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MARITIME & COASTGUARD AGENCY

Research Project 571
Intact Stability Severe Wind and Rolling Criterion – An Equivalent Standard

Final Report

EXECUTIVE SUMMARY

This report describes a research project to investigate the validity of the application of the severe wind and rolling criterion, or weather criterion, to all seagoing passenger vessels on domestic voyages. Following the introduction of EC Directive 98/18, the weather criterion is to be applied to such vessels, for which it was not previously mandated. Initial submissions to the MCA have indicated that a significant number of these vessels will not comply with the criterion, although they have a record of safe operation.

In particular the project was directed at the prediction of the roll angle to windward for vessels of relatively high beam to draught ratio, which was believed to be unrealistic.

The origins of the criterion, and its development at IMO were reviewed. Other administrations have experienced problems with its application, and their research and proposals for its adjustment were studied.

A database of the UK fleet was compiled and in most cases the hull parameters were found to lie outside the envelope of data used in the development of the criterion. Five vessels were selected for modelling, representing a range of beam to draught ratios and hull forms. They were prepared for testing with variations of displacement, vertical centre of gravity and bilge keel arrangement, giving a total of nineteen model configurations. The models were somewhat smaller than generally recommended for this type of test, but an investigation of possible scale effects indicated that the results should be considered as reliable.

Tests were conducted in a towing tank, in regular beam seas representative of the conditions assumed by the weather criterion. The models were unrestrained. In each case a range of wave frequencies was used, and the maximum roll response was determined from gyroscope measurements. The very steep waves assumed in the criterion resulted in significant difficulties, requiring some development of the testing and analysis techniques.

Comparisons were made between the measured values of roll period and roll angle, with those predicted by the weather criterion. Correlation was poor in most cases, with measured roll angles being lower than predicted values for models with low beam to draught ratios, and measured values higher than predicted for high beam to draught ratios. For vessels without bilge keels the correlation was very poor, with measured roll angles considerably higher than those predicted.

Development of the prediction method was considered, using new factors that would give close correlation for the test cases. Just as the existing criterion fails to give accurate predictions for vessels outside the range of parameters used in its development, any new formula is likely to prove inadequate if applied to a wider range of vessel types. This option therefore was not adopted.

Possible alternative methods of prediction of the roll angle were not considered likely to be popular in the current international regulatory climate and so the effective wave slope coefficient and the damping factor used in the weather criterion were studied in relation to previous proposals for their adjustment. Although the test results did not correlate closely with the adjusted predictions, there was a more consistent difference between them than when using the existing factors.

Other experimenters have published data in relation to these proposals, and these were incorporated into the study in an effort to expand the effective model test database. Although their data correlated with the results of this project in some respects, their range of hull parameters was more restricted, particularly in terms of the beam to draught ratios, and showed considerable scatter. Their data provide further evidence that the weather criterion does not provide a realistic estimate of ship behaviour in the assumed conditions.

The study concluded that the weather criterion does not provide a realistic assessment of the level of safety in the assumed conditions. It recognises, however, that the international community is likely to continue to rely on the criterion in the short term. It therefore recommends that the proposals for adjustment of the criterion, which have been tabled by others for consideration at IMO, be supported on the grounds that they offer a more consistent assessment of safety across the range of beam to draught ratios of today’s fleet.

The influences of roll inertia, keels, bilge keels and bilge shape were studied, and suggestions made for clarification of the interpretation of the weather criterion.

CONTENTS

1 INTRODUCTION

This report describes a research project to study the validity of the application of the IMO Severe Wind and Rolling Criterion to UK seagoing passenger ships engaged on domestic voyages. The criterion is commonly referred to as the "Weather Criterion" or abbreviated to SWRC. The project addressed the method used in the criterion to predict the roll angle of a vessel in beam seas. Model tests were conducted on a selection of UK vessels with a range of beam to draught ratios to determine the accuracy of the existing method, and develop an alternative if appropriate. The remit for the work was described in the MCA invitation to tender ref. MSA 10/9/242, and a programme of work was described in Wolfson Unit Proposal ref. 2995bd. Award of the contract was notified by the MCA in a letter ref. MSA 10/9/242, dated 10th November 2006.

2 BACKGROUND

The current intact stability standards that are required by EC Directive 98/18 (Ref.1) are to be applied to seagoing passenger ships on domestic voyages built post October 2002, and phased in for earlier ships. The standards are contained in IMO resolution A.749(18): the Code on Intact Stability (Ref.2).

The Severe Wind and Rolling Criterion is an internationally developed recommendation, previously published as IMO Resolution A.562(14), which has not previously been mandated for United Kingdom ships. In the past, the MCA have applied to some ship types a wind pressure criterion which differed from A.562(14) in specifying a fixed angle for roll to windward, not one which is a function of hull form. The magnitude of this assumed roll to windward was never formally validated. In contrast, the roll to windward in the IMO criterion was based on semi empirical form factors, and was validated for conventional hull forms of the time. The IMO criterion is believed not to correctly predict behaviour of wide, flat bottomed ships or ships with high centre of gravity relative to the waterline. It cannot be satisfied by, typically, small ferries operating to the Scottish Isles. The current IMO criterion has been the subject of other objections, but it is the assumed roll to windward, which predicts angles not observed in some ships in service, that is the subject of this study.

The MCA suggested that the criterion should be adjusted to predict the roll to windward for such ships with greater accuracy. This would allow those of more extreme form than were considered when the criterion was developed, and which are safely operated, to show compliance. This adjustment could take the form of revising the values of X1 (B/d) and possibly of r (= 0.73 +/- 0.6 OG/d) in the formula for θ_1.

The alternative, comprising model testing of individual designs at their design stage, and the making of individual submissions to the European Commission, was not believed to be an efficient solution.

3 OBJECTIVES

The objectives stated in the Invitation to Tender were as follows:

1. Compare performances of physical or mathematical models of hull forms of conventional, with those of extreme, proportions. Regular beam seas may be assumed. At least one basis hull form and two wide beam variants should be examined.

2. Adjust the severe wind and rolling criterion so that it better predicts roll to windward as defined in that standard, so that the revised standard can be applied to more extreme forms to define a safe operational level of stability.

3. Document the analysis so as to enable submissions of the method to the European Commission, and possibly to IMO.

4 LITERATURE REVIEW

A search for relevant published work was conducted to enable a review of other studies on the subject. Research into ship stability has been a very active field for many academics and research organisations, and many documents have been published in recent years. The weather criterion has been the subject of studies in several countries, some of them with very similar objectives to this project, although generally they have been aimed at larger vessels. The documents listed in section 25 of this report represent those that have been found to have most relevance to this project, rather than a comprehensive bibliography of the wider subject.

5 DEVELOPMENT OF THE WEATHER CRITERION

The weather criterion can be traced back to proposals by Watanabe in 1938, Ref.3. A description of the origins and development of the weather criterion was presented to the IMO in 2005 by Japan, Ref. 4, and is included in the explanatory notes, in Part C of Ref.5. Over the last 70 years a number of methods have been developed to address the energy balance between beam wind heeling and righting moments. Early developments considered the application of wind on an upright vessel in calm water. The IMO criterion is based on that developed in Japan, which appears to have been the first regulation to consider the effects of rolling in beam seas, Ref.6.

The Japanese method incorporated a formula for roll amplitude of the form:

$$\phi = \sqrt{C\,r\,s\,/\,N} \qquad 1$$

Where:
ϕ is the roll angle to windward, measured from the equilibrium heel angle due to the steady beam wind.
C is a constant. Since this formula applies to synchronous rolling in regular waves, the constant includes a reduction factor of 0.7 to provide representative results in irregular waves.
N is a roll damping coefficient. In the absence of reliable formulae or more detailed data, a value of 0.02 was recommended for normal ships with bilge keels.
The remaining two parameters represent the wave forcing. s is a wave steepness factor; an estimate of the maximum wave steepness. This is a function of the natural roll period on the basis that maximum excitation occurs with a wave period equal to the ship natural roll period, and waves of long period tend to be of lower steepness.
r is an effective wave slope coefficient:

$$r = 0.73 + 0.6\,\overline{OG}\,/\,d \qquad 2$$

Where: $\overline{OG}$ is the height of the centre of gravity above the waterline, and d is the draught. This simple formula was derived from a fit to data for 60 vessels, calculated using a more precise formula derived from the Froude-Krylov hypotheseis, and presented in 1938, Ref.3.

The original Japanese method of estimating the natural roll period was regarded as tedious, and modified following the collation of measurements on 71 vessels by Morita in 1982. The following simple formula adopted by IMO gave roll period predictions within 7.5% of those measured values:

$$T = 2\,C\,B\,/\sqrt{GM} \qquad 3$$

Where: B is the moulded beam, GM is the metacentric height, and

$$C = 0.373 + 0.023(B/d) - 0.043(L/100) \qquad 4$$

Where: L is the waterline length and d is the draught.

In the Japanese method, the roll damping was not dependent on the hull form, and an alternative method, as used in the regulations of the Russian Register of Shipping, was adopted. This comprised the formula for roll amplitude of the form:

$$\phi_R = k\,X_1\,X_2\,\varphi_A \qquad 5$$

where ϕ_R is the maximum roll amplitude of 50 cycles, and φ_A is the roll amplitude of a standard ship. The other three parameters are damping factors. k is a function of bilge keel area, X_1 is a function of beam/draught, X_2 is a function of the block coefficient.

The two methods were combined to give the formula used in IMO Resolution A.562, which was adopted in 1985, and in the current IMO Intact Stability Code:

$$\text{Roll Amplitude to Windward} = C\,k\,X_1\,X_2\,\sqrt{rs} \qquad 6$$

Where:
C is a constant, with the value 109 chosen to give parity with the level of safety provided by the original Japanese method.
The damping factors k, X_1 and X_2 are functions of bilge keel area, beam/draught ratio and block coefficient, as in the Russian formula.
The wave forcing factors r and s are the effective wave slope coefficient and wave steepness factor as in the Japanese method.

The factors k, X_1, X_2 and s are presented in the Intact Stability Code in tabular form. They are reproduced in graphical form in Figure 1.

6 PROBLEMS WITH THE WEATHER CRITERION

Problems were encountered with the weather criterion shortly after its adoption by IMO, and considerable research has been conducted to address various aspects of the method and factors involved. Some criticisms were raised regarding the wind heeling aspects, but only the rolling aspects are addressed in this report.

6.1 Japan

A study was conducted in Japan on the application of their criterion to small passenger vessels, Ref.7. It included rolling tests on a number of models. The findings of this work were that their recommended damping coefficient of 0.02 was too low, and the calculated effective wave slope coefficient was too high. The latter was the same as that used in the IMO method. Both factors led to the roll angle predictions being overestimated.

6.2 Italy

In Italy, researchers were concerned with problems encountered when applying the IMO criterion to large passenger vessels, and they found that the criterion overestimated roll angle predictions for ships with large values of OG/d, B/d and roll period. Preliminary results of model tests were reported in Ref.8. Their research led to a submission to IMO in 2002, proposing significant adjustments to the criterion, Ref.9. The Italian concerns regarding the roll angle prediction were based on the following four issues.

Equation 2 was derived for vessels with values of OG/d in the range -0.4 to 0.6, whereas many modern vessels have OG/d values in excess of 1. This results in values of r substantially greater than 1, and the Italian proposal was to adopt 1 as the maximum value for r.

The tabulated list of values for X_1 has a roughly linear relationship with B/d, for B/d values in the range 2.4 to 3.5. Outside this range constant values are assumed, as illustrated by Figure 1, but many modern vessels have B/d values in excess of 3.5.

The IMO method was calibrated to give the same level of safety as the Japanese method for vessels with B/d = 2.9, C_B = 0.6, and with 2% bilge keel area, but many modern vessels differ significantly from these parameters.

The tabulated list of values for s is for vessels with roll periods of 6 to 20 seconds. Outside this range constant values are assumed, as illustrated by Figure 1, but many modern vessels have roll periods in excess of 20 seconds.

6.3 Germany

In Germany, concerns were raised regarding application of the criterion to RoRo, RoPax and some container vessels, Ref.10. Again, the concerns were that the roll angle was overestimated in some cases, but some additional factors were described.

It was pointed out that many of these vessels have GZ curves characterised by high initial stability, but with reducing slope at increasing heel angles. The roll period calculation is based on GM, but should be a function of heel angle, with greater roll periods associated with the lower effective GM at the larger angles.

Concern was also expressed that some vessels, particularly those carrying deck cargoes, have mass moments of inertia greater than the standard normally assumed, and greater than the vessels used in the development of the formulae. Many vessels have high beam draught ratios, and hence higher section added masses. This compounds the problem associated with the GM.

7 PROPOSED ADJUSTMENTS TO THE WEATHER CRITERION

These problems were raised, and discussions took place regarding possible ways of rectifying them, at IMO meetings SLF 45 and SLF 46 in 2002 and 2003.

Three adjustments to the criterion were proposed in 2002:
1. The effective wave slope coefficient, r, given by equation 2, should be assigned a maximum value of 1.
2. The table of values for the wave steepness factor, s, should be extended to larger roll periods, up to 30 seconds.
3. The table of values for the damping factor X_1 should be extended to larger beam/draught ratios, up to 6.5.

Refs. 9 and 11 present proposals by Italy and Russia for adjustments to the values r and X_1, and Figure 2 illustrates the proposals for X_1 and s. Some discussion of the proposals, and notes on the related decisions taken at these IMO meetings, are given in Ref. 12. It appears that there was some agreement on the first two of these proposals, but not the third. The submission from Germany, Ref. 13, presents the results of calculations by Germany on sample vessels using the adjusted factors, r and s, which had been proposed. Germany argued that adjusted factors might not provide a valid solution for all ship types. The sub committee agreed that, due to the interrelation of coefficients, any change of coefficients requires thorough investigation and validation, making it difficult to accomplish the revision process in the short term.

Further recommendations were for the option to use model experiments to determine some parameters of the weather criterion.

8 PROPOSED PROVISION FOR MODEL TESTS IN THE WEATHER CRITERION

The review of the Intact Stability Code resulted in proposals for model testing to be used as an alternative to calculation for some parameters of the weather criterion. Interim Guidelines for such model tests are presented in Ref. 5.

There are separate guidelines for conducting tests in a wind tunnel to determine the wind heeling moment, and in a towing tank to determine the hydrodynamic moment due to drifting, and the angle of roll to windward due to wave action.

For the latter of these there are further options. The angle may be determined by direct measurement in regular waves, although it is acknowledged in the Guidelines that such tests may prove problematic because the waves are very steep and may break, and because very large heel angles can occur, perhaps leading to capsize. This is because the weather criterion includes the assumption that the maximum roll angle in an irregular seastate will be 70% of that induced by regular waves, so such tests represent extreme circumstances with synchronous rolling. The weather criterion uses a wave of extreme steepness, with a period matching the natural roll period of the vessel, and so the synchronous rolling exhibited by the model will be a worst possible case. The method does not allow for corrections for scale effects on roll damping, so large models are preferred, increasing the difficulty and cost of testing.

In recognition of these difficulties, two alternative test methods are offered for extrapolation of the results of tests in lower wave steepness. The first is known as the “Three Steps Procedure”. The first step comprises roll decrement tests in calm water to quantify roll damping. The second step may use roll tests in beam seas of moderate steepness, or measurement of the roll excitation moment with a captive model, to determine the wave slope coefficient. The third step is an iterative calculation to determine the maximum roll angle to windward.

The second alternative procedure is known as the “Parameter Identification Technique”. This is a combination of physical and mathematical modelling, where roll response tests in regular waves of two different, moderate, steepness are used to determine parameters with which the response to steep waves can be calculated. A differential equation is provided as a recommended mathematical model.

Some organisations have followed these guidelines for the various methods, and findings have been reported in Refs. 14, 15, 16, 17, and 18. In general it has been found that the experimental options enable compliance to be achieved with lower stability than would be required using the standard weather criterion assumptions.

9 THE UK FLEET

A database of UK passenger vessels was compiled with the assistance of the MCA, and with access to a number of their files. UK vessels are classified as follows, according to the type of voyages they make:

I	Long international voyage
II	Short international voyage
II(A)	Domestic voyage, geographically unlimited
III	Domestic voyage, up to 70 miles duration and 18 miles offshore, with period restrictions
IV, V	Restricted to smooth or partially smooth waters
VI, VI(A)	Sea voyage, with geographic, passenger number and period restrictions

European classes have also been introduced, with different definitions:

European A	Unlimited (except to Europe)
European B	Roughly equivalent to III above

The database includes examples of all of these classes of vessel. Although the weather criterion is not applied to all of these classes, it was considered appropriate to include them in the database because some vessels might be subject to a change of use during their lifetime. The database excludes those classified as High Speed Craft, many of which are catamarans.

The variations of beam and draught with length are presented in Figure 3. The first graph, of beam variation with length, indicates an almost linear relationship, but the adjacent graph shows that the length/beam ratio is much lower for the smaller vessels in the fleet.

