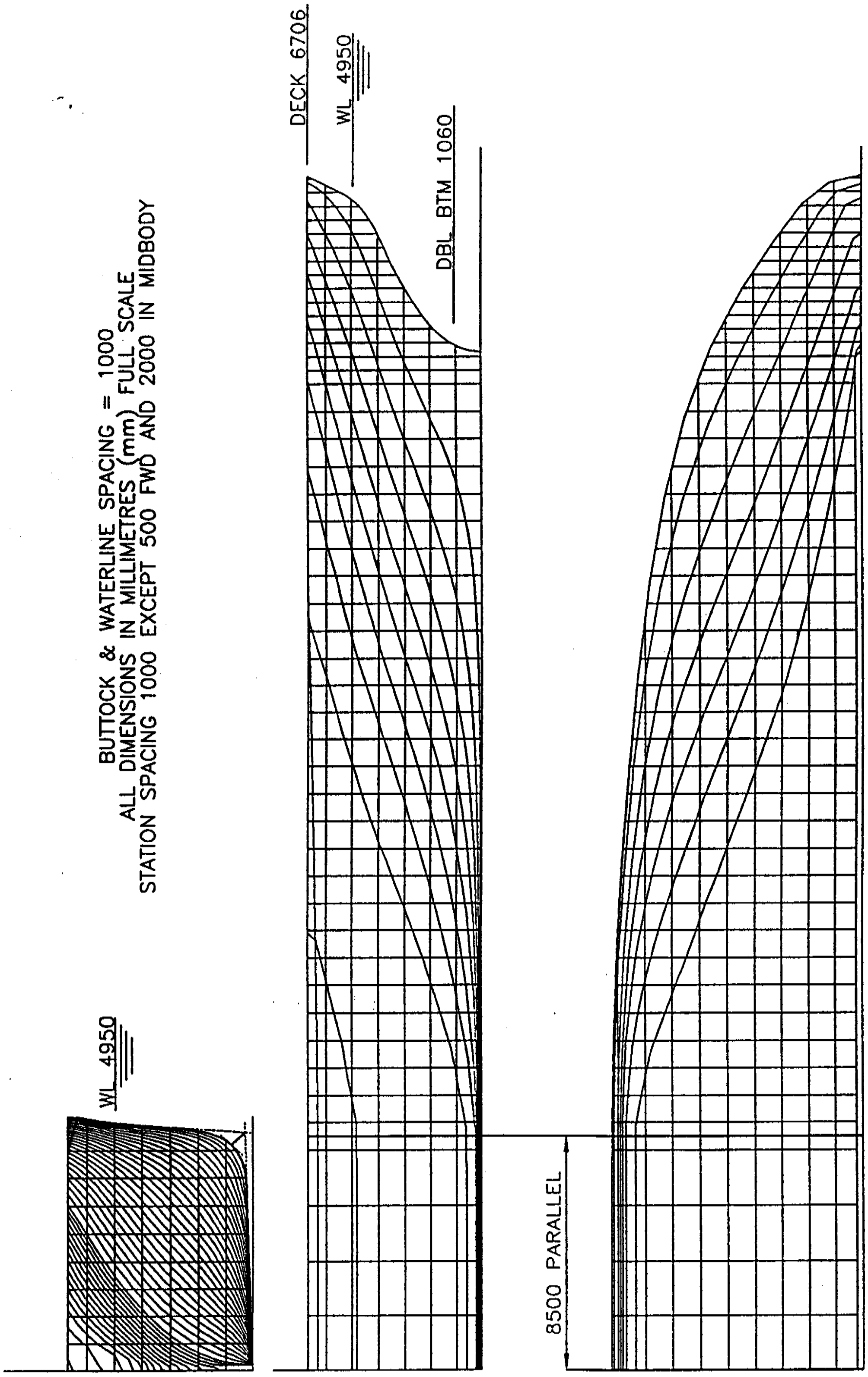

Figure 2 Lines plan of second model

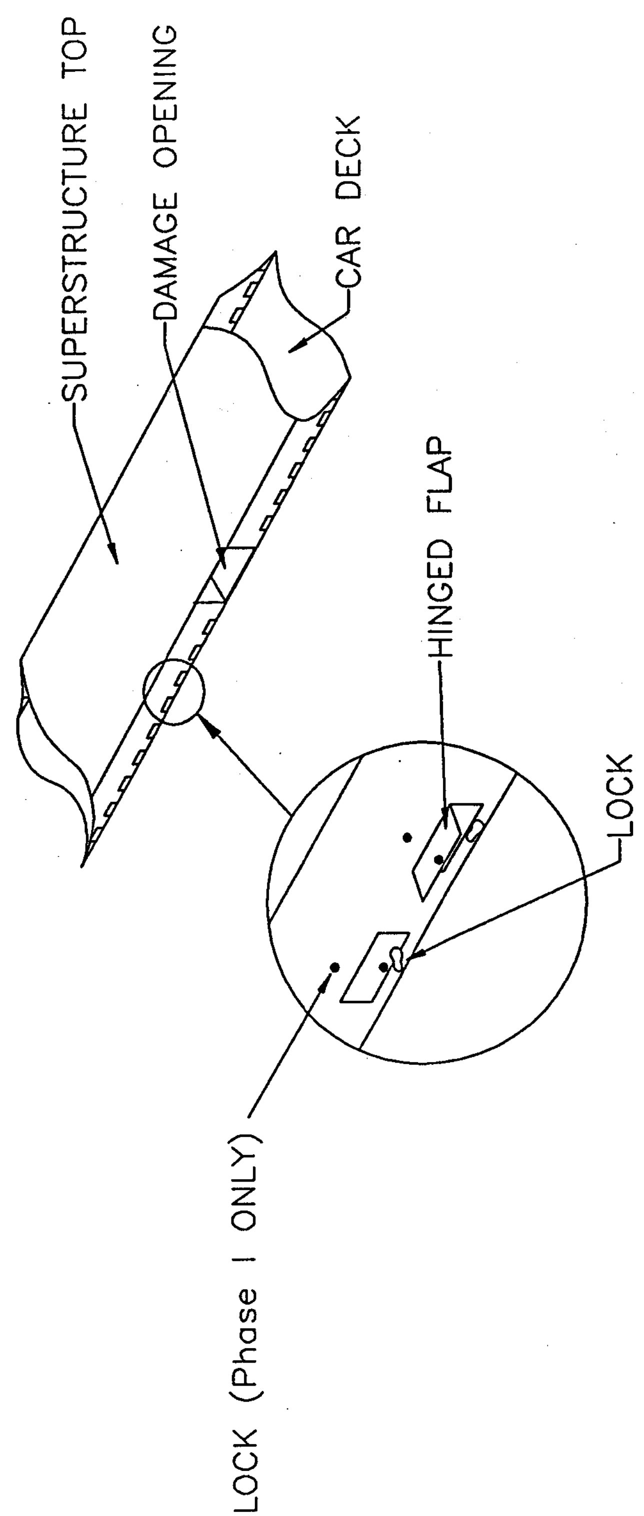

