Exploration Of The Applicability Of The Static Equivalency Method Using Experimental Data

Andrew Kendrick[1], David Molyneux[2], Andre Taschereau[3], and Tom Peirce[4]

[1] Fleet Technology, Ltd;
[2] Institute for Marine Dynamics
[3] Transportation Development Centre
[4] Operational Dynamics

ABSTRACT

The Static Equivalency Method (SEM) developed by the Strathclyde University research team offers a simple predictor of capsize for a wide range of ship conditions. Data generated by Transport Canada's experiment program of capsize investigations was reanalyzed to investigate the validity of the predictor equations, and their range of applicability. Excellent agreement was found for cases in which the dynamic roll component of ship behaviour is small, and where internal sloshing is limited, in particular for ships with centreline casings. The SEM capsize predictor was also applied successfully to cases with freeing ports, though more work is needed to define water build-up under these conditions. Some limitations of the model predictions were highlighted, and potential sources of error identified.

Results of the project were used to provide recommendations as to how the SEM could be applied as a component of deterministic or fully probabilistic damaged stability criteria.

1. INTRODUCTION

The extensive international research which followed the ferry catastrophes of the 1980's and early 1990's led to the development of numerous proposals for ways in which safety could be enhanced in future operations. These included recommendations for new stability criteria, for design features and operational procedures. Under considerable time pressure, IMO introduced amendments to the SOLAS Convention in 1990, and then declined to make further global modifications in 1995, leading to a number of Northern European nations adopting by regional agreement their own, more stringent, requirements.

As is too often the case, the regulatory decisions were made before the researchers tasked with clarifying the issues had managed to fully disseminate, assimilate, and evaluate each other's results. In some cases, the fact that policy decisions were taken removed the support for continuing with promising research which had only yielded preliminary or inconclusive results. However, the Canadian government decided to persevere with its own program to try and provide explanations for some puzzling phenomena and indicate the most promising directions for future safety initiatives.

2. BACKGROUND

2.1 Transport Canada Research Program

Transport Canada 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, which used a highly simplified model of a large Ro-Ro vessel was completed in March 1995 and a set of reports, with supporting data which confirmed the benefits of freeing ports, were provided to IMO and summarized [1] and [2] . 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, using a more ship-shaped model of a smaller ferry. The results of this work are summarized in [3], [4] and [5], and were also provided in full 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 Canada had decided to remain with the standard SOLAS 90 approach for the time being, it was recognized that both this and the SOLAS '90+50' option are imperfect predictors of safety. There was thus a continuing desire to develop a better understanding of the mechanisms causing capsizes involving water on deck, which are quite different from those which govern intact capsize under more extreme wave climates.

2.2 The Static Equivalency Method

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 the Transport Canada project. References such as [6] provide more details of its workings.

It is presumed that it is the accumulation of water on the vehicle deck that causes the ship to capsize. 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, θ_{GZm} , 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, h, above the mean external sea level, and this elevation can, in turn, be correlated with the significant wave height, H_S , through an empirical equation:

$$h = 0.085 H_S^{1.3}$$

Kinetic wave energy is, in effect, transformed into potential energy.

It is assumed that the process is quasi-static, as the time frames associated with capsize are significantly longer than the wave or ship roll periods. Based on this assumption, dynamic effects do need to be accounted for either in the stability calculation approach or in the correlation of water elevation and wave height.

It is worth noting that the relationship given above has been modified, to include residual freeboard [7].

The new version is:

$$h = 0.088 H_S^{(0.97+0.46F)}$$

where F is the residual freeboard.

The stability calculations needed to predict capsize water volume can be undertaken in several ways which should yield essentially identical results. None of these are 'standard' routines for commercial stability analysis software packages, but reprocessing of their normal output data allows the important quantities to be calculated with modest effort.

2.3 Project Objectives

The basic Static Equivalency Method, as outlined above, offers an appealingly simple means to predict capsize. However, the published descriptions of the method left a number of concerns, including:

i) the influence of relative motions on the accuracy of the results;

ii) the influence (if any) of sea spectrum;

iii) the influence of ship size and configuration;

iv) the ability of the method to represent adequately centre and side casing influences;
v) the potential for treating freeing port effects in the method.

As all of these variables had been explored (to varying degrees) in the Canadian experimental program. It was therefore hoped that the experimental data could be used, first, to check the basic validity of the SEM predictions, and then to examine some or all of these presumed second-order effects.