The variation of draught shows a similar trend, as illustrated by the lower left graph in Figure 3. The variation of draught with length is linear, albeit with greater variation than the beam, and the ratio of length to draught tends to be lower for the smaller vessels.

The final graph of Figure 3 presents the variation of beam/draught ratio with length. The beam/draught ratios of the smaller vessels extend over a wide range, over 9 in one extreme case, whilst the larger vessels lie in the range 3 to 5. This graph shows how the distribution of beam/draught ratio within the fleet compares with the range of beam/draught ratios for which the damping factor X_1 is tabulated in the current criterion. 87% of the fleet have beam/draught ratios greater than that covered by the current method.

Those vessels which are known to have been assessed against the weather criterion are highlighted as having passed or failed. On these graphs, the vessels that cannot comply do not show any particular trends, nor lie outside the envelope of those that pass. It must be borne in mind that the windage of a vessel is a major factor in its ability to comply with the criterion, and variations in the superstructure will have a significant influence on the distribution of these pass and fail data.

A high beam/draught ratio provides the potential for a high GM, but usually results in a low angle of maximum GZ and a low range of stability. The relationship between the angle of maximum GZ and the beam/draught ratio is presented in Figure 4. Vessels with low beam/draught ratios exhibit a wide range of maximum GZ, but there are no vessels with high beam/draught ratios and large angles of maximum GZ. Those vessels that do not comply with the weather criterion have relatively low angles of maximum GZ, and so it follows that vessels of wide beam and shallow draught are more likely to encounter difficulties with compliance.

10 SELECTION OF MODELS

The stated aim of the project was to compare performances of models of hull forms of conventional, with those of extreme, proportions. The term “conventional” referred to beam/draught ratios within the range covered by the weather criterion, that is, in the range 2.4 to 3.5. Two models of conventional form were envisaged, with three others distributed within the range of higher beam/draught ratios.

Although twenty two vessels were found to have quoted beam/draught ratios between 2.4 and 3.5, few were considered suitable for modelling. Some were sister vessels, reducing the number of different forms. Nine were over 25 years old and not representative of vessels likely to be constructed now or in the future. Six were over 100 metres long, and five were less than 24 metres long, and so outside the size range of interest. Some were considered unsuitable because they were of unusual form, for example as a result of lengthening or other modifications. The remaining vessels were of similar form and it was decided to model one only. Bearing in mind that the models could be tested at draughts different to those at which the vessels operate, it would be possible to obtain other data close to the range of beam/draught ratios covered by the criterion.

Four other vessels were selected with various forms of round bilge and chine hulls. The actual beam/draught ratios of the vessels ranged from 3.06 to 6.23. Principal dimensions of the vessels modelled are presented in Table 1, and photographs are presented in Figure 5. At the request of the vessel designers and owners, the modelled vessels have not been identified in this report. They are referred to by their Wolfson Unit model number. The models did not include hull structure above the upper deck, stern overhangs or vehicle ramps, so the LOA values quoted typically are 1 – 2 metres less than the vessels upon which the models were based.

11 MODEL CONSTRUCTION

The object of the model tests was to compare rolling behaviour of a range of hulls forms with that predicted by the weather criterion, and not to attempt to model actual full scale vessel conditions. This unusual requirement enabled some characteristics of the designs to be adjusted to suit the requirements of the test programme, particularly as there were no full scale data available for a correlation exercise.

For each vessel a model scale was selected that would enable tests to be conducted in regular waves corresponding to those assumed in the weather criterion. This resulted in the use of models about 1.8 metres in length, and smaller than recommended by the testing guidelines given in Ref. 5. The possibility of scale effects on roll damping therefore was a consideration. For this reason, the models of round bilge or double chine form were tested with bilge keels fitted to minimise scale effects, and in some cases the keels were made deeper than those on the full size vessel. Other centreline keels and skegs were fitted as designed.

The models were of strip plank on frame construction, sheathed in GRP to ensure a rugged and stable structure. They were built with a flat deck at upper deck level with a simple access hatch to facilitate ballasting and fitting of the roll gyro. Although the actual vessels might not be fully watertight to this level, their large angle stability is not considered in predicting the roll behaviour in the weather criterion, so this simplification of the designs did not affect the calculations. The high freeboard minimised the incidence of water on deck and the associated dynamic effects that might influence the roll behaviour.

Brackets were fitted on deck fore and aft to facilitate measurement of the vertical centre of gravity and roll inertia. These comprised points or knife edges that could be adjusted in height to match the required KG, from which the model was suspended in air for the ballasting procedure. The brackets formed part of the ballast and were left in place for the tests, or repositioned inside the model in such a way that the vertical centre of gravity and roll inertia remained the same.

12 TEST CONDITIONS

In general, the models were tested in a loading condition taken from the stability booklet. This was supplemented with additional conditions selected to provide a range of parameters and address specific items of interest. Variations included testing at alternative displacements, vertical centres of gravity, and with different bilge keel configurations. A full list of test conditions is presented in Table 1. The model conditions are identified by the model number, with additional letters to indicate light or heavy displacement, an alternative KG and the presence of bilge keels.

The distribution of the model conditions, in terms of their length, beam and draught, are presented in relation to the smaller vessels in the UK fleet in Figure 6. The tested beam/draught ratios ranged from 3.03 to 6.23 and, although some vessels in the fleet have more extreme beam/draught ratios, this range is representative of the majority of the fleet

Figure 7 presents the angles of maximum GZ value for the test conditions, again in relation to the available data for the fleet, and the GZ curves for each test condition are presented in Figure 8.

Each model was tested at more than one displacement. In some cases the GM was kept constant, but in others a different GM was used in order to obtain a condition such that the required test wave heights were within the capability of the towing tank.

In all test conditions the roll inertial was adjusted to a radius of gyration equal to 0.35B.

13 TEST FACILITY

The tests were conducted in No. 3 towing tank at GKN Westland, Isle of Wight. The tank is 200m long, by 4.6m wide, by 1.7m deep. It is equipped with a hinged flap wave maker capable of generating regular waves of up to 0.36 metres in height, although this is at one particular frequency, and waves generated at other frequencies are limited by wave maker mechanism characteristics, tank depth and wave breaking.

14 ROLL DECREMENT TESTS

Prior to testing in waves, roll decrement tests were conducted on each model configuration. These provided a measurement of the model natural roll period, which was used to determine the appropriate wave steepness factor, s, as defined in the weather criterion, and as a basis for the selection of wave frequencies in the roll response tests. An example of a roll decrement record is presented in Figure 9. The roll period was determined from the time taken for a number of complete roll cycles, typically about 10.

15 TEST TECHNIQUE

Each model was allowed to float unrestrained, beam on to the waves. The roll gyro required a light umbilical connection, but this was kept slack and supported directly above the model on a movable carriage. Any tendency for the model to yaw in response to the waves was minimised by manual realignment. A number of methods were used, depending on the behaviour of the particular model. Two of the models were symmetric about midships, and these required little or no realignment. Where the tendency to yaw was small, the alignment was adjusted with a hand held boat hook. Model M937, with a deep forefoot and no keel or skeg aft, had a strong tendency to turn bow towards the waves. It was fitted with a light line attached at the waterline on the transom, which was paid out or restrained manually as necessary. Model M935 had a strong tendency to move astern, but remained beam on to the waves. It was fitted with a light line near the waterline at the bow, and this remained fixed to the moving carriage. All of these techniques were used with due regard for the importance of minimal interference with the roll motions.

The model was tracked by a lightweight movable carriage, propelled manually to maintain its position relative to the model. The carriage supported the umbilical and carried all instrumentation including a wave probe and video camera. This technique enabled one experimenter to maintain model alignment and ensure that the model remained in the video camera's field of view. It also provided a local measurement of the waves encountered. The wave probe was located between one end of the model and the tank side, where waves reflected from the model might cause some interference, but it was considered that such measurements might be of use in the analysis.

A second wave probe was mounted in a fixed location between the model and the wave maker. This was at a sufficient distance from the model to eliminate any interference with the wave measurement from waves generated by the model's motion. Data monitored with this probe are presented in Figure 10.

Tests were commenced with the model 30 metres from the wave maker, and in most cases the model drifted down wave for a distance of several metres.

Typically, the first waves encountered gave a relatively large roll response. This was because the first waves tended to be higher than desired, and because the model roll response was greater with the model stationary than when the natural drift had developed. These data therefore were excluded in the analysis. Despite these large preliminary roll responses, no capsizes occurred.

The guidelines for testing given in Ref. 5 suggest the following ratios of wave frequency to natural roll frequency: 0.8, 0.9, 0.95, 0.975, 1.0, 1.05 and 1.2. In some cases these test points were found to be inappropriate because the encounter frequency was significantly different to the wave frequency. Wave frequencies therefore were selected as the tests proceeded, such that they enabled the relationship between roll response and wave frequency to be defined adequately for the purpose of the project.

16 DATA ANALYSIS AND RESULTS

16.1 Measured Wave Height

Because the waves generated were very steep, and sometimes breaking, the waves encountered by the model were not as regular as would be the case if generating waves of lower slope. This is a known problem with simulation of the weather criterion conditions, and is one of the reasons for the alternative methods of testing described in Ref. 5.

The wave height measurements were used to obtain a mean value for each run, and these were collated at the end of the test programme, as presented in Figure 10. The data were used to derive a mean curve, also presented on the graph, and this was used in the final analysis of the experimental data, in preference to the measured data for each run. It was considered that this procedure offered better accuracy and consistency, and it enabled data to be incorporated for a small number of tests where reliable wave records were not available.

16.2 Natural Roll Period

The roll decrement test records were analysed to determine the time between successive peaks in the roll motion, and hence the natural roll period. The period varies slightly with roll angle, as can be seen in Figure 11, where the model scale roll periods are presented for different model configurations.

16.3 Wave Steepness Factor

In the analysis following the tests, Figure 11 was used to determine a more accurate value of the wave steepness required by the weather criterion, using the natural roll period at the angle corresponding to the maximum roll response to the waves. In most cases the variation of period with roll angle is small, and all of the wave steepness values were in the range 0.092 to 0.1, so the final values were the same or very close to those obtained from the initial roll decrement analysis, where a value was obtained from about 10 cycles.

Because, in some cases, there were differences between the predicted natural roll period and the measured period, the values of wave steepness factor used in the test analysis were not necessarily the same as those used in the weather criterion prediction.

16.4 Roll Angles in Waves

The recorded roll angle data were inspected, in conjunction with the video records of the tests, to select test periods when the roll angles were reasonably regular and consistent, and when the model was beam on to the waves. The average roll amplitude and encounter frequency were determined from these gyro records, over as large a number of cycles as possible.

These values then were adjusted by the factor Wave Height Required / Wave height Used. The wave height required was that assumed in the weather criterion, using the natural roll period and wave steepness determined as described in section 16.3. The wave height used was that determined as described in section 16.1.

This adjustment was made on the assumption that the roll angle of the model was proportional to the wave height at that wave frequency. It is recognised that the roll motion at large amplitudes is non-linear, but it was considered that these small adjustments to the data were acceptable. In most cases they had a smoothing effect on the plots of roll angle against frequency.

The adjusted average roll angles are presented in Figure 12, plotted against the ratio of wave frequency to model natural frequency. In most cases the maximum roll angle occurred in waves of frequency similar to the model natural frequency. Whilst one might expect such a result for a stationary model, it was rather surprising in view of the fact that the models drifted with the waves so that the encounter frequency was lower than the wave frequency. The data are presented in a similar way in Figure 14, but in relation to the encounter frequency rather than the wave frequency. Unfortunately the data file for M915 was lost prior to generating these plots, so is absent from the latter.

In the case of M928 and its variants, no clear maximum roll angle was found and a linear fit has been used on the graphs. The model drift rate was relatively high, and it proved difficult to obtain an encounter frequency as high as the natural roll frequency. This was because, for waves of constant steepness, the high frequency waves were small and became unacceptable in terms of their regularity a short distance from the wave maker. This model exhibited higher roll angles in response to the higher waves at the lower frequencies. This behaviour may be the result of the very high damping provided by the hard chine hull. This trend for higher roll angles at lower frequencies may be seen as a background trend in the plots for the models with bilge keels, with a peak response at resonance superimposed upon it.

In some cases the roll angles were slightly asymmetric about upright, zero roll, attitude. In such cases the roll angles towards the waves, as addressed by the weather criterion, tended to be less than those away from the waves. In all cases, however, the roll angles presented are an average of the port and starboard values, as appears to have been customary in other studies of this subject. With a beam wind the ship would have a different equilibrium attitude and no attempt was made to simulate this in the tests, because the models represented hull forms only, and different superstructure arrangements would result in different wind heeling moments. Initial heel might affect the results but such effects were not expected to have a significant bearing on the result of this project.

16.5 Maximum Roll Angles

The maximum roll angle for each model configuration was determined by inspection of the curves presented in Figure 12. These maxima are shown on the GZ curves for each model in Figure 8.

17 OBSERVATIONS OF ROLL MOTION

The roll response to the waves, and its variation with wave frequency, was observed closely with the aid of the video records.

Those models which exhibited distinctly resonant behaviour, such as M929, were characterised by a peak roll response at a wave frequency greater than the measured natural frequency, but at an encounter frequency significantly less than the natural frequency because of drift. It is known that the resonant frequency of a forced, damped, system is lower than that determined by free vibration, so this result reflects that phenomenon. Observation of these tests confirmed that the roll motion at frequencies lower than the resonant frequency was in phase with the wave. That is, the model rolled such that the angle of the deck was in the same direction as the local wave surface. At the resonant frequency the roll angle away from the wave reached a maximum at the wave crest, and towards the wave in the trough. At frequencies above resonance the model was out of phase with the wave, rolling towards the oncoming wave slope. Photographic sequences are presented in Figure 13 to illustrate this behaviour.

Models which show a less distinct peak, with an underlying trend of larger roll angles at low frequencies, such as M935LK, showed very similar behaviour, rolling in phase at frequencies below, and out of phase at frequencies above the resonant peak. No change in the rolling behaviour was observed to explain the trend for increasing roll angle at the lowest frequencies.

Models which exhibited no resonant peak response, such as M928H, rolled in phase with the waves at all frequencies, because their drift rate was such that the encounter frequency remained lower than the resonant frequency.

Model M937K appeared to be somewhat anomalous, with a resonant peak at a wave frequency significantly lower than the natural frequency. Observation of these tests revealed that the model roll motion was in phase with the waves at ratios of wave frequency to natural frequency below 1.1, and it was the motion at a frequency ratio of 1.15 that had the characteristics of resonant motion, with maximum roll angles at the wave crests and troughs.

None of the models appeared to be in danger of capsizing during these tests, although M915 rolled to very large angles, where its stability in calm water was negligible. The waterlines at the roll angles measured do not correspond to those that would occur at the same roll angles in calm water, and the relationship depends on the wave frequency, as illustrated in Figure 13. If the vessel is in relatively long waves, so that the motion is in phase with the waves, the angle of the local wave surface relative to the hull will be less than at the same roll angle in calm water. In short waves, when the roll motion is out of phase, the water surface inclination will be relatively high. This will have implications for the likelihood of water on deck, and perhaps downflooding. It is one of the reasons frequently cited in the argument against using calm water stability characteristics in safety assessment. The finding from Ref.20, however, was that vessels in waves tend to capsize only when their roll angle exceeds their range of positive stability in calm water. There is no evidence to suggest that a vessel may be in danger of capsizing because the angle of the wave surface relative to the hull exceeds the range of positive stability.

18 COMPARISON OF RESULTS WITH WEATHER CRITERION PREDICTIONS

18.1 Roll Period

The measured roll periods are compared with those predicted by the weather criterion in Figure 15. In most cases the measured and predicted values were within 2 or 3%, but in some cases the measured values were substantially less than those predicted. This is particularly noticeable for the models tested without keels.

Close inspection of this plot reveals a trend in the ratio for each model, with a tendency for lower values with increasing displacement. This might suggest a trend of increasing ratio with increasing beam/draught ratio, but such a trend is not apparent from the data set as a whole. A search was made for trends in this ratio when plotted against other parameters, but no clear trends were found.

The reliability of the roll period prediction was claimed to be good by Morita when he developed the formula using full scale data from 72 vessels in 1982. His results are presented in Ref.5, Annex, paragraph 3.3.4.3 as a graph of C values calculated as in the weather criterion, compared with C values derived from measurements. The model roll period data were used to produce an equivalent graph for comparison, and this is presented as Figure 16. Morita's results generally fell within the +/- 7.5%

envelope indicated, but these test results do not show such close correlation, particularly for the models without bilge keels.

These results reflect similar findings by experimenters in Italy, Ref.8, who found that the weather criterion provided an overestimate of the roll period.

18.2 Maximum Roll Angles

The maximum roll angles are presented in Figure 17 to show their variation with beam/draught ratio. For clarity, Figure 17 is divided into two graphs, with models without bilge keels displayed on the first, and those fitted with bilge keels on the second.