Figure 3 Freeing port details

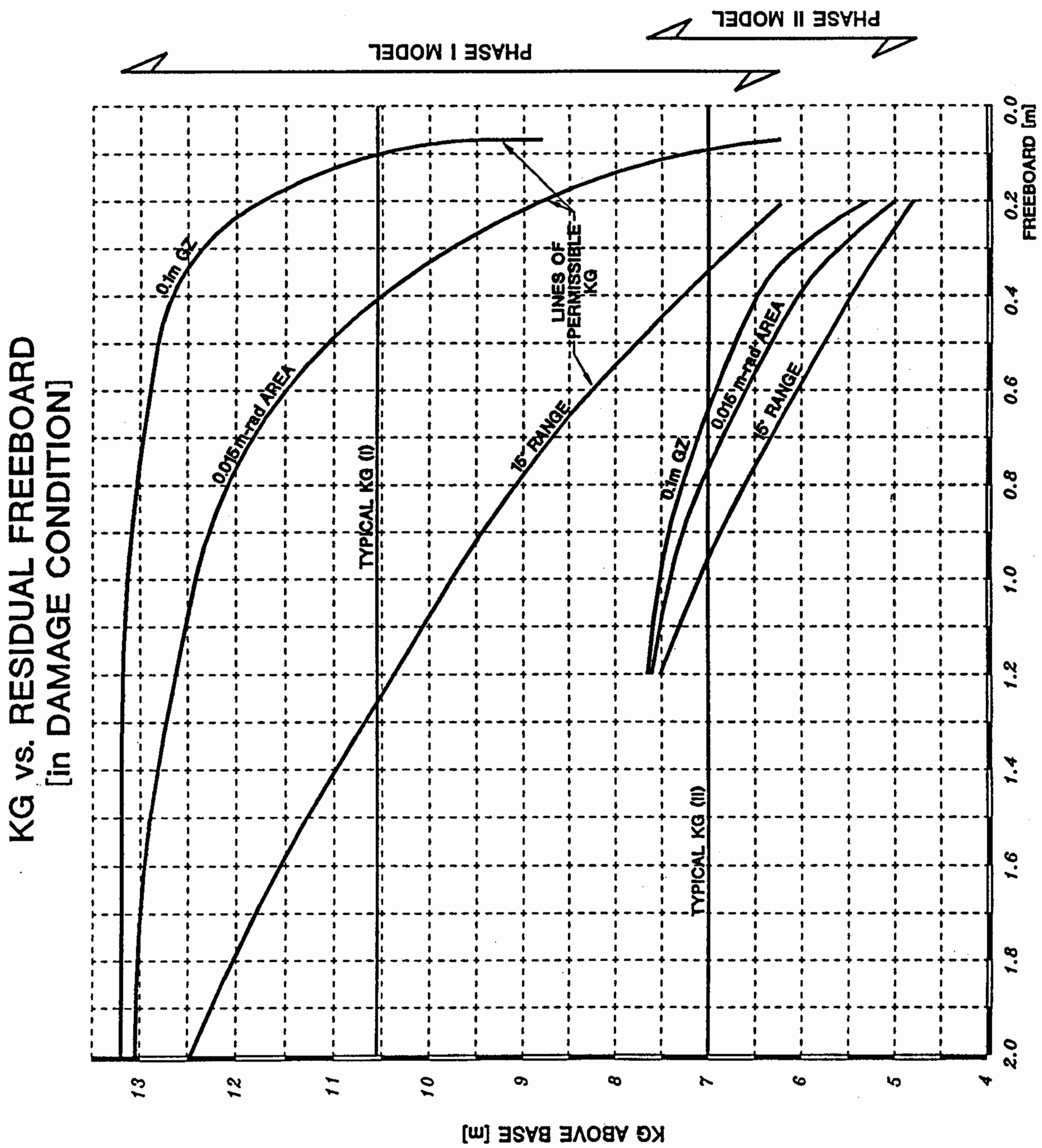

