EVALUATION OF THE ROLL PREDICTION METHOD IN THE WEATHER CRITERION

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SUMMARY

This paper describes some background to the IMO Severe Wind and Rolling Criterion (SWRC), or 'Weather Criterion', and a research project to study the validity of its application to UK seagoing passenger ships engaged on domestic voyages. 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. Correlation between the measured and predicted values of roll period and roll angle was poor in most cases and the study concluded that the weather criterion does not provide a realistic assessment of the level of safety in the assumed conditions.

1. INTRODUCTION

The weather criterion is one of the requirements of EC Directive 98/18 (Ref.1), and is a new requirement for some vessels, notably seagoing passenger ships on domestic voyages. The standards are contained in IMO resolution A.749(18): the Code on Intact Stability (Ref.1).

The formulation for the roll to windward was based on semi-empirical form factors, and was validated for conventional hull forms of the early to mid 20th century. Some UK vessels, such as the small ferries operating to the Scottish Isles, are of different form, characterised by high beam to draught ratio, and have difficulty complying with the criterion. The vessels have a history of safe operation, so the Maritime & Coastguard Agency decided to commission this study into the application of the criterion to such vessels.

2. THE WEATHER CRITERION

2.1 ORIGINS

The development of the weather criterion at IMO is described in Ref.3. It combines methods originating in Japan and Russia in an attempt to assess the ability to survive a severe wind gust when rolling in extreme beam seas.

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 Bertin's coefficient for roll damping. 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 hypothesis.

The original Japanese method of estimating the natural roll period was 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:

$$T = 2CB\big/\sqrt{GM} \qquad 3$$

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, and 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 as in the Russian formula, and the wave forcing factors r and s are as in the Japanese method.

The factors k, X_1, X_2 and s are presented in the Intact Stability Code in tabular form.

2.2 PROBLEMS WITH THE 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.

A study was conducted in Japan on the application of their criterion to small passenger vessels, Ref.4. 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, as adopted at IMO, was too high. Both factors led to the roll angle predictions being overestimated.

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.5. Their research led to a submission to IMO in 2002, proposing significant adjustments to the criterion, Ref.6. Their concerns 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, 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, but many modern vessels have roll periods in excess of 20 seconds.

In Germany concerns were raised regarding application of the criterion to RoRo, RoPax and some container vessels, Ref.7. Again, the concerns were that the roll angle was overestimated in some cases, but some additional factors were described.

2.3 PROPOSED ADJUSTMENTS TO THE 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. 6 and 8 present proposals by Italy and Russia for adjustments to the values X_1, r and s, and Figure 1 illustrates the proposals for X_1 and s.

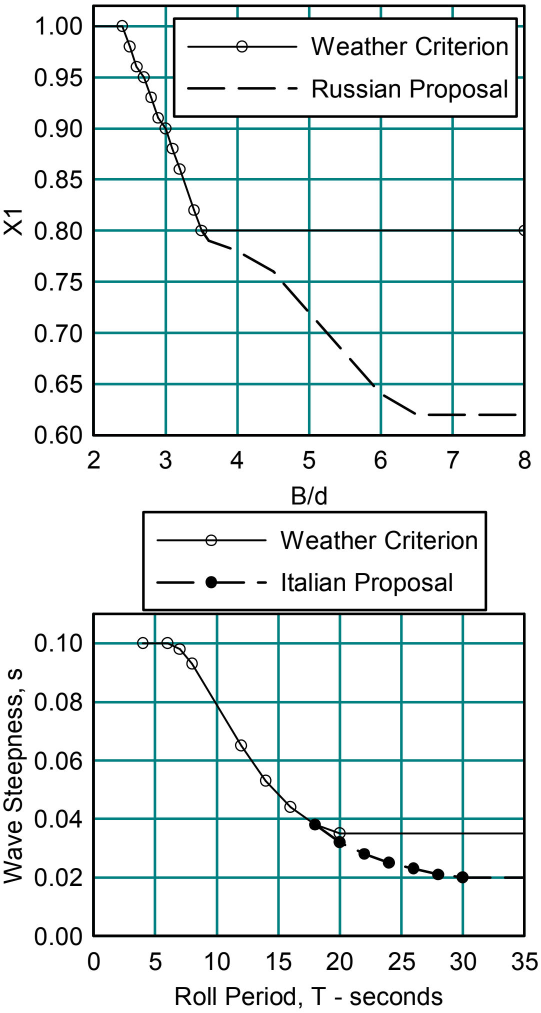


Figure 1 Proposed adjustments to factors presented in the IMO Weather Criterion.

3. MODELS

The remit of the study was to consider vessels of 24 to 100 metres, and model some "extreme" vessels with beam/draught ratios outside the range for which the criterion was developed. In fact, few UK vessels exhibit the "conventional" proportions catered for in the weather criterion formulae, shown as a shaded area in Figure 2. Five vessels were selected, with a range of proportions and hull types, on which to base the models.

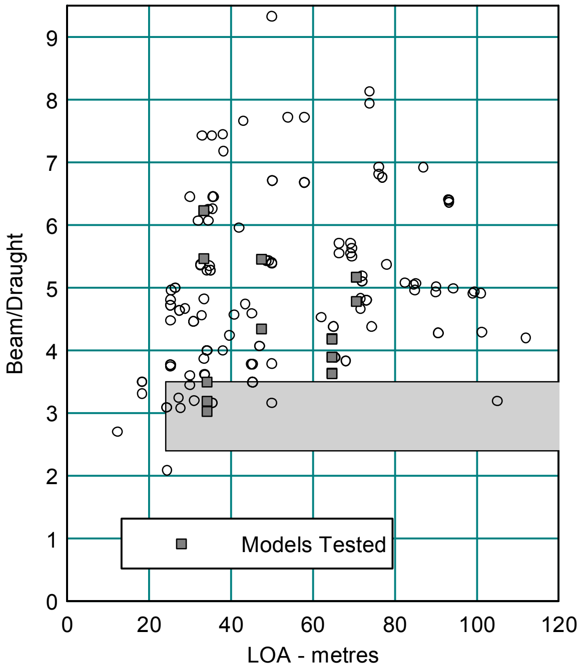


Figure 2 Distribution of models relative to the UK fleet, in terms of beam/draught ratio and length.

The object was to compare rolling behaviour 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 guidelines given in Ref.9. 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 built with a flat deck at upper deck level. 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 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.

In general, the models were tested in a base condition taken from the stability booklet and at additional displacements, further increasing the number of beam/draught ratios to 12. The number of cases was increased to 19 with VCG variation and the removal of bilge keels. Each test condition was identified by a model number, with dimensions as listed in Table 1. In all test conditions the roll inertia was adjusted to a radius of gyration equal to 0.35B. GZ curves for the models are presented in Figure 3.

4. TEST TECHNIQUE

Tests were conducted in the towing tank at GKN Westland, Isle of Wight. The tank is 200m, by 4.6m, by 1.7m deep. It is equipped with a 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.

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.

Each model was allowed to float unrestrained, beam on to the waves. The roll gyro required a light umbilical connection, kept slack and supported directly above the model on a movable carriage. Any tendency for the model to yaw was minimised by manual realignment, with due regard for the importance of minimal interference with the roll motions.

Tests 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 given in Ref. 9 suggest ratios of wave frequency to natural roll frequency of 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.

5. DATA ANALYSIS AND RESULTS

5.1 WAVE HEIGHT

Because the waves generated were very steep, and sometimes breaking, those 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.

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. The data were used to derive a mean curve, 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.

5.2 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, with lower periods at smaller angles. The variation was similar for all cases, despite variations in the hull forms and GZ