For comparison with weather criterion predictions, three points are presented for each model configuration: Those labelled ‘SWRC’ are the values of roll angle calculated using the current formulation of the weather criterion. Those labelled ‘Proposed’ are the values calculated using proposals made to IMO in 2002 and 2003, as described in section 7. Only proposals 1 and 3, as listed in that section, are relevant here as proposal 2 refers to vessels with very large roll periods. The third points on the graphs are the ‘Measured’ values derived from these tests.

For the models without keels the measured roll angles are greater than those predicted for all but one of the models. For the model with the highest B/d ratio the measured roll was less than that predicted by the weather criterion but the same as that predicted with the proposed adjustments.

For the models with bilge keels the correlation between measured and predicted roll angles is much closer. The results follow a similar pattern, however, and the greater number of tests reveals a trend in the comparisons. It is evident that the measured values exceed those predicted at low B/d ratios, but are lower than the predictions at high B/d ratios. Furthermore, the difference between the SWRC predictions and the measured values increases as B/d ratio increases above a value of about 4.5.

Correlation between the measured values and those calculated using the proposed adjustments is better at the higher B/d ratios than with the current criterion. Measured values are greater than the predicted values in all cases apart from the three with the highest B/d ratios.

18.3 Sensitivity to Roll Inertia

In drawing conclusions from the comparisons of roll periods, one must bear in mind the fact that the roll period is proportional to the roll inertia, since:

$$\text{Roll Period} = \frac{C_A \, 2\pi \, k_{xx}}{\sqrt{g\,\overline{GM}}} \qquad 7$$

Where C_A is a factor resulting from the added inertia of the vessel rolling in water, and k_{xx} is the roll radius of gyration.

In the absence of any full scale data on roll inertia for the ships modelled, all of the models were tested with a roll radius of gyration of 0.35B. This may be lower than the typical inertias of the vessels used in the development of equation 4. A higher value of 0.4B is assumed by some technicians, and Ref.10 refers to some modern RoRo vessels where this value is too low an estimate. If the models had been ballasted with a higher roll inertia the measured roll periods would have been greater. Using equation 7, estimates were made of the roll periods that would have been measured had the models been ballasted to the value 0.4B, assuming that the added inertias remained the same, and these were used to adjust the values presented in Figure 16. The adjusted values are presented in the right hand graph of that figure. All of the data for models without bilge keels fall within the 7.5% envelope. They are generally lower than the calculated values, but that may be expected as their added inertia is relatively low. Some of the models with bilge keels lie above the 7.5% envelope, but again, that may be expected because some of the bilge keels were very large, providing more added inertia than for typical ships.

This exercise suggests that the models were tested with roll inertias lower than those of the vessels used in the development of the criterion, and demonstrates the sensitivity of the roll period to roll inertia. The roll inertias of small domestic passenger vessels is likely to be highly variable. Vessels with relatively wide beam and little superstructure will have a relatively low ratio of radius of gyration to beam. Vessels with a single open car deck with accommodation above might have a relatively high ratio, because the ship structure is concentrated in a ring with little or no weight near the centre. This variation will decrease the accuracy of the roll period estimate because it does not incorporate an estimate of roll inertia.

If the models had been tested with greater roll inertia, their roll periods would have been greater. In some cases this would have led to a lower value of the wave steepness, s, although in many cases it had the maximum value of 0.1 and would not have been affected. In those cases where the wave steepness would have been lower, notably some of the models without bilge keels, the maximum roll angle also would have been reduced. An estimate of the roll angles that would have been measured was made by adjusting the measured angles by the ratios of wave steepness, and the derived values are presented in Figure 18. The differences between these estimated roll angles and those measured illustrate the dependence of the roll angle on the roll inertia. This 14% difference in the dry inertia of the vessel results in a reduction in the roll angle of less than 1 degree in most cases.

18.4 The Effects of Keels and Skegs

The predicted values presented in Figure 17 were calculated on the assumption that all lateral keel areas should be included in the calculation of A_k. The Intact Stability Code defines A_k as *total overall area of bilge keels, or area of the lateral projection of the bar keel, or sum of these areas*. Inspection of calculations approved by the MCA, and correspondence with consultants who submit calculations for MCA approval, suggested some differences of interpretation in terms of what areas have been allowed for inclusion. In some cases all keels, skegs and thruster struts were included, whereas in other cases only bilge keels and bar keels were allowed. To quantify the effects of such differences, the predictions presented in Figure 17 were re-calculated with all centreline keels and skegs excluded. Although the Code specifies that bar keels should be included, on these models their areas were small in relation to the skegs, and to include them would have required some subjective judgment regarding their definitions. Excluding all centreline keel areas therefore was a simpler option. This affected models M915, M929, M935, and their variants. The alternative derivations of the factor k are shown in Table 3, where the differences have been highlighted, and revised versions of the roll angle plots are presented in Figure 19.

The effect of reducing the keel area is to increase the predicted roll angle because of the reduction in damping. The relevant factor, k, is limited however, and may not be less than 0.7 regardless of how large the area of keels might be.

Correlation between the measured roll angles and the values predicted is closer with the centre keels excluded. This is most noticeable for the models without bilge keels. The centreline keels and skegs contribute to the damping in a similar way to bilge keels, and so it does not seem reasonable to exclude them in the predictions. The closer correlation perhaps is misleading and should be treated with caution.

18.5 The Definition of 'Sharp Bilges'

The weather criterion specifies the minimum value of the factor k, of 0.7, *for a ship having sharp bilges* but these are not defined in the text of the Code. A definition is given, however, in Ref.5, in a footnote to Annex 1, paragraph 2.3.2: *"sharp bilges" used here means that bilge radius is smaller than 1% of the ship's breadth and the angle between piece-wise lines representing the bilge is smaller than 120°.*

Model M928 has very sharp bilges, but has a high B/d ratio, where few of the weather criterion predictions correlate well with the measured values. M937 has a double chine hull form that some might interpret as sharp bilges. The weather criterion predictions were calculated for this model, and its variant M937H, using k values of 1.0 and 0.7, and using both the current and proposed IMO factors. The results are tabulated below, together with the measured values.

Model	Predicted roll	Predicted roll	Predicted roll	Predicted roll	Measured roll
	Current IMO method		Proposed adjustments to IMO method		
	k=0.7	k=1.0	k=0.7	k=1.0	
M937	20.4	29.2	15.5	22.1	21.70
M937H	18.5	26.5	17.5	25.0	27.65

The closest correlation with the measured value is highlighted in each case. In one case the current method provides the closest correlation and in the other closer correlation is with the proposed adjustments. In both cases, however, the values calculated assuming that the vessel has round bilges give the best correlation. It appears this double chine form therefore should be considered as equivalent to a round bilge vessel in terms of the damping offered by these soft chines.

This result supports the definition given in Ref.5, because the angles at both of the chines are greater than 120 degrees.

19 POSSIBLE SCALE EFFECTS

The models used in this project were smaller than recommended in Ref.5, Annex 1. Those guidelines for testing suggest that models should be not less than 2 metres long overall, or a scale of 1:75, whichever is greater. Compared with typical models of large ships these models were of relatively large scale, ranging from 1:20 to 1:40, but were between 1.67 and 1.85 metres long. The guidelines also suggest that models of round bilge form without bilge keels or sharp chines should be at least 4 metres long, so it is possible that the results for models without bilge keels may be subject to scaling errors.

With small models the skin friction resistance coefficient is higher than at full scale, even if flow at the bilge is laminar, so the frictional damping is expected to be greater on the models, and the roll angles therefore reduced.

The models most likely to be affected by a scaling error were M915, M929, M929H and M929L, all of them round bilge hulls with no bilge keels. The measured roll angles for these were all significantly greater than predicted by the weather criterion however.

The roll damping coefficient normally referred to in studies of rolling and the weather criterion is Bertin's N coefficient:

$$\mathrm{N}_{\phi_{\mathrm{m}}} = \frac{\delta\phi}{\phi_{\mathrm{m}}{}^{2}} \tag{8}$$

Where $\delta\phi$ is the difference between consecutive roll angles, and ϕ_{m} is the mean roll angle. Thus, N varies with roll angle. In the original Japanese method of the weather criterion, the value of N_{20} was assumed to be 0.02 for "normal" ships with bilge keels. Some experimental data are presented in Ref.5, and these are reproduced here as Figure 20. They suggest that the value of 0.02 is reasonable for the vessels illustrated, and that the value of N at 10 degrees is somewhat higher.

Values were derived from the roll decrement tests for each model configuration, and are presented in Table 4. There is a marked difference between the values for models with and without keels, as might be expected. The models tested without bilge keels or sharp bilges have lower N coefficients, commensurate with their lower damping.

A procedure is given in Ref.5, Annex 1, paragraph2.6.1.2, for correction of N to account for frictional scale effects. Using this formula the corrections calculated for N_{20} were in the range 0.0002 to 0.0007, and for N_{10} were in the range 0.0004 to 0.0014. These are relatively small corrections to the measured N values. The adjusted values, which have been reduced by subtracting the corrections from the measured values, are presented in Figure 21 for comparison with those presented in Ref.5. For the models with bilge keels, the values for N_{20}, in general, are greater than those given in Ref.5 but it should be borne in mind that some of the models tested had bilge keels larger than typically fitted to ships.

The corrections to N were found to be small and, if applied as an adjustment to the measured roll angles, would result in increases of between 0.1 and 1.85 degrees. The roll angles used here in the correlation between weather criterion predictions and model tests are the angles in irregular waves, so these adjustments need to be reduced with the factor 0.7. The potential scaling errors in the correlation therefore are only in the range 0.07 to 1.3 degrees, where the angles measured in the tests might be too small. Since the corrections were small and not considered to be precise, it was not considered worthwhile to adjust the measured data. The data are considered to be reliable in relation to the expectations of the predictions.

Other experimenters have come to similar conclusions regarding scale effects on small models. Ref.7 describes tests on eight small models, some of them less than 1.5 metres long. The experimenters conducted roll tests at full scale on one small vessel and found good correlation with tests on the 1:10 scale model of just 1.2 metres LBP.

20 POSSIBLE ADJUSTMENTS TO THE WEATHER CRITERION

On the basis of these test results one may attempt to adjust one or more factors in the weather criterion method.

20.1 Effective Wave Slope Coefficient

The formula used for this factor, r, in the weather criterion is an approximate one. The Froude-Krylov hypothesis gives a rather more complicated formula, as presented in Ref.3, and again in Ref.7, but this has been considered inappropriate for general regulatory purposes. The Froude-Krylov formula was used to calculate the effective wave slope coefficients for the model configurations to assess the validity of the weather criterion approximation. The results are presented in Figure 22.

It is apparent that the approximate formula gives an overestimate of the coefficient. This supports the findings presented in Ref.7, which concludes that the approximate formula provides small craft with excessive exciting roll moment. The graph also provides some support the proposal to IMO, to limit r to a maximum value of 1.0.

If these calculated values of r are substituted into the weather criterion predictions, they reduce the predicted roll angles in most cases. This results in greater differences between the predicted values and those measured in the tests, as illustrated by comparison of Figure 23 with Figure 22.

20.2 Damping Factor X_1

Together with the effective wave slope coefficient, this was also the subject of the Russian submission to the IMO in 2003, where an extension of the tabulated values of X_1 was proposed. Assuming that all other factors of the current formula are valid, we may derive values for X_1 that would give predicted roll angles equal to the measured values. The result is illustrated in Figure 24, where the differences between the values presented in Figure 17 have been eliminated by adjusting the value of X_1 as necessary. A solid line has been fitted through the data to indicate the relationship that these results suggest for the variation of X_1 with B/d. The data for models without keels or chines (M915, M929, M929H and M929L) have not been included here. Much greater X_1 values would be required to correlate their measured and calculated roll angles.

A second data set is presented in Figure 24, fitted with a broken line, and these values have been calculated in the same way, but assuming that the values of r are not greater than 1.0, as proposed to the IMO by Russia in 2002.

It is interesting to note that the lines intersect the line for the Russian proposal near the middle of its B/d range, but are parallel with the IMO line, denoted SWRC on the graph. Although the Russian proposal has been harmonised with the current IMO tabulated values, it does not form a fair extension of the original line, and the existing IMO values were not affected. The Russian proposal was formulated following model tests on 15 vessels ranging in length from 50 to 182 metres. Ten of the vessels had B/d ratios between 3.60 and 5, and the remaining five extended the range up to 6.96. Their results are presented in Ref.21. This includes a graph similar to Figure 24, but with very little scatter of the data points through which their curve was fitted. The paper is in the Russian language and a translation has not been obtained so the details of their testing and analysis are unclear.

20.3 Problems Associated with Adjustment

The weather criterion was developed around experimental data and, it is understood, gave reasonably reliable predictions of their behaviour. The difficulties that naval architects have experienced with the application of the criterion for various modern ship types have prompted a number of proposed adjustments or modifications. With regard to the rolling prediction these have been proposals for adjustments to one or more factors in the roll angle formula.

These have been discussed at great length, at IMO and elsewhere. The argument made against adjustment of a particular factor is that all of the factors were developed together and therefore are inter-related. Adjustment of one factor, on the basis of tests on a particular ship type, may render the method less accurate for other types of ship. See, for example, Ref.13,

21 OTHER DATA

Other experimenters have conducted similar tests to study the weather criterion, and model test results have been presented in Refs.8 and 15. Their results are presented in Figure 25, in the same format as Figure 17 for ease of comparison. The Italian experimenters found that the weather criterion generally overestimated the roll angles. Their models had B/d ratios in the range 4.16 to 4.74. It is within this range that the correlation in this study changed from an under prediction to an over prediction by the weather criterion. The Japanese study presents data for only one model, and in this case the weather criterion gave a substantial under prediction at a B/d ratio of 4.12, which compares closely with the findings of this study.

To facilitate comparison of these various experimental results they have been plotted together in the form of a ratio of measured to calculated values, using the current IMO method, in Figure 26. Lines have been fitted through the data derived in this study. Although the correlation between measurement and prediction seem rather poor, they are closer than found by the other experimenters.

22 COMMENT ON THE GENERAL PRINCIPLE OF THE WEATHER CRITERION

This criterion attempts to represent the scenario of a vessel beam on to the highest and steepest waves, excluding breaking waves, that may be encountered with a period that corresponds to the natural roll period of the vessel. That is, the worst possible wave conditions in terms of roll behaviour. The waves represented can be regarded as extremely severe, as revealed by Table 5. In addition to this, the vessel is subjected to an extreme wind gust at the worst possible phase of the roll motion.

A master would not willingly subject his vessel to such severe conditions, and the situation would only occur if the vessel were disabled in some way, such as with a loss of propulsion or steering. The combination of these factors all occurring together is highly improbable.

In this respect the scenario may be considered as similar to damage stability criteria, where the probability of suffering damage in the most severe seastates is not considered to be sufficiently high to justify regulation. Damage stability requirements for passenger vessels, therefore, typically assume much lower seastates.

It is the opinion of the Wolfson Unit that the weather criterion is unrealistically onerous. There have been many suggestions for improving the accuracy of the method because for many vessels the criterion is a critical one and restricts the design, frequently when other stability criteria indicate a good margin of safety. The accuracy with which the criterion represents real conditions and vessels' responses to them appears to be unreliable and, while we may continue to refine the criterion to improve this situation, it is suggested that the fundamental philosophy behind it should be reconsidered.

This opinion is not shared by all researchers. Ref.22, for example, suggests that it should be possible to achieve a satisfactory criterion, albeit with substantial further development, while Ref.23 concludes that the weather criterion does not provide an adequate level of safety. Perhaps the range of opinions is indicative of the unreliable nature of the method, and the difficulties associated with predicting the behaviour in extreme situations.

23 RECOMMENDATION

It is appreciated that, whilst the weather criterion may not be a satisfactory method of assessing safety, it is unlikely to be replaced by an alternative in the short term. For this reason it is recommended that support be given to the Russian and Italian proposals to IMO, and that these adjustments to the weather criterion be used in the application of EC Directive 98/18.

The ratio of measured roll angle to that predicted by the weather criterion with the proposed modifications is included on Figure 26.

The adjusted method does not provide a reliable estimate of the roll response, but it appears to give closer and more consistent correlation with the experimental data. It will, therefore, offer a more consistent measure of safety and is less likely to penalise some types of vessel.

24 CONCLUSIONS

1. Five ship models have been tested in a total of 19 configurations. The results provide roll period and roll angle data representative of vessels with a wide range of hull forms and beam/draught ratios.

2. The weather criterion does not provide a reliable estimate of the roll angle experienced by a vessel in the dead ship condition, beam on to extreme waves. The method is particularly unreliable for vessels without bilge keels, where it gives an under estimate, and for vessels with large beam/draught ratios, where it gives an over estimate.

3. The modifications proposed to the IMO by Russia and Italy improve the accuracy of the estimate for vessels of large beam/draught ratio, but not for vessels of low beam/draught or those without bilge keels. These modifications provide roll estimates that show a more consistent correlation with the model test data.

4. It is recommended that the Russian and Italian proposals be supported, and used in the application of the criterion in EC Directive 98/18 to provide a more consistent assessment of the level of safety of vessels, regardless of the beam/draught ratio. The method should not, however, be regarded as providing a reliable representation of actual vessel behaviour.