Figure 4 SOLAS compliant centres of gravity

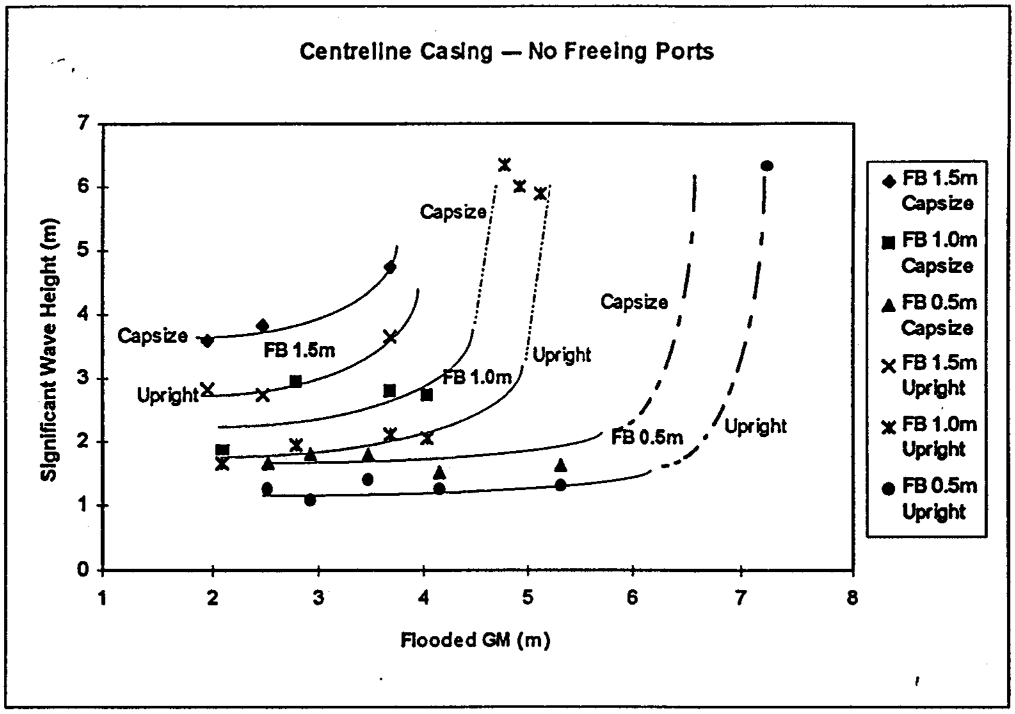

Figure 5 Results from first phase for GM