3. ANALYSES

3.1 Numerical Analyses

The predicted volumes of water associated with capsize were calculated as outlined in 2.2 above. The desired value of θ_{GZ_m} was first 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 was then established for this (imposed) heel angle. Sinkage, deck edge immersion, and internal water level were 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. 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.

3.2 Selection of Experiment Data Sets

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. The data was reprocessed to obtain a set of results aligned as closely as possible to the predictions of critical volumes, heel angles, and relative motions at the damage opening. These values were re-plotted over time periods of interest prior to capsize, and mean values the time intervals were calculated. The critical volume was picked as the highest steady volume, prior to a capsize.It was not always possible to obtain meaningful values for all of the parameters of interest, due to some data acquisition problems during the first phase of the work. Despite this, all phases of the project were found to have generated valuable data.

The data sets obtained during the earlier phases were reviewed to identify conditions expected to be most relevant to the testing of the static equivalency hypotheses. This was done both qualitatively (through the characteristics of the data traces) and quantitatively (through comparisons with the numerical analyses). Initially the selection of specific experiments was undertaken independently by the authors, 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.

3.3 Basic Capsize Prediction

As explained above, the Static Equivalency Method predicts wave height to cause a capsize by relating this to the buildup 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 SEM considered its ability to predict the critical volume of water on deck and the corresponding wave height to cause a capsize. Secondly, heel angles and relative motions just prior to capsize were compared.

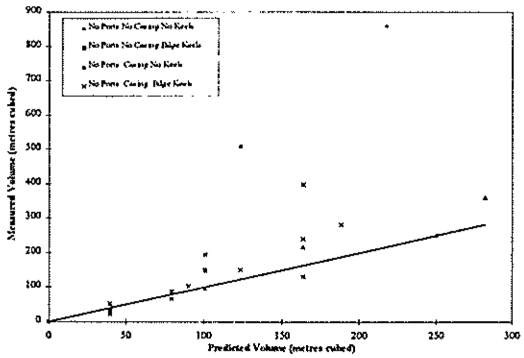

Figure 1, Phase II Volume Comparisons

Comparisons of predicted and actual volumes of water in capsize conditions for the Phase II model is shown in Figure 1. (Phase I results were similar.) As can be seen, the critical volume data shows some scatter about the expected lines, with a tendency to under predict the volumes at the higher values. Neither the scatter nor this under prediction was unexpected. As explained in [6], the capsize process is itself random in nature, and any model tests have some lack of precision. This work also observed an under prediction of survivability under conditions where the damaged ship has high residual stability.

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 2** and **3**. In the experimental program, the significant wave heights were pre-determined and spaced sufficiently to obtain differences that were more than those obtained due to random nature of wave height. This provided two data points for each condition, the maximum significant wave height the model survived and the minimum significant wave height to cause a capsize. These data are shown in Figures 1 and 2 by diamonds and squares respectively. In cases where no capsize was observed during experiments, the measured data is shown with an arrow, to indicate that the capsize would most likely occur in higher waves. There were also cases where no survival was observed, and these are also marked with arrows pointing to lower wave heights.

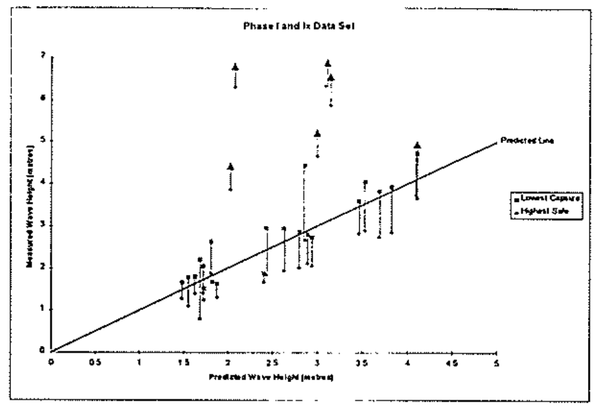

Figure 2: Predicted and Measured Capsize Wave Heights, all Phase I data

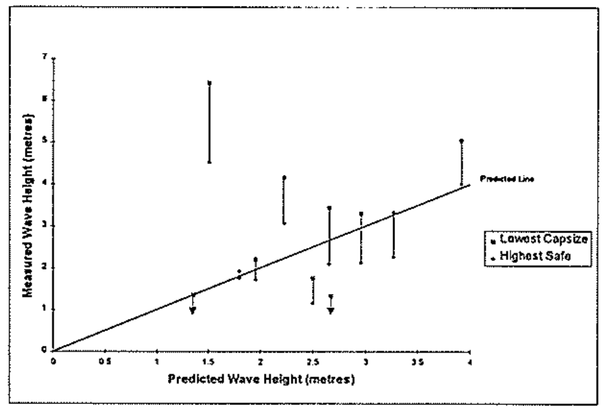

Figure 3: Predicted and Measured Capsize Wave Heights, Phase II

As can be seen, almost all the measurements bracket the predicted value for both models tested. 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 prediction capability holds good for both the large, simplified, and small 'realistic' models, answering another of the important questions regarding the method.