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Table 1 Principal dimensions of the vessels modelled

Model	LOA	LWL	BWL	d	B/d	Disp.	Cb	KG	GM	OG/d	Scale
	m	m	m	m		tonnes		m	m		
Models without bilge keels											
M915	70.6	67.8	15.2	2.95	5.17	1640	0.525	6.570	3.03	1.23	40
M929	64.6	58.4	13.8	3.55	3.90	1436	0.489	6.133	2.10	0.73	35
M929H	64.6	58.4	13.8	3.80	3.64	1601	0.509	5.908	2.10	0.55	35
M929L	64.6	58.4	13.8	3.30	4.19	1276	0.467	5.700	2.82	0.73	35
M937	47.5	41.5	11.4	2.10	5.45	607	0.594	4.00	2.86	0.90	27
M937H	47.5	43.0	11.5	2.65	4.34	833	0.620	4.00	2.01	0.51	27
Models with bilge keels											
M915K	70.6	67.8	15.2	2.95	5.17	1640	0.525	6.570	3.03	1.23	40
M915HK	70.6	67.8	15.2	3.20	4.76	1851	0.547	6.167	3.03	0.93	40
M928	33.4	30.2	10.0	1.60	6.23	288	0.583	3.010	6.16	0.88	20
M928G	33.4	30.2	10.0	1.60	6.23	288	0.583	4.000	5.17	1.50	20
M928H	33.4	30.2	10.0	1.82	5.47	354	0.631	3.430	4.47	0.88	20
M929K	64.6	58.4	13.8	3.55	3.90	1436	0.489	6.133	2.10	0.73	35
M929HK	64.6	58.4	13.8	3.80	3.64	1601	0.509	5.908	2.10	0.55	35
M929LK	64.6	58.4	13.8	3.30	4.19	1276	0.467	5.700	2.82	0.73	35
M935K	34.2	34.8	9.1	2.85	3.19	559	0.605	2.60	1.86	-0.09	20
M935LK	34.2	34.8	9.1	2.6	3.49	494	0.586	2.60	1.97	0.00	20
M935HK	34.2	34.8	9.1	3.0	3.03	599	0.616	2.60	1.81	-0.13	20
M937K	47.5	41.5	11.4	2.10	5.45	607	0.594	4.00	2.86	0.90	27
M937HK	47.5	43.0	11.5	2.65	4.34	833	0.620	4.00	2.01	0.51	27

Table 2 Weather criterion calculation

Model	C	T	OG/d	k	X1	X2	r	s	θ1	X1	r	θ1
				Using current weather criterion						Using proposed mods		
Models without bilge keels												
M915	0.463	8.10	1.23	0.81	0.800	0.85	1.47	0.092	22.1	0.706	1.00	16.1
M929	0.437	8.35	0.73	0.74	0.800	0.81	1.17	0.091	16.9	0.784	1.00	15.4
M929H	0.432	8.24	0.55	0.74	0.800	0.83	1.06	0.091	16.7	0.790	1.00	16.0
M929L	0.444	7.31	0.73	0.74	0.800	0.78	1.17	0.096	16.7	0.770	1.00	14.9
M937	0.480	6.50	0.90	1.00	0.800	0.94	1.27	0.099	29.2	0.685	1.00	22.1
M937H	0.454	7.36	0.51	1.00	0.800	0.96	1.04	0.097	26.5	0.768	1.00	25.0
Models with bilge keels												
M915K	0.463	8.10	1.23	0.70	0.800	0.85	1.47	0.092	19.1	0.706	1.00	13.9
M915HK	0.453	7.94	0.93	0.70	0.800	0.88	1.29	0.093	18.6	0.738	1.00	15.1
M928	0.503	4.04	0.88	0.70	0.800	0.93	1.26	0.100	20.1	0.630	1.00	14.1
M928G	0.503	4.41	1.50	0.70	0.800	0.93	1.63	0.100	22.9	0.630	1.00	14.1
M928H	0.486	4.58	0.88	0.70	0.800	0.96	1.26	0.100	20.8	0.680	1.00	15.8
M929K	0.437	8.35	0.73	0.70	0.800	0.81	1.17	0.091	16.1	0.780	1.00	14.5
M929HK	0.432	8.24	0.55	0.70	0.800	0.83	1.06	0.091	15.8	0.790	1.00	15.2
M929LK	0.444	7.31	0.73	0.70	0.800	0.78	1.17	0.096	15.8	0.770	1.00	14.1
M935K	0.431	5.75	-0.09	0.70	0.862	0.95	0.68	0.100	16.3	0.862	0.68	16.3
M935LK	0.438	5.68	0.00	0.70	0.802	0.94	0.73	0.100	15.5	0.802	0.73	15.5
M935HK	0.428	5.77	-0.13	0.70	0.894	0.96	0.65	0.100	16.7	0.894	0.65	16.7
M937K	0.480	6.50	0.90	0.73	0.800	0.94	1.27	0.099	21.2	0.690	1.00	16.2
M937HK	0.453	7.29	0.51	0.73	0.800	0.96	1.04	0.097	19.4	0.770	1.00	18.3

Table 3 Alternative derivations of the factor k

Model	Area of keel & skegs	Area of bilge keels	Total area, A_k	$100A_k/LB$	k	$100A_k/LB$	k
	m^2	m^2	m^2	All keels & skegs included		Bilge keels only	
Models without bilge keels							
M915	24.62	0.00	24.62	2.38	0.810	0.00	1.000
M929	25.08	0.00	25.08	3.11	0.740	0.00	1.000
M929H	25.08	0.00	25.08	3.11	0.740	0.00	1.000
M929L	25.08	0.00	25.08	3.11	0.740	0.00	1.000
M937	0.00	0.00	0.00	0.00	1.000	0.00	1.000
M937H	0.00	0.00	0.00	0.00	1.000	0.00	1.000
Models with bilge keels							
M915K	24.62	35.00	59.62	5.77	0.700	3.39	0.725
M915HK	24.62	35.00	59.62	5.77	0.700	3.39	0.725
M928	0.00	0.00	0.00	0.00	0.700	0.00	0.700
M928G	0.00	0.00	0.00	0.00	0.700	0.00	0.700
M928H	0.00	0.00	0.00	0.00	0.700	0.00	0.700
M929K	25.08	19.94	45.02	5.57	0.700	2.47	0.790
M929HK	25.08	19.94	45.02	5.57	0.700	2.47	0.790
M929LK	25.08	19.94	45.02	5.57	0.700	2.47	0.790
M935K	11.81	13.60	25.41	8.03	0.700	4.30	0.700
M935LK	11.81	13.60	25.41	8.03	0.700	4.30	0.700
M935HK	11.81	13.60	25.41	8.03	0.700	4.30	0.700
M937K	0.00	16.00	16.00	3.37	0.730	3.37	0.730
M937HK	0.00	16.00	16.00	3.24	0.730	3.24	0.730

Table 4 Measured values of the damping coefficient, N

Model	Measured	
	N @ 20°	N @ 10°
Models without bilge keels		
M915	-	-
M929	0.011	0.010
M929H	0.010	0.009
M929L	0.010	0.009
M937	0.011	0.015
M937H	0.007	0.009
Models with bilge keels		
M915K	0.026	0.044
M915HK	0.028	0.041
M928	0.029	0.051
M928G	0.030	0.045
M928H	0.025	0.037
M929K	0.026	0.038
M929HK	0.030	0.041
M929LK	0.028	0.038
M935K	0.016	0.024
M935LK	0.019	0.026
M935HK	0.015	0.022
M937K	0.018	0.029
M937HK	0.014	0.022

Table 5 Wave characteristics assumed by the weather criterion for the vessels modelled

Model	LOA	T	s	Wave length	Wave height	Probable Beaufort Force
	m	Measured s		m	m	
M915	70.6	6.79	0.098	72	7.1	8-9
M929	64.6	7.16	0.097	80	7.8	8-9
M929H	64.6	6.82	0.098	73	7.1	8-9
M929L	64.6	6.62	0.099	68	6.8	8-9
M937	47.5	5.50	0.100	47	4.7	7-8
M937H	47.5	5.98	0.100	56	5.6	8
M915K	70.6	8.22	0.092	105	9.7	9-10
M915HK	70.6	7.78	0.094	95	8.9	9-10
M928	33.4	3.92	0.100	24	2.4	5-6
M928G	33.4	4.49	0.100	31	3.1	5-6
M928H	33.4	4.22	0.100	28	2.8	5-6
M929K	64.6	8.07	0.093	102	9.5	9-10
M929HK	64.6	7.50	0.095	88	8.3	9
M929LK	64.6	7.35	0.096	84	8.1	9
M935K	34.2	5.63	0.100	49	4.9	7-8
M935LK	34.2	5.67	0.100	50	5.0	7-8
M935HK	34.2	5.74	0.100	51	5.1	7-8
M937K	47.5	5.89	0.100	54	5.4	7-8
M937HK	47.5	6.40	0.099	64	6.3	8

Figure 1 Factors presented in the IMO Weather Criterion

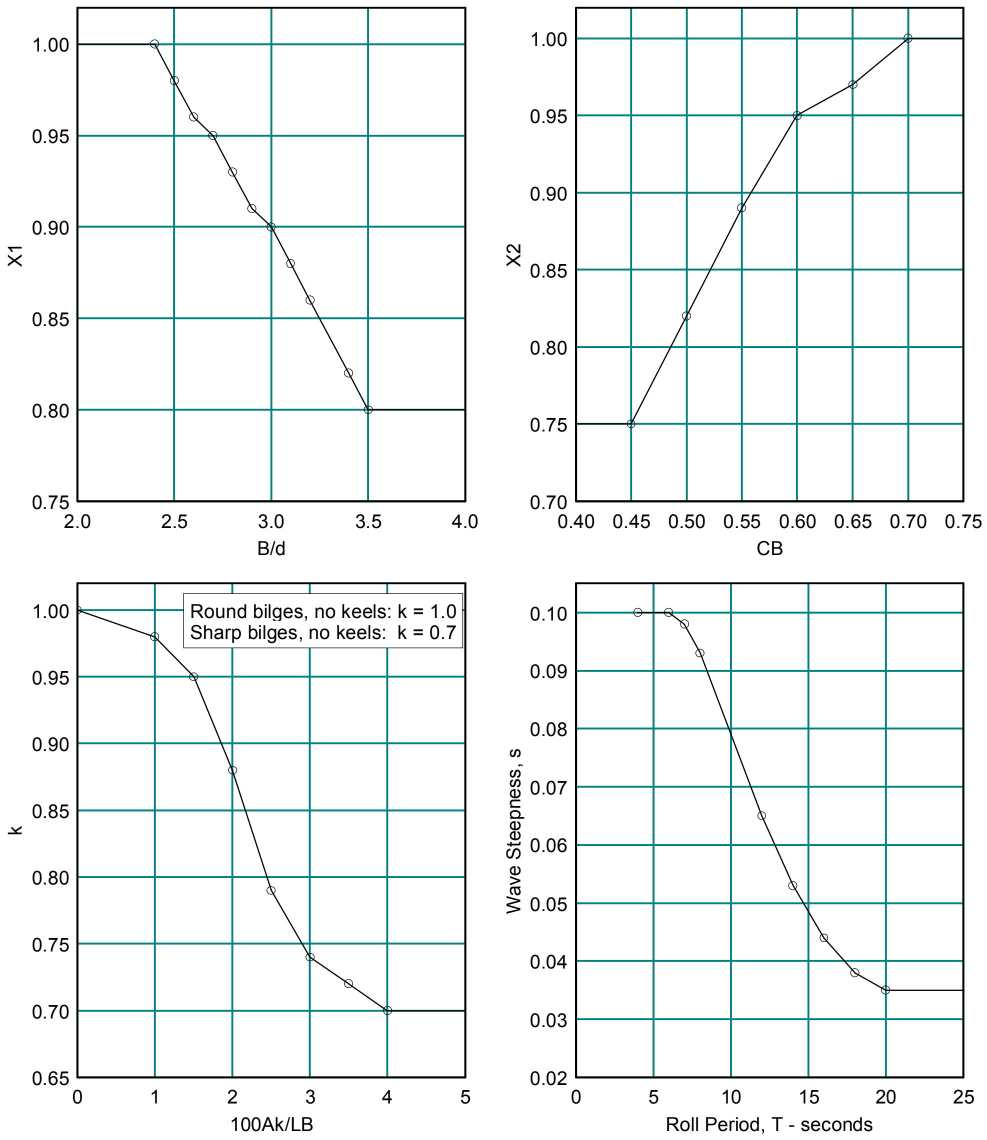


Figure 2 Proposed adjustments to factors presented in the IMO Weather Criterion

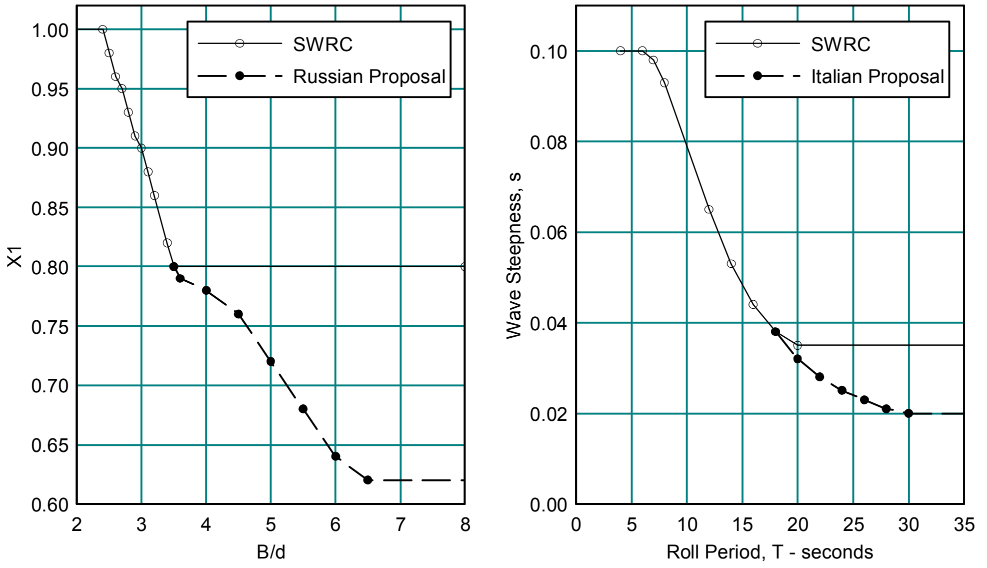


Figure 3 Variation of length, beam and draught within the UK fleet

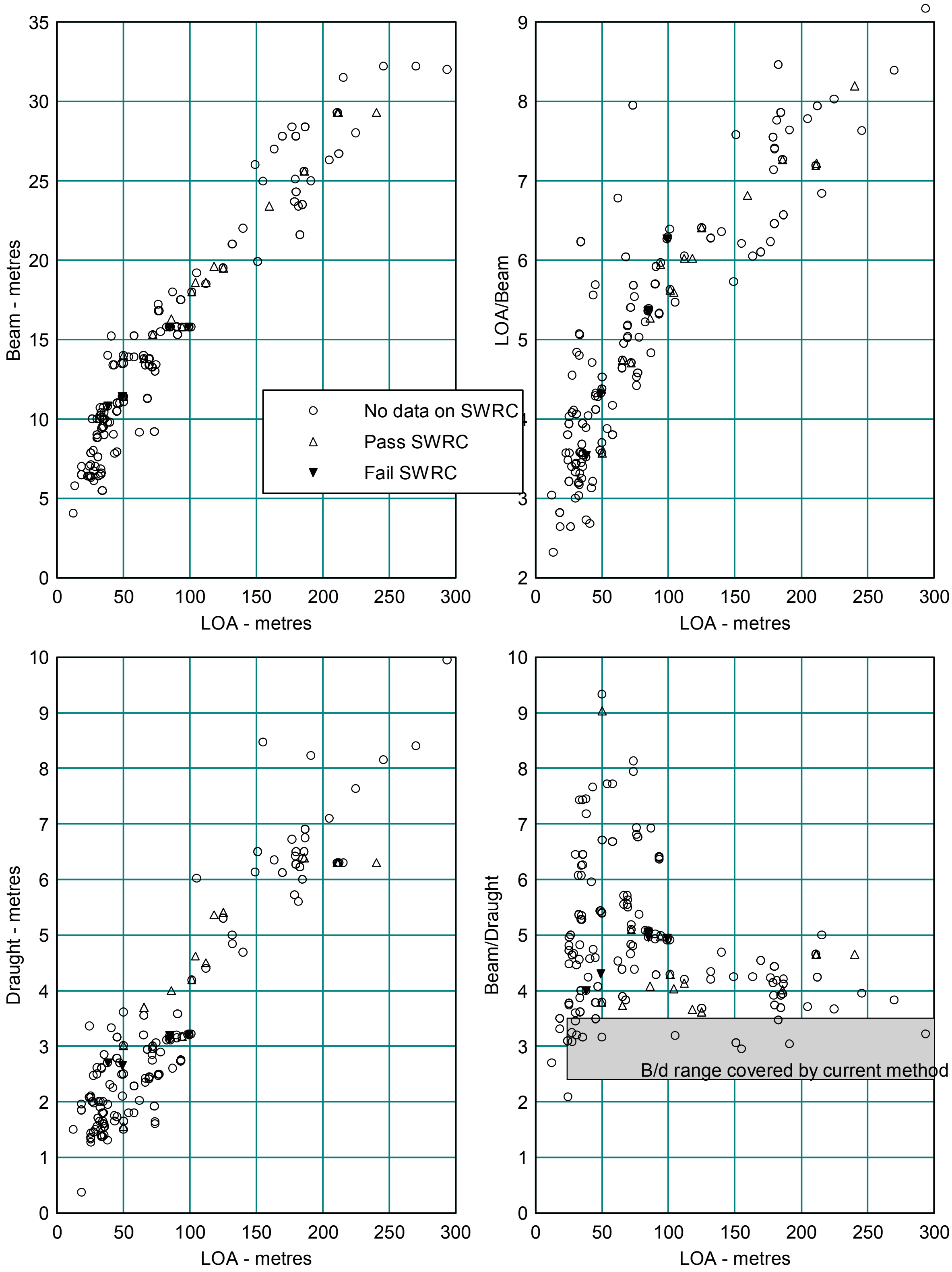


Figure 4 Variation of the angle of maximum GZ with the beam/draught ratio

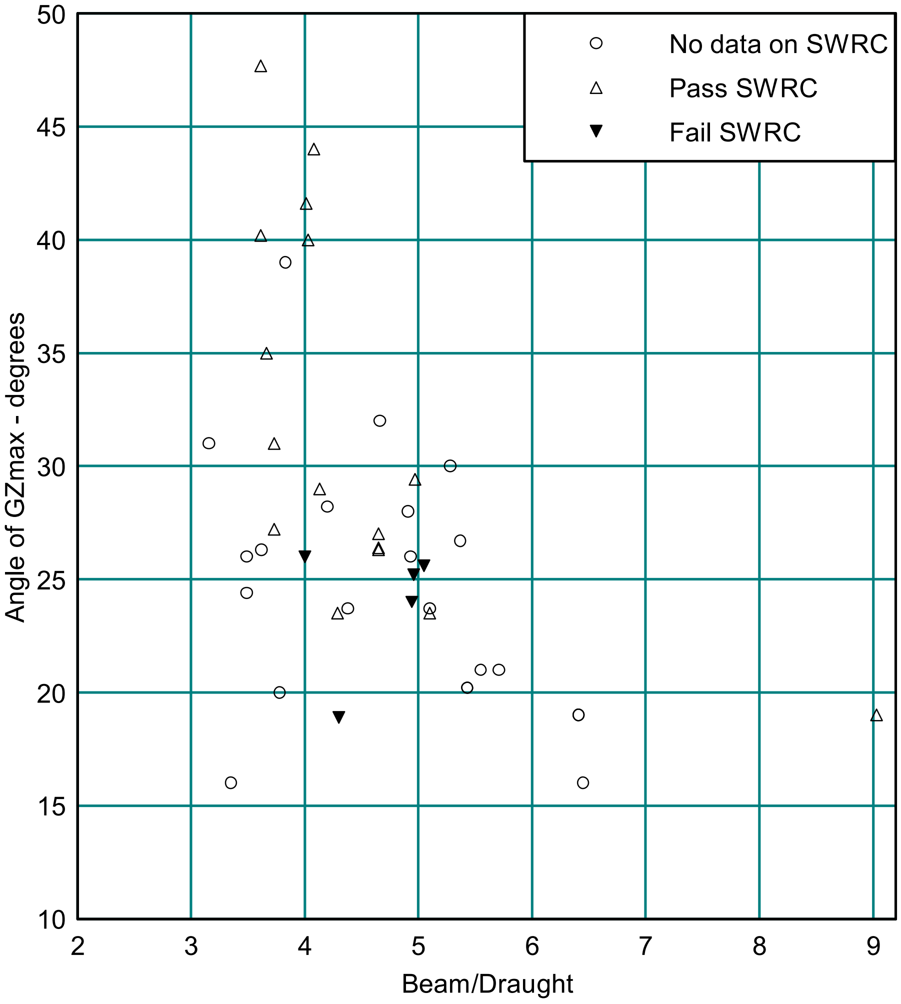


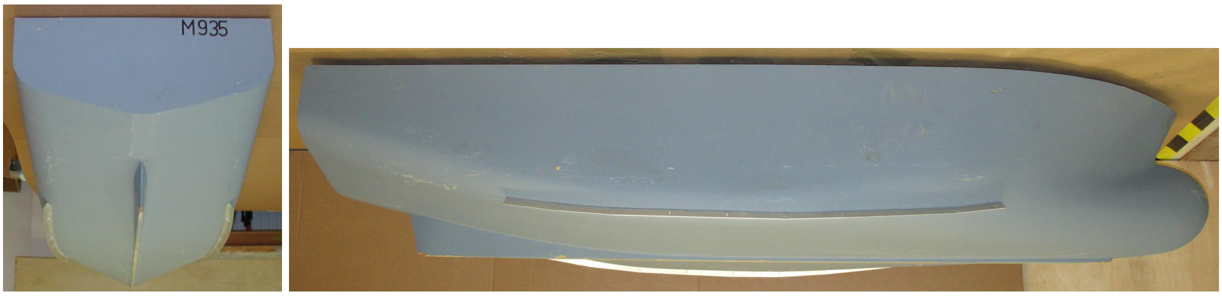
Figure 5 Photographs of the models, from the stern and starboard side

M915

M928

M929

M935



M937

Figure 6 Distribution of the model configurations in relation to the fleet

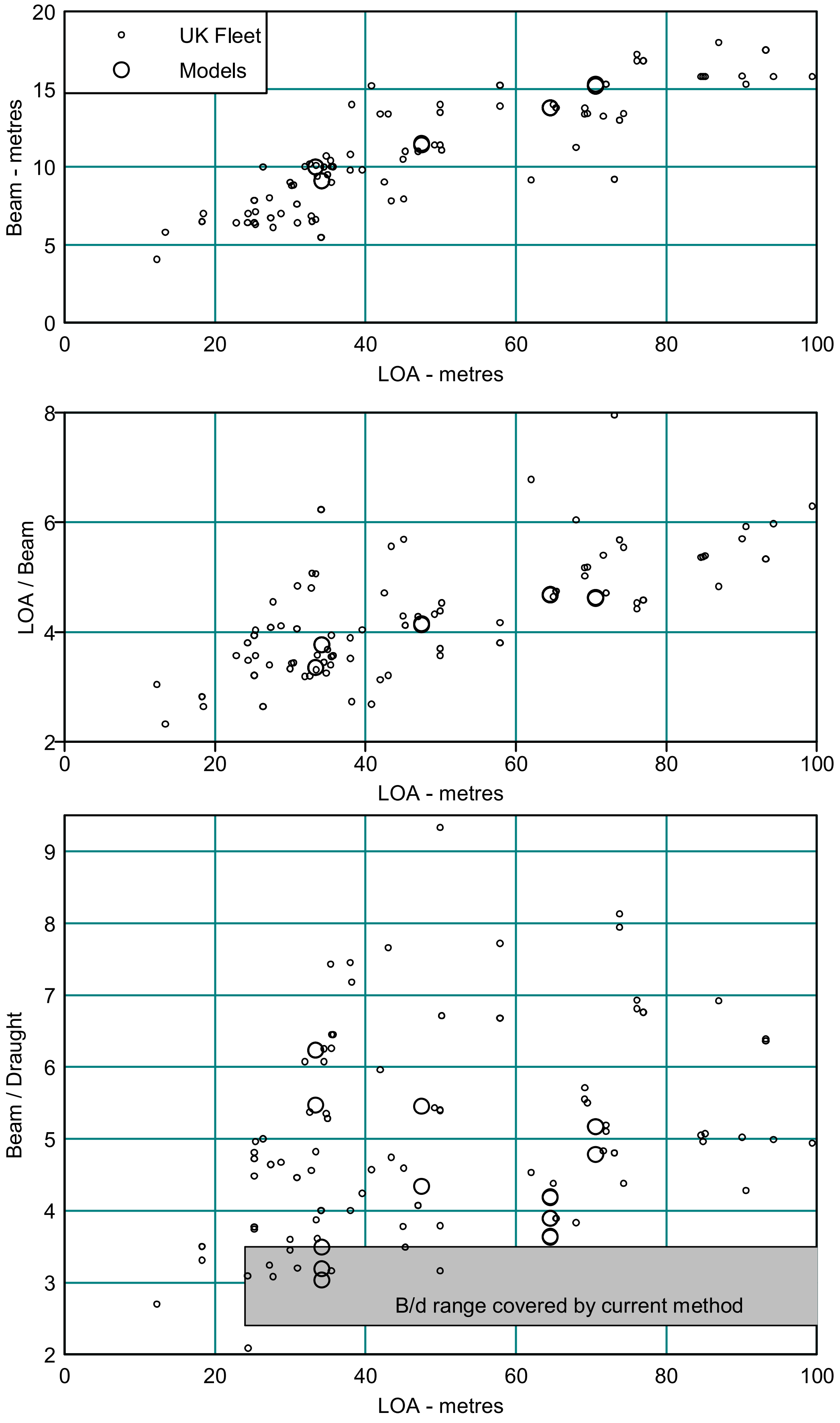


Figure 7 Angles of maximum GZ for the models, compared with those of the fleet

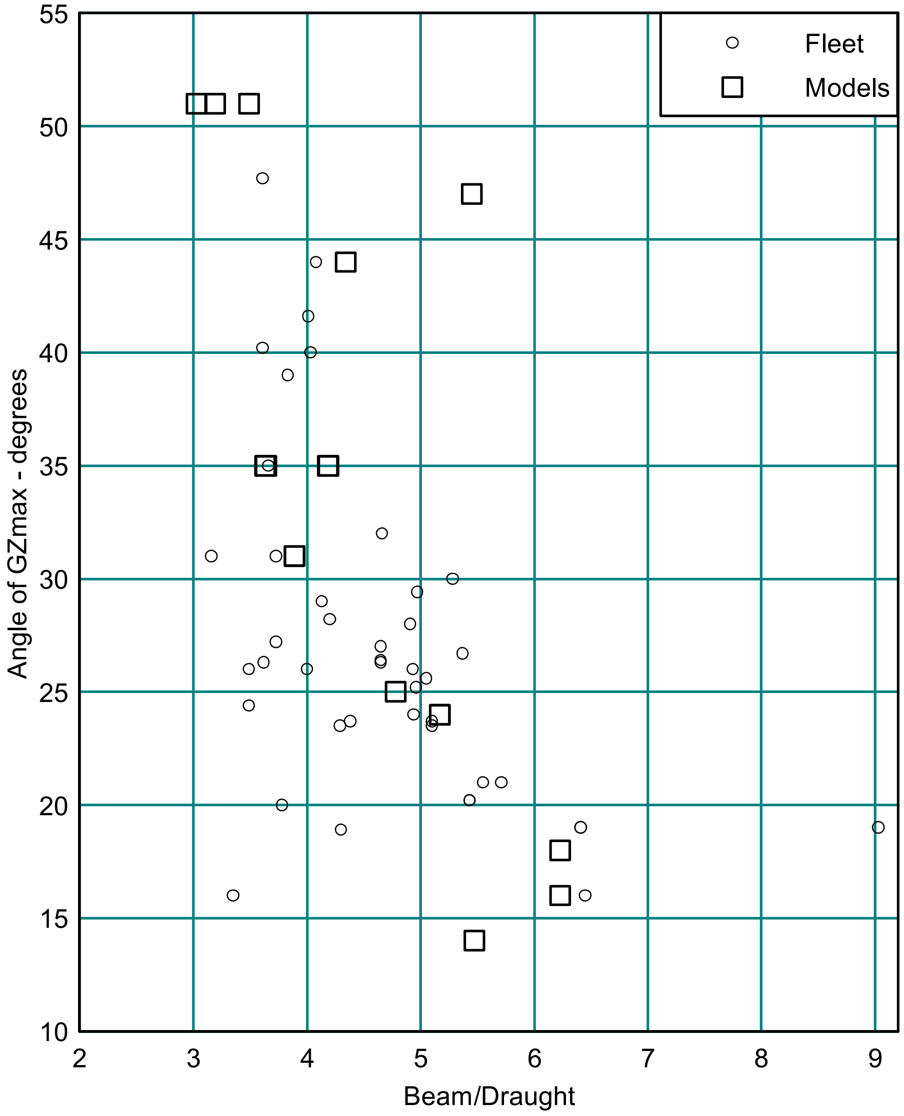


Figure 8 GZ curves of the tested model conditions

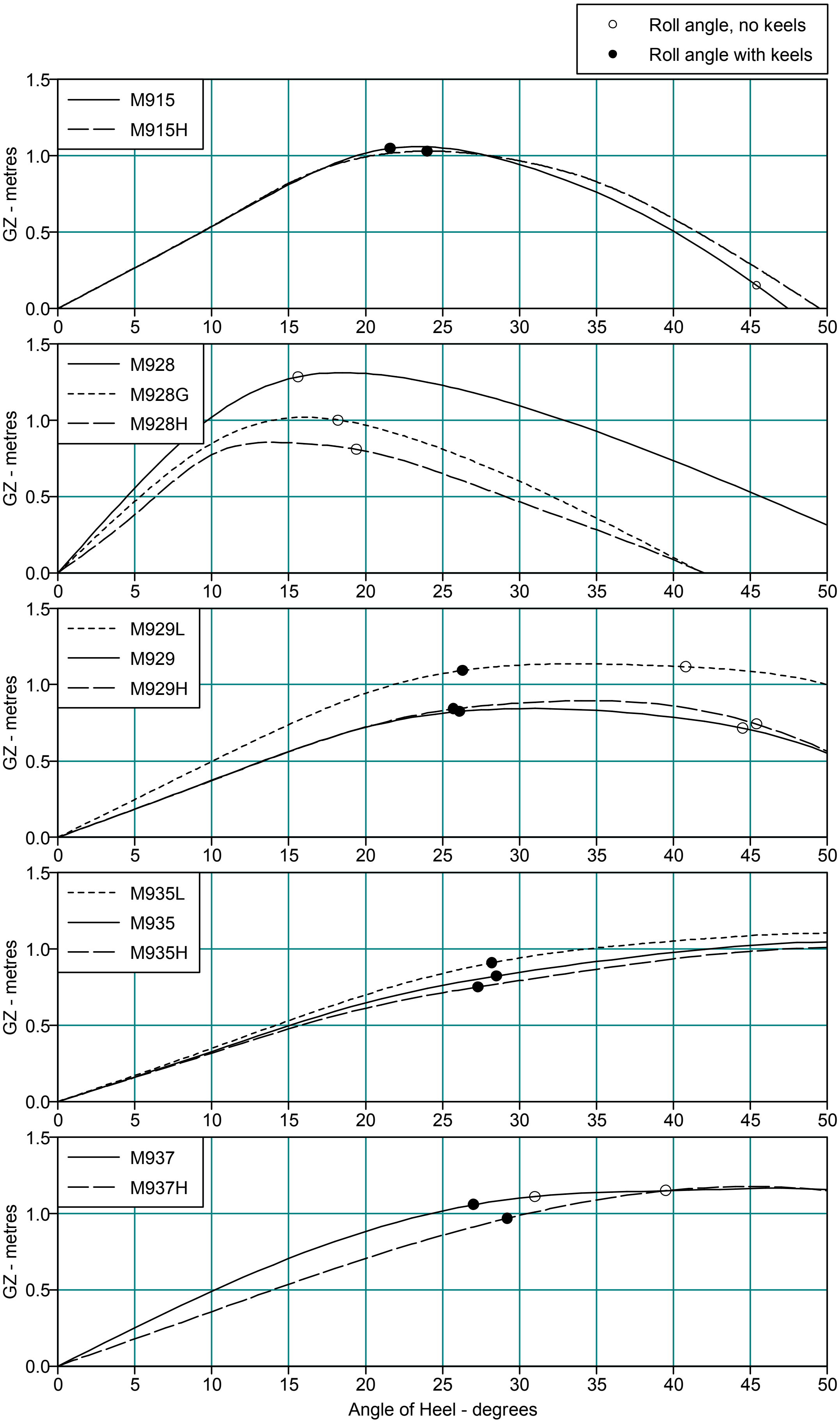


Figure 9 Example of a roll decrement record

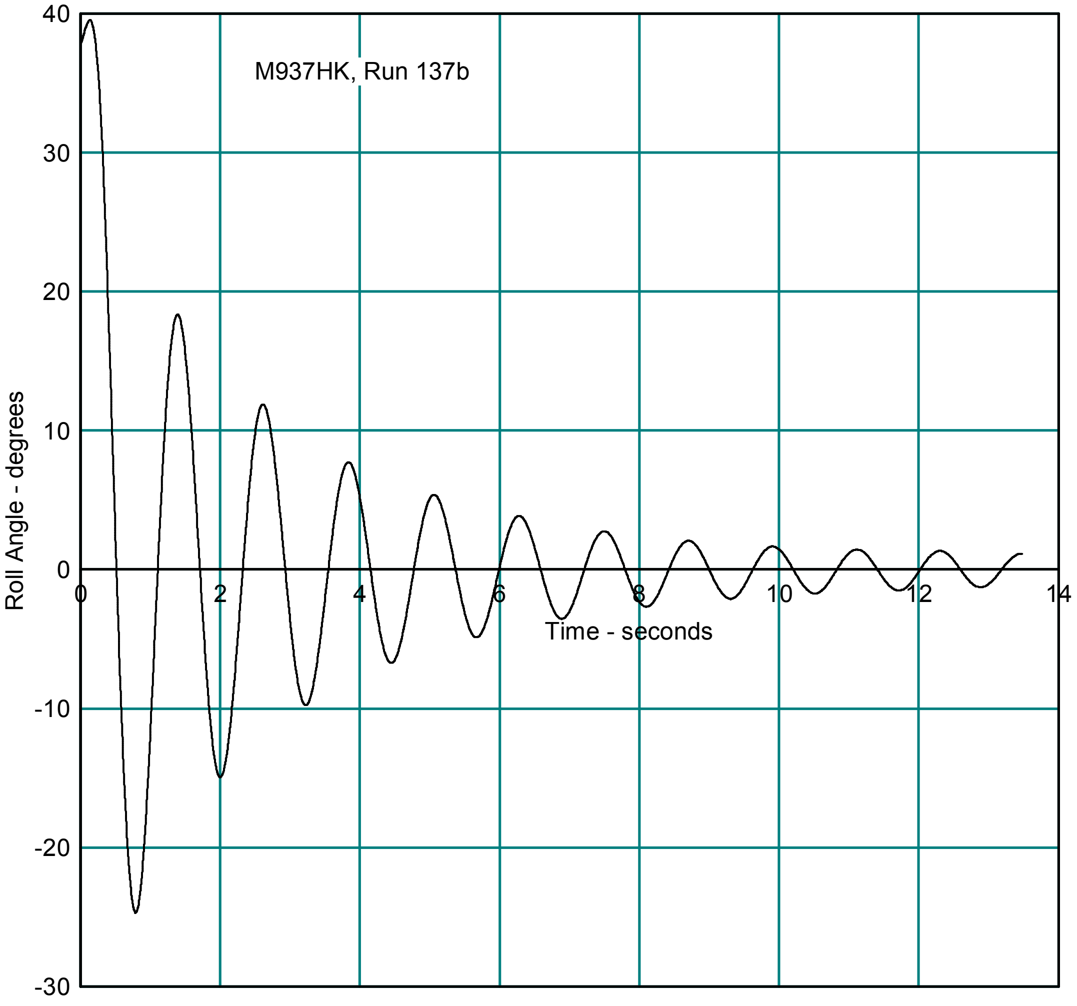


Figure 10 Variation of measured mean wave heights

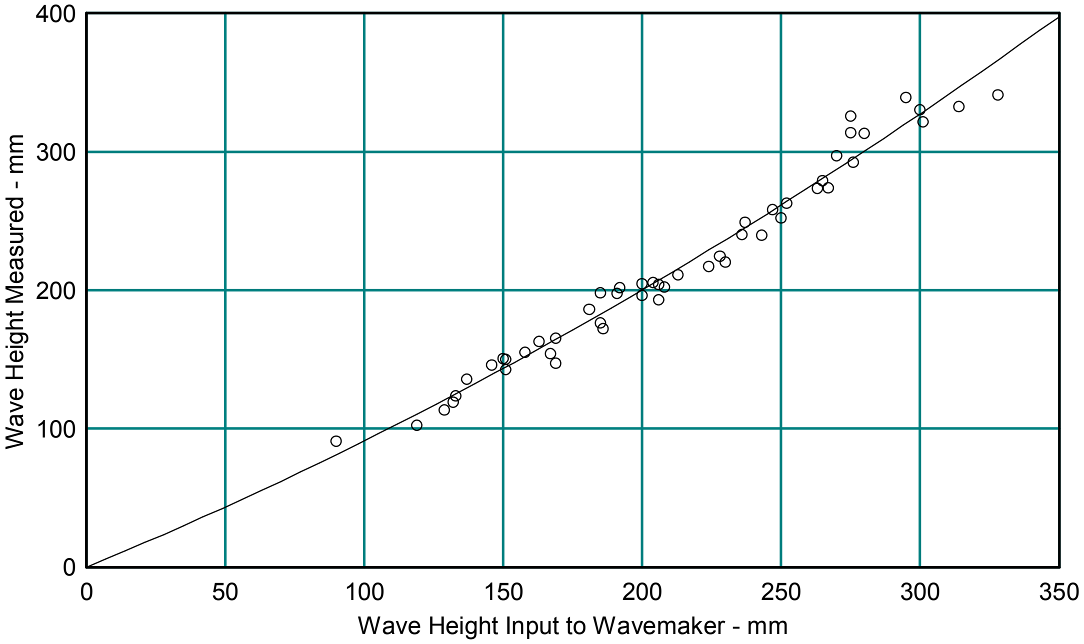


Figure 11 Model roll period data derived from roll decrement tests

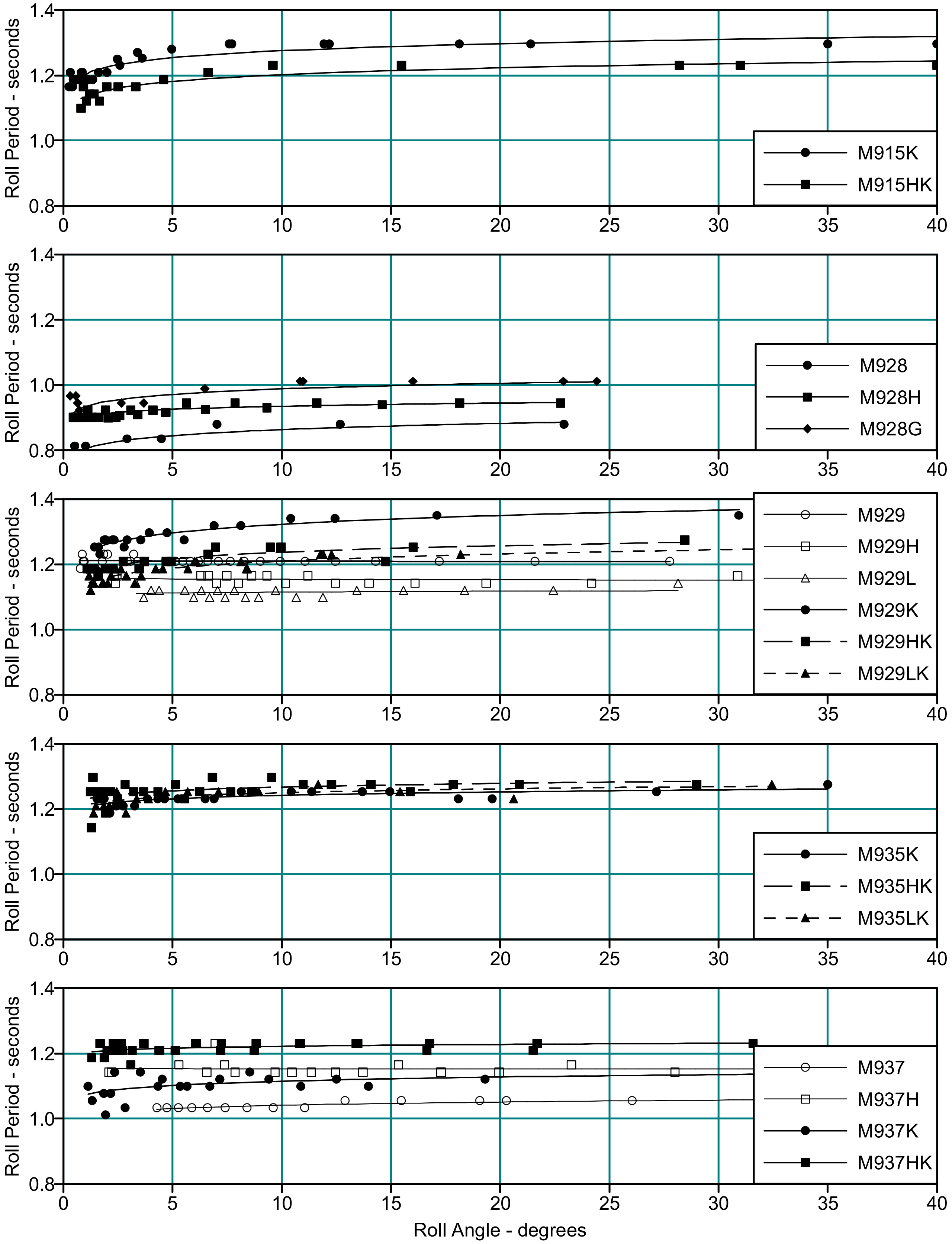


Figure 12 Variation of roll angle with wave frequency for all model configurations

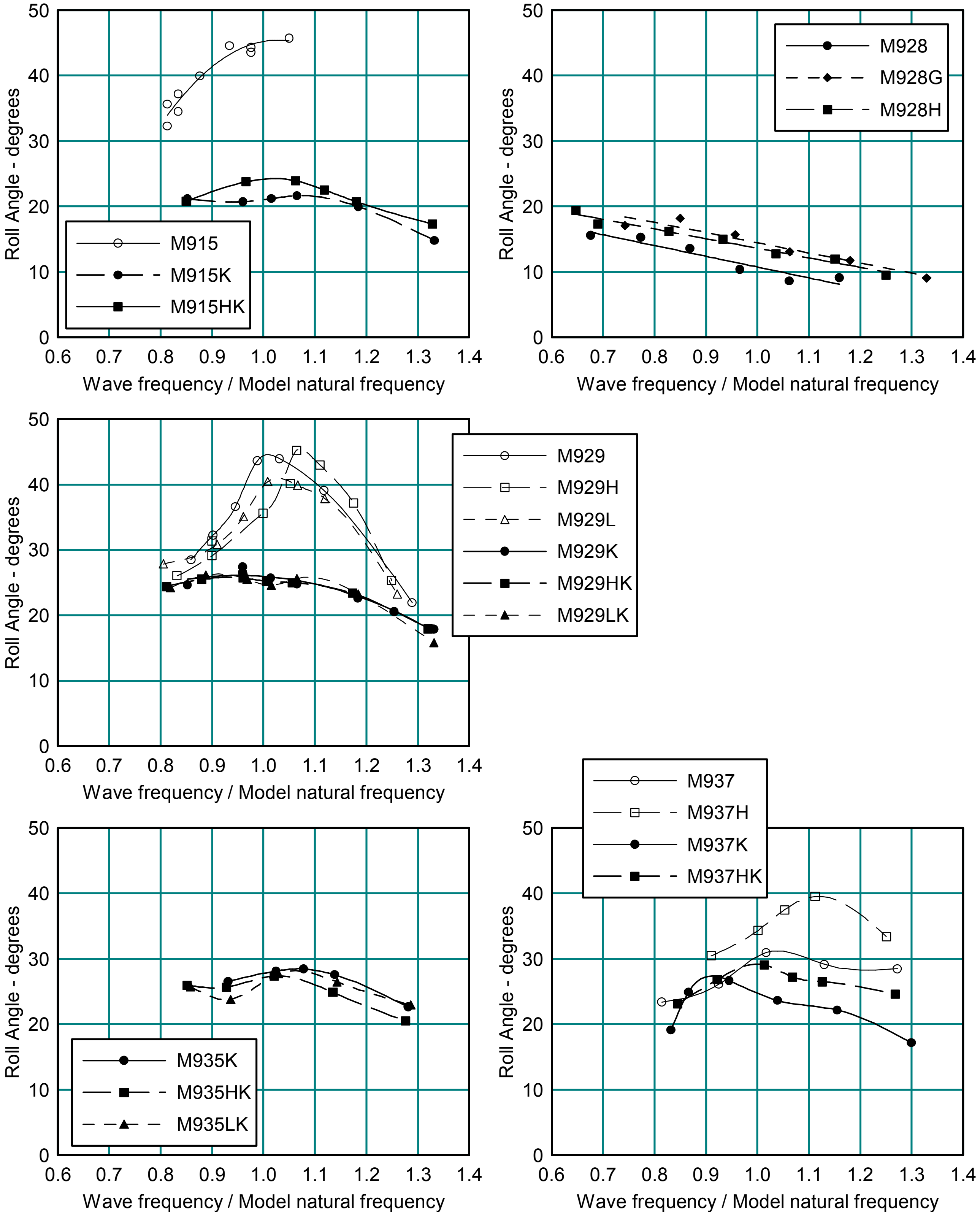
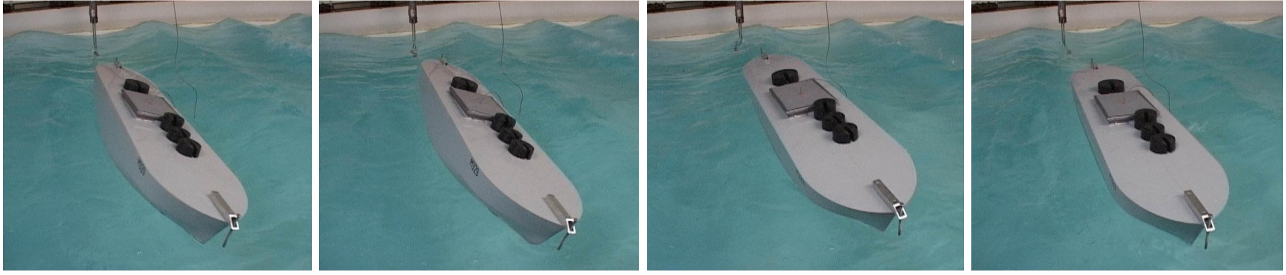


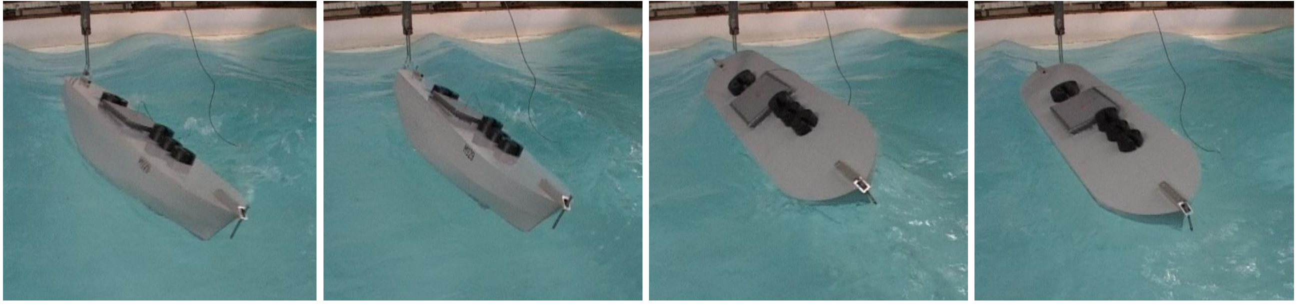
Figure 13 M929H at various positions on the wave, for different wave frequencies

Run 49. Wave frequency / model natural frequency = 1.25



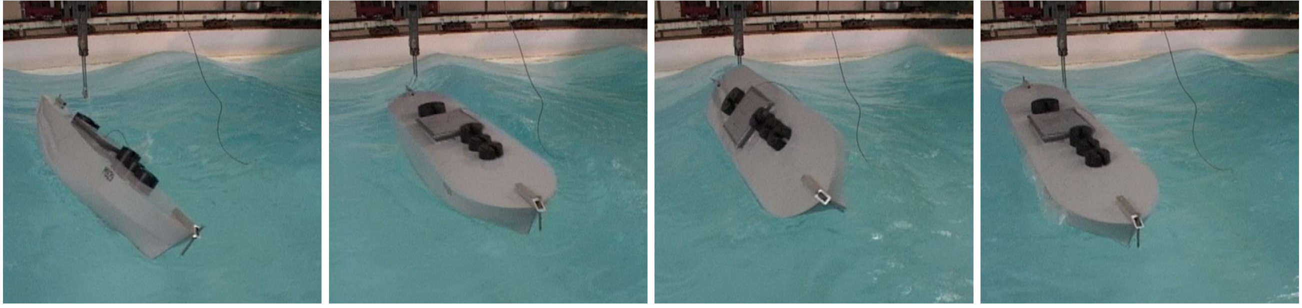
Trough Face Crest Back

Run 52. Wave frequency / model natural frequency = 1.17



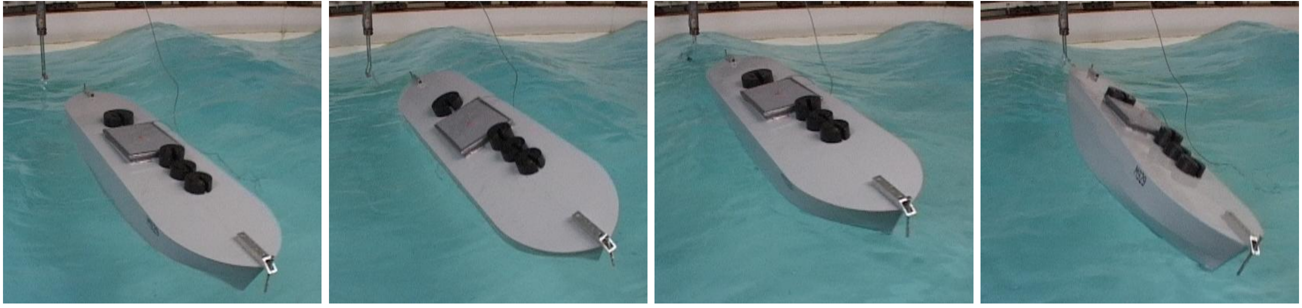
Trough Face Crest Back

Run 53. Wave frequency / model natural frequency = 1.05



Trough Face Crest Back

Run 54. Wave frequency / model natural frequency = 0.9



Trough Face Crest Back

Waves are travelling from right to left.

Figure 14 Variation of roll angle with encounter frequency for all model configurations

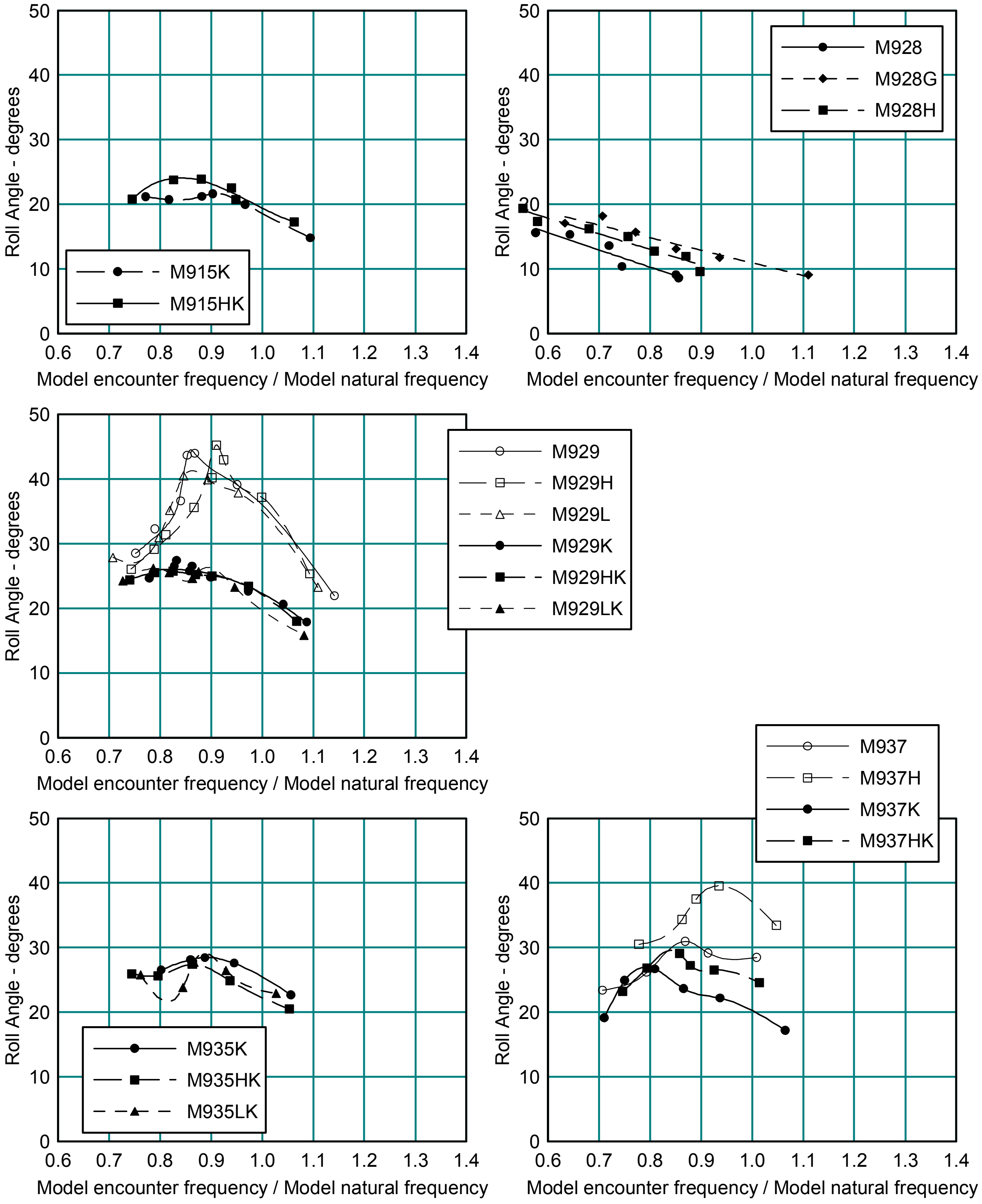


Figure 15 Measured natural roll periods compared with values predicted by the weather criterion

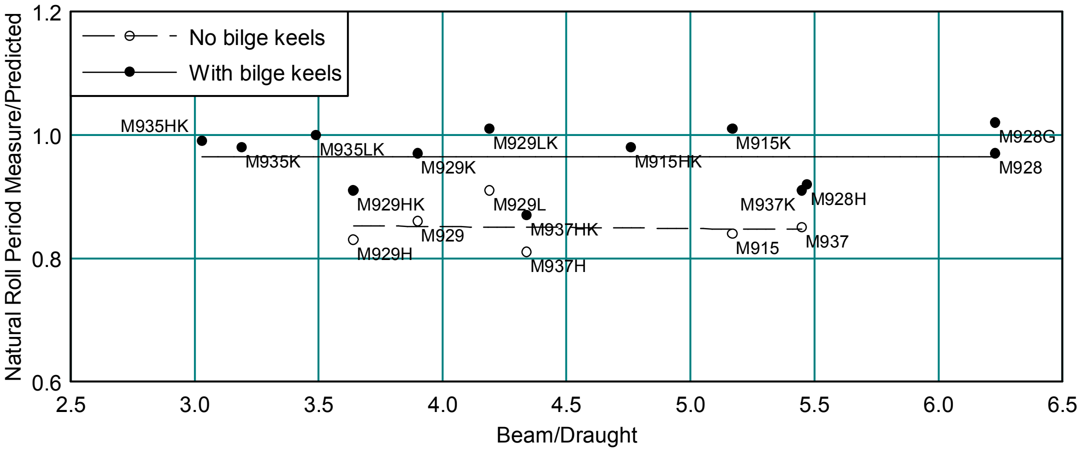


Figure 16 Comparison of calculated and measured values of the roll period coefficient, C

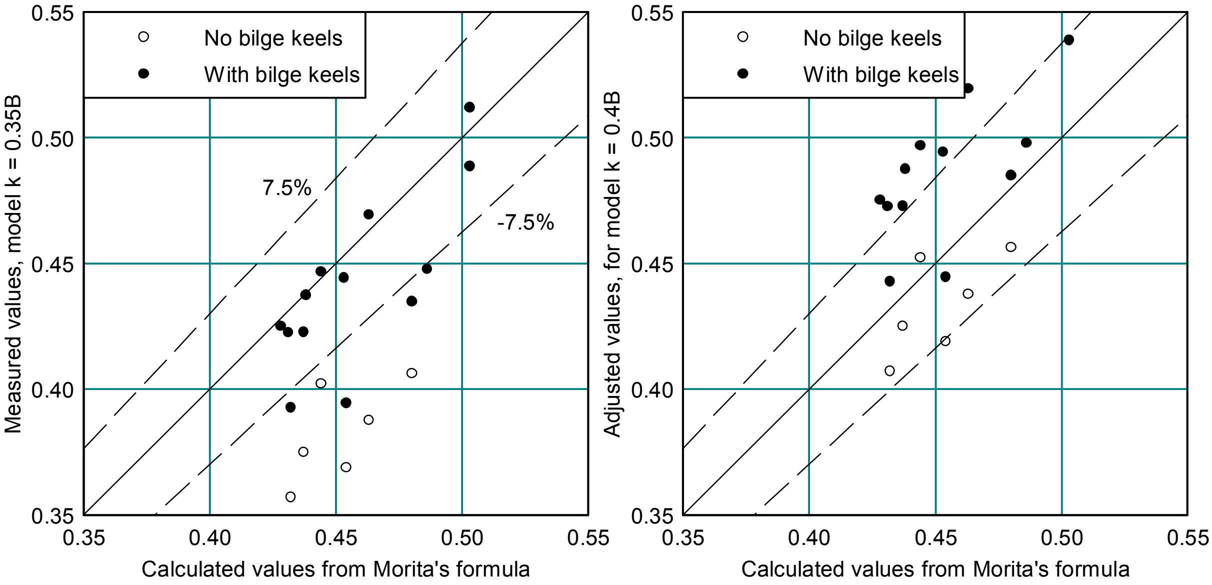
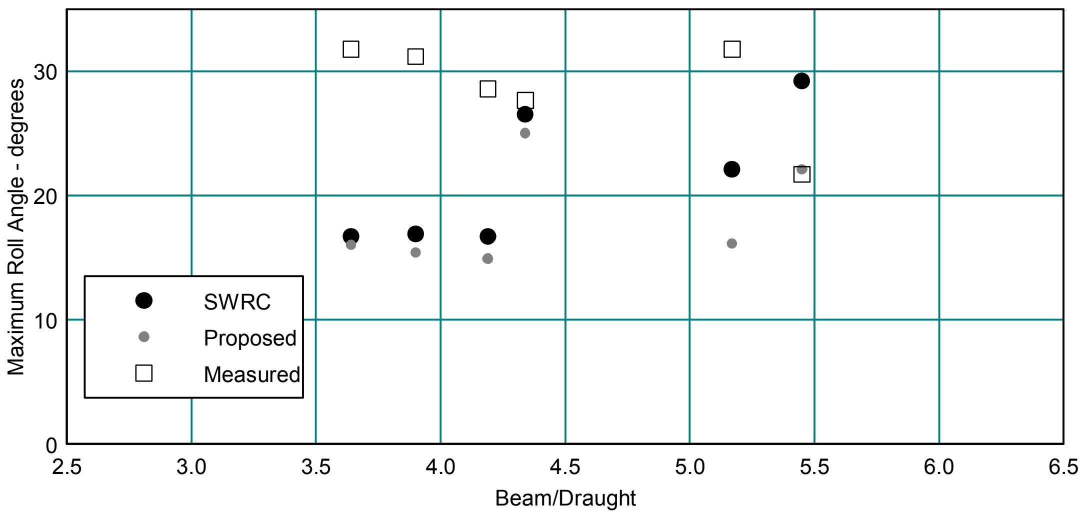


Figure 17 Maximum roll angles presented in relation to the beam/draught ratio

Models tested without keels or chines



Models tested with keels or chines

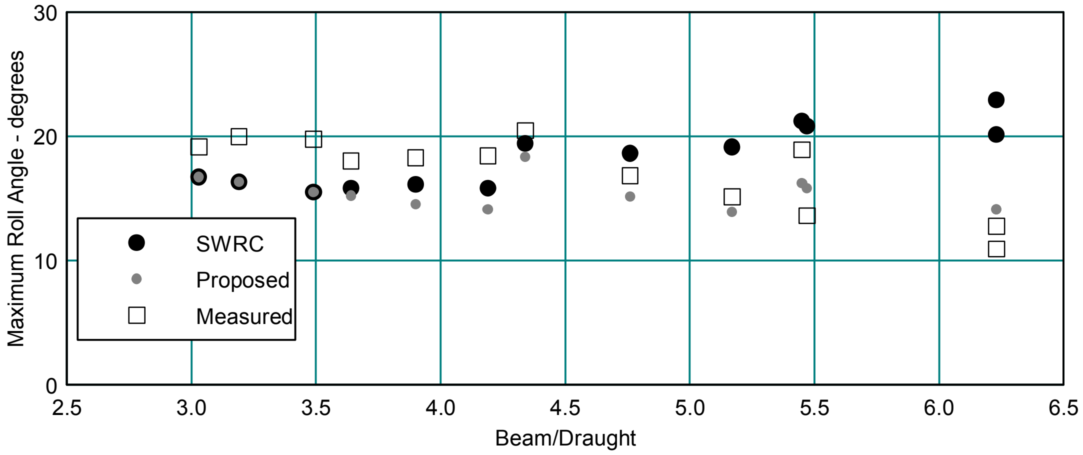


Figure 18 Estimated maximum roll angles for models ballasted to radius of gyration = 0.4B

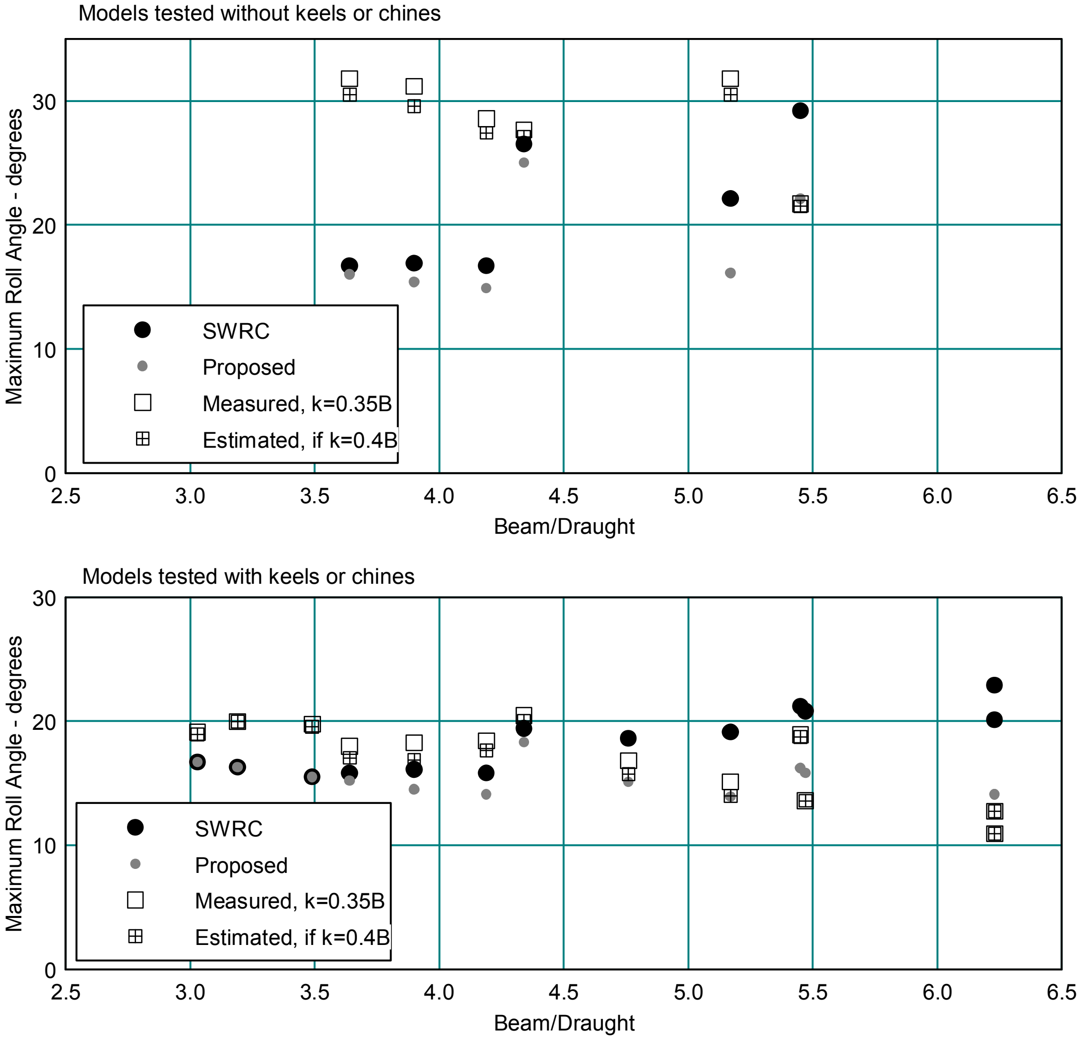


Figure 19 Maximum roll angles compared with predictions calculated with centreline keels and skegs excluded

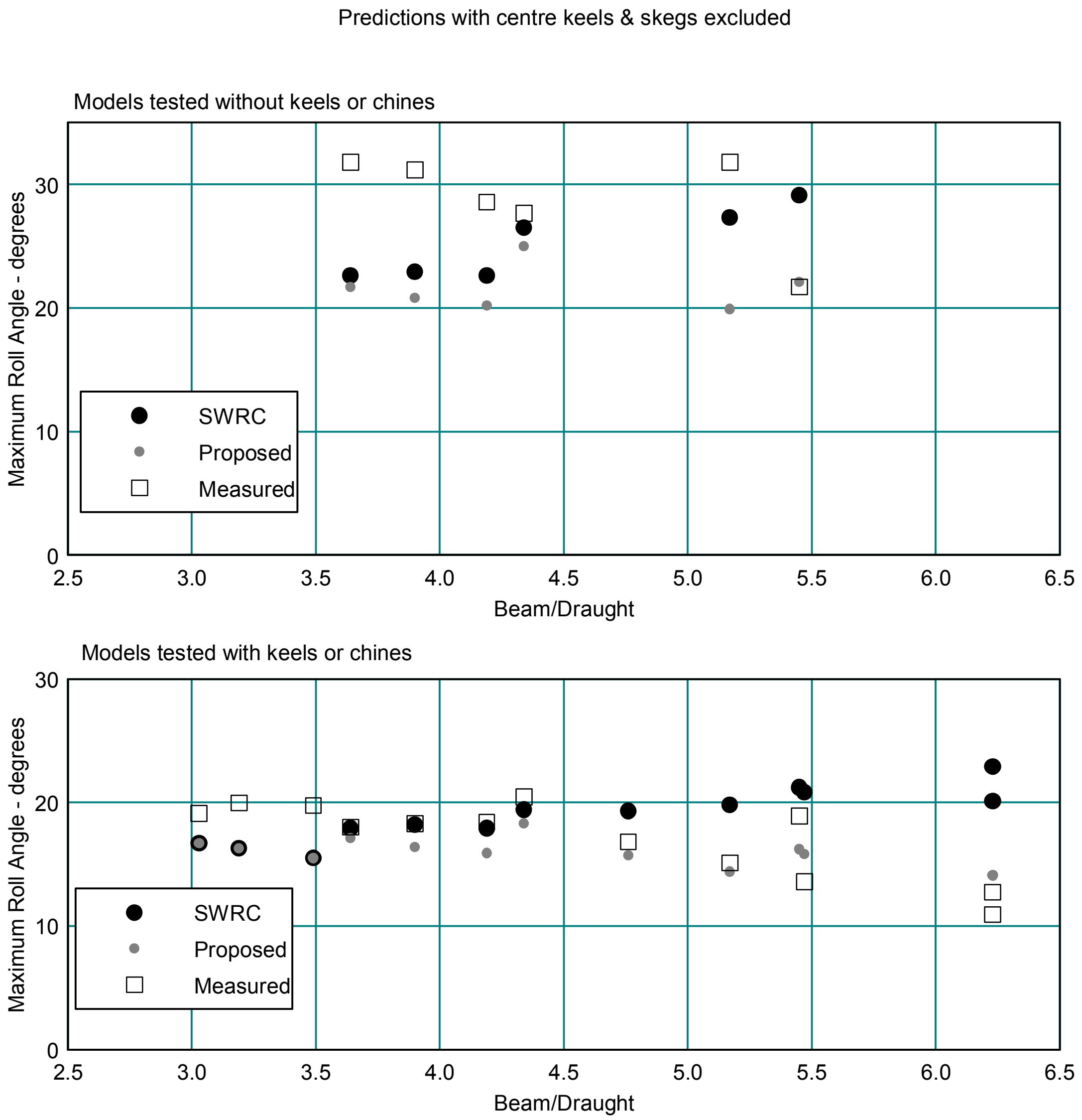


Figure 20 Examples of N coefficients measured in model experiments, as presented in Ref.5

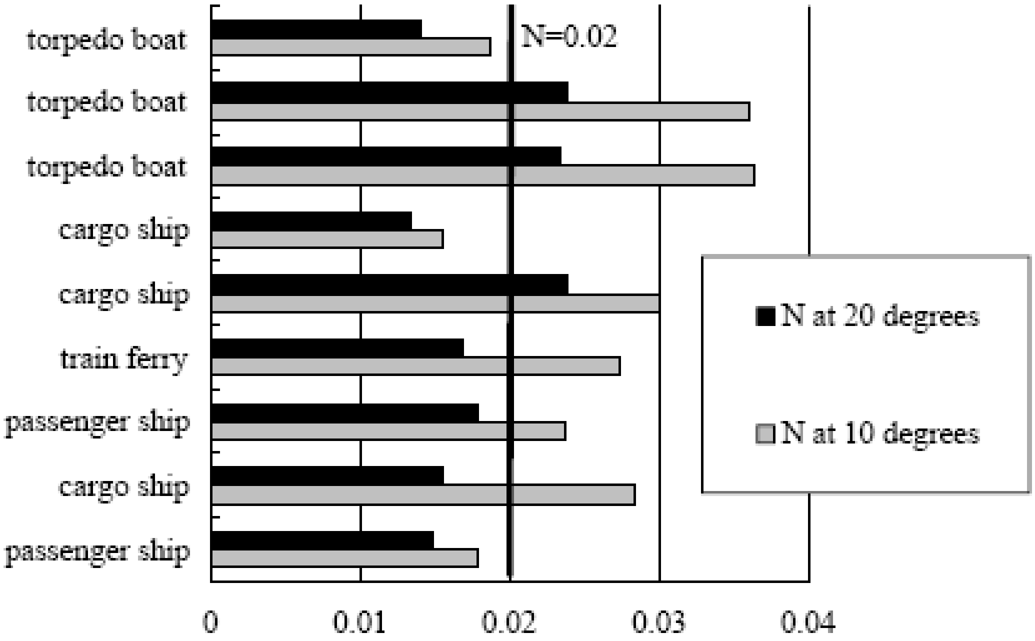


Figure 21 N coefficients derived for the models in this study

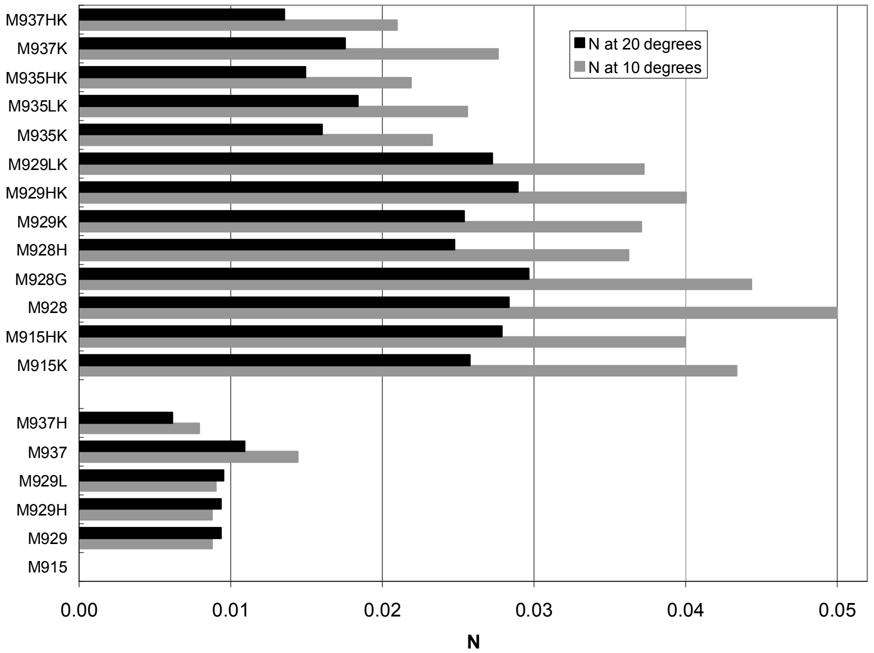


Figure 22 Effective wave slope coefficients for the models compared with the predicted values

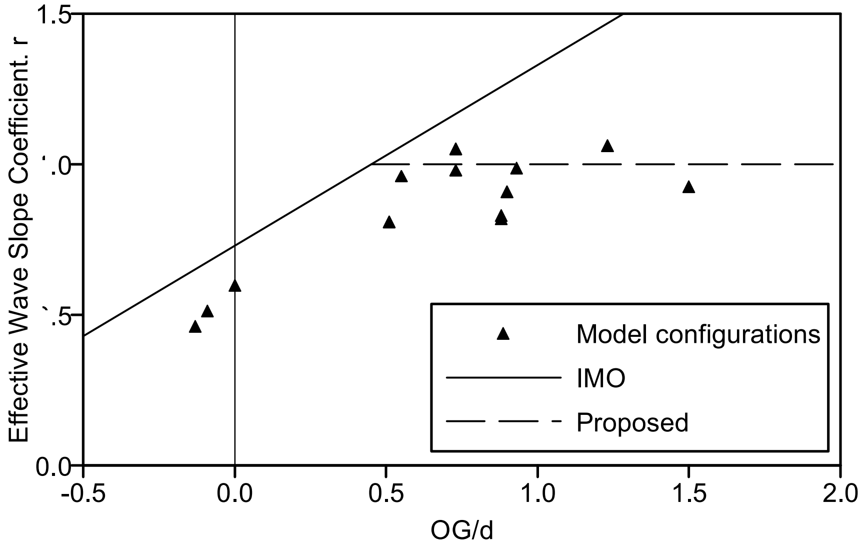


Figure 23 Roll angles compared with calculations using the proposed values of X1 with values of r calculated using the Froude-Krylov hypothesis

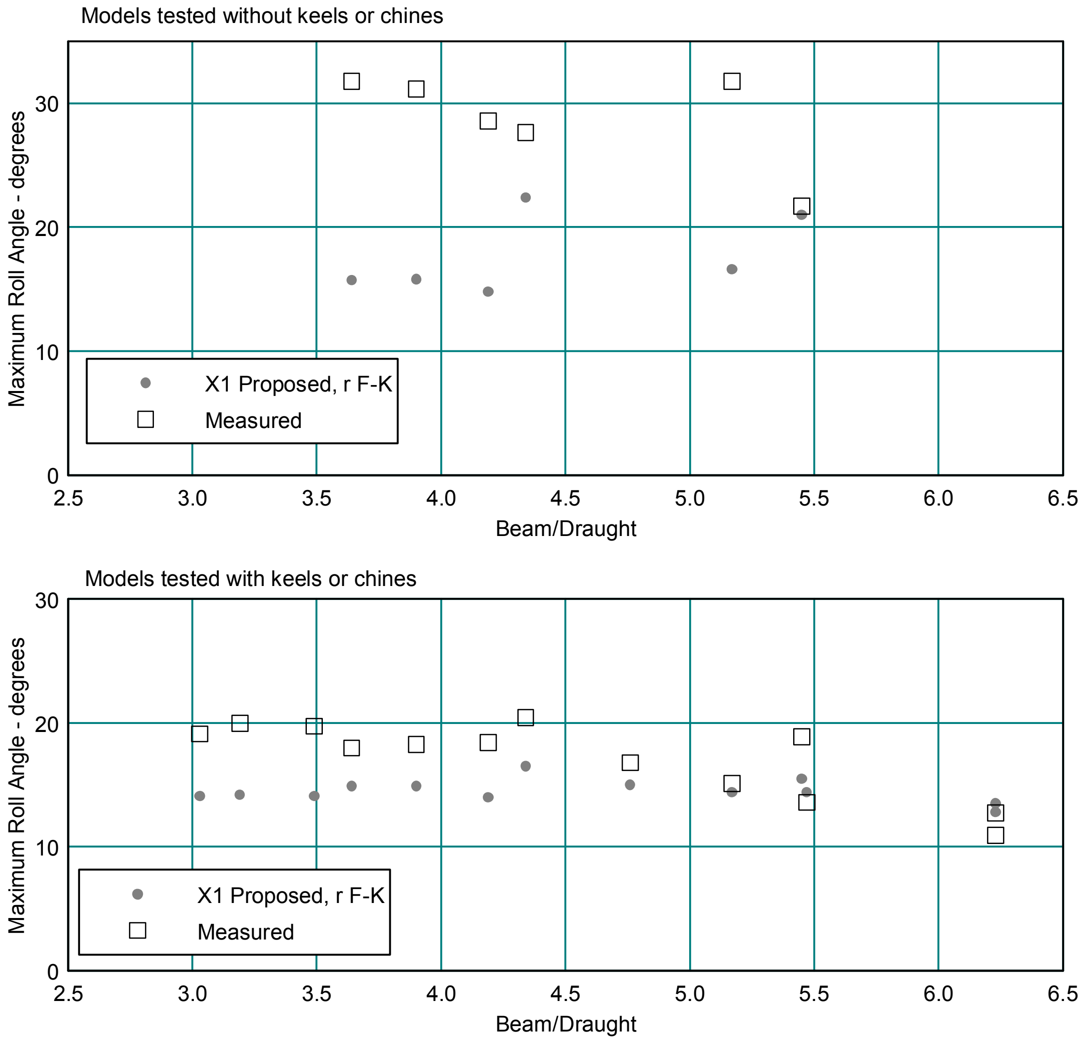


Figure 24 Values of X_1 required for accurate prediction of the model results

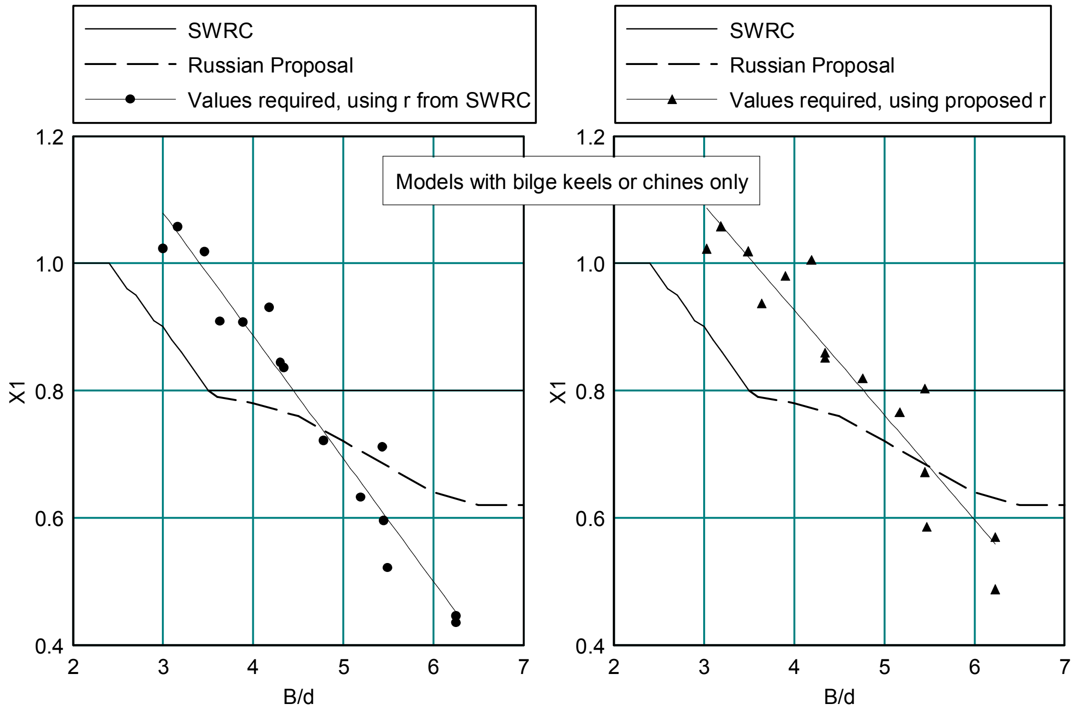


Figure 25 Correlation of other model test results with the weather criterion

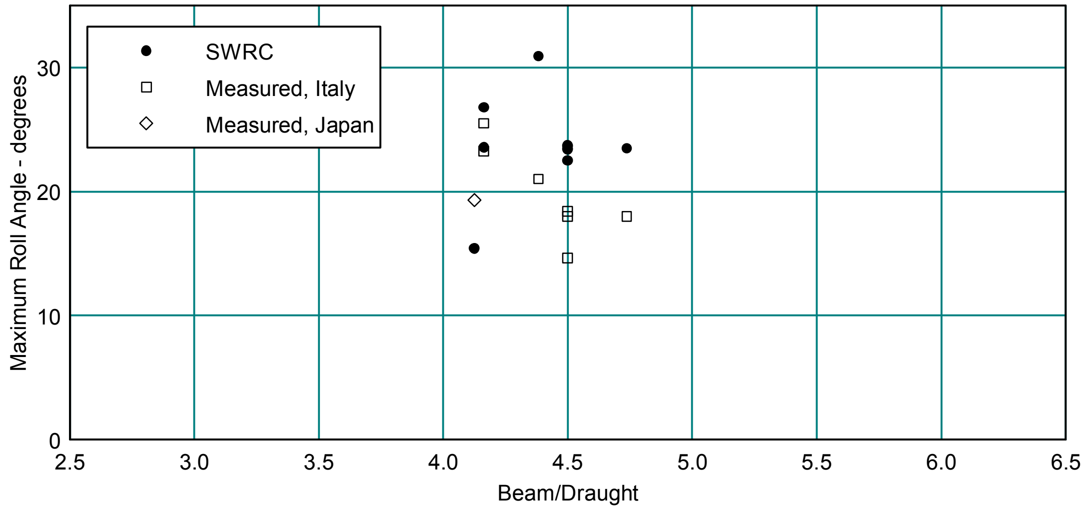


Figure 26 Ratio of measured to calculated roll angles, including data by other experimenters