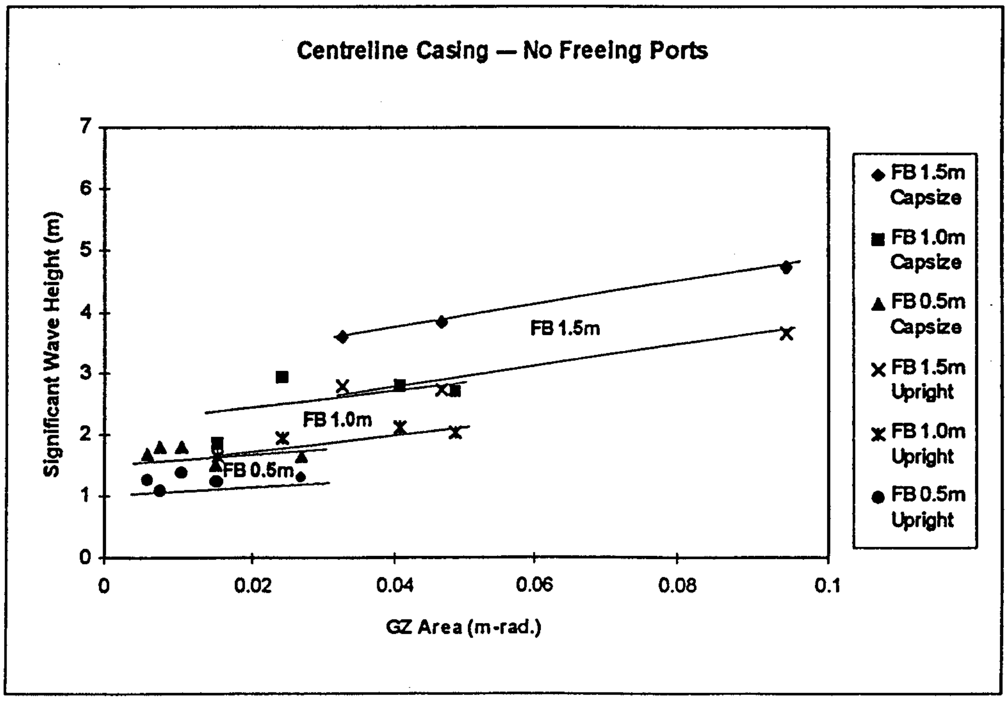

Figure 6 Results from first phase for area under stability curve