The data sets plotted here cover only cases with a centre casing; the set without casing is discussed at 3.4.

3.4 Effects of Supplementary Factors

Two of the factors within the SEM that the authors felt required further investigation were the regression equation linking internal water elevation and wave height, and the physical meaning of the relationship. The capsize prediction capability appeared to provide a reasonable validation of the equation, but closer examination of the significant wave height and relative motion data indicated that the relationship was more complex than implied by the SEM's basic formula. Understanding this mechanism is important for applying the SEM to deigns outside the data set used to develop the method.

Figure 4 relates the Phase I motion data at the damage opening 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 which led to the development of the SEM. The resulting equation derived during the simulations for the SEM was

$$Hsr = 3.185\ Hs^{-0.69}$$

The values derived from the analysis of the experiment data were

$$Hsr = 3.125\ Hs^{-0.54}$$

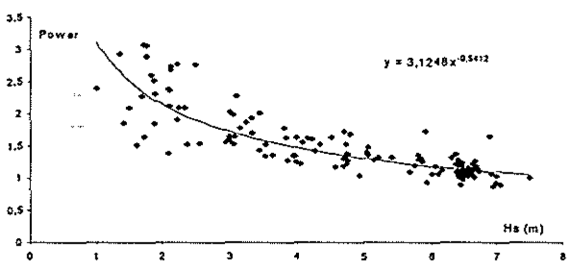

Figure 4: Regression on power p between significant height of relative motion $H_{sr} = H_s^{\ p}$ and significant wave height H_s for all data from Phase I. Average value of $p = 1.50$.

However, changing the formulation of the SEM to include the more complex relationship between Hsr and Hs does not significantly improve the accuracy of the predicted significant waveheight to cause a capsize. 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, as will be seen from discussions below.

Freeing Ports

A considerable amount of effort was used 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. Compared to a fully enclosed deck, the first arrangement 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.

Experiments with open freeing ports were reanalyzed, with the main focus on flapped ports. The SEM was not originally intended to account for either option, though it appeared probable that it could be modified relatively easily to investigate flapped ports. Comparing the results with those for the same basic ship conditions, as shown (for example) in Figure 5, the following observations were 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.

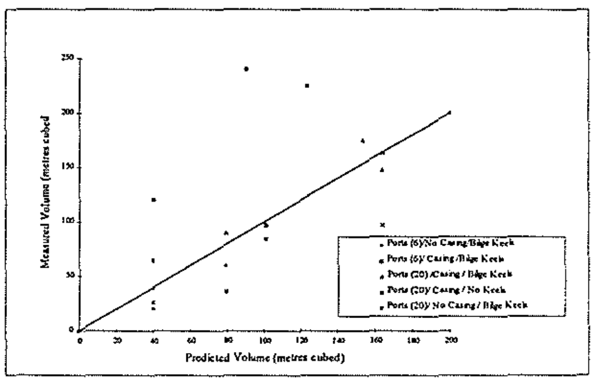

Figure 5: Phase II Volume with Ports

Unfortunately, although the first observation suggests that the basic SEM should remain applicable, insufficient time and resources were available within the project to develop a revised formulation for the wave height/water elevation relationship to account for the ports. This could probably be based on the types of inflow/outflow balancing originally proposed by Hutchison [8], but taking better account of the responses of the ship and the port flow characteristics.

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 Figure 1 and help illustrate the results discussed below.

Sea Spectrum

A very limited number of runs were made with a spectrum other than JONSWAP, 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 conditions were tested with two spectra of equivalent significant waveheights, 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 when the ITTC spectrum was used. This was 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 which 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.

Bilge Keels/Roll Motion

The experiments in Phase II treated bilge keels fitted as the standard condition, but included a small number of runs without keels. There does not appear to be anything in the data to suggest that the build-up of water between the with and without bilge keel conditions followed different relationships, although there was some difference in relative motions due to the increase in roll motion, when the bilge keels were removed. 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.