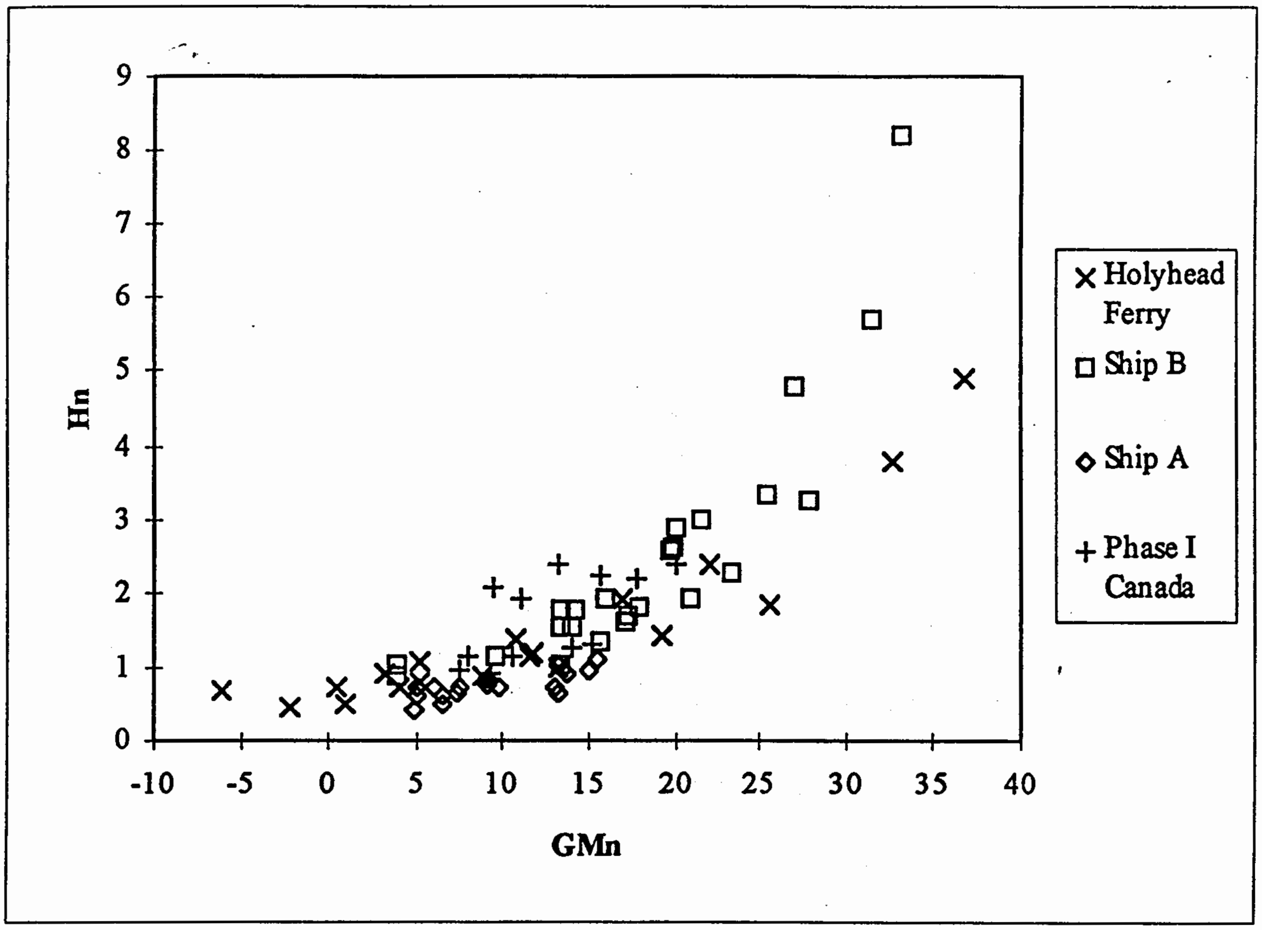

Figure 7 Comparison of results from various sources