Casing Influences

The SEM predicts differences in the behaviour of ships with side, centre, or no casings, based on the differences in 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 Canadian work 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.

Figure 1 shows some of 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 previous numerical simulations [6]. 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 [9].

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. It is questionable as to 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 from a theoretical standpoint.

4. DAMAGED STABILITY CRITERIA

4.1 Deterministic Approaches

The levels (and limitations) of accuracy of the SEM are considered to be acceptable for the capsize analysis of a fairly wide range of Ro-Ro ships, in comparison with other existing or proposed methods. However, its use would involve a rather different type of criteria than those currently found in SOLAS, which would accept that safety levels for these specialized ships can be matched to expected conditions. Since the SEM 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 limit could be selected using a variety of approaches.

One might be to compare the predicted performance of a design against other vessels assessed as being satisfactory against current criteria. Here it would only be necessary to assess all the vessels against their operational wave climates. If the "successful" designs could withstand (say) an average of 80% of the 20 year maximum wave height, then this could provide a basis for the evaluation of the questionable design. Obviously, this approach would requires the analysis of a range of ships using the SEM to establish an appropriate evaluation baseline.

4.2 Probabilistic Considerations

There is general acceptance that future stability criteria should include a much more rational treatment of risk - i.e. the probability and consequences of incidents - than existing standards. In the case of ferry stability, this should in principle consider not only the wave climate (which is relatively easy to define), but also the joint probabilities of damage (location and extent), loading condition, residual capability (e.g. the ability to keep any hole on the less dangerous leeward side), and other significant parameters. An advantage of the SEM approach is that it offers an ability to generate directly comparable results for any initial damage configurations, and thus to construct a meaningful component of any desired safety index.

5. CONCLUSIONS

The results of the two experimental phases of this program compared very well with the predictions of the Static Equivalency Method for most, though not all, of the conditions investigated. This ability of the SEM to work 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.

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 SEM is based on the relationship between static head, h, and relative motion, Hsr. Relative motion was first defined as a function of waveheight and later as a function of waveheight and residual freeboard. We should note that these two equations give different probabilities of survival. The first equation will give a 50% probability, whilst the second predicts the ship will survive for one hour. Based on the results of model experiments and simulations, it appears that relative motion is a more complex function than waveheight alone. Preliminary investigation of the data in this paper does not show a better fit to the more complex equation than to the simple one, and so was omitted from this presentation.

In order to develop the SEM further, it may be necessary to get a better definition of the relationship between h and Hs. Physical model data alone is not sufficient for modifying this relationship with confidence. The combination of numerical simulation and physical model experiments for validation seems to be a more logical way to proceed.

The original data on the SEM does not quantify the amount of scatter in the predicted boundary between survival and capsize. 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 modified version is based on a pre-determined probability of survival in a given time, which partially addresses this concern.

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 forwards analytically, though it is probable that additional numerical simulations would also be required to bring the work to a conclusion.

ACKNOWLEDGEMENTS

The authors would like to thank Transport Canada, Ship Safety Branch and Transportation Development Centre for sponsoring this work, along with the Institute for Marine Dynamics and the Canadian Ferry Operators Association, who provided additional support.

We would especially like to acknowledge the contributions made by Prof. M. Pawlowski, from the University of Gdansk, who was working in North America at the time this analysis was carried out, as well as Mariusz Koniecki and David Cumming, who also made significant contributions to the work. In addition we would like to thank the numerous members of staff of the Institute for Marine Dynamics, Fleet Technology Limited and Polar Design Associates who all contributed to this project.

REFERENCES

[1] "Flooding Protection of Ro-Ro Ferries, Phase I", (Volumes 1 and 2), TP12310E, March 1995

[2] Stubbs, J. T. et al "Flooding Protection of RO-RO Ferries" Spring Meetings, RINA, 1996.

[3] "Flooding Protection of Ro-Ro Ferries, Phase I extension", (Volumes 1 and 2), TP12581E, October 1995

[4] "Flooding Protection of Ro-Ro Ferries, Phase II" TP12991E, March 1997

[5] Molyneux, W. D. et al "Model Experiments to Determine the Survivability Limits of RO-RO Ferries", Trans. SNAME, October, 1997.

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

[7] Vassalos, D. et al "Time Based Survival Criteria for RO-RO Vessels", Spring Meetings, RINA, 1998.

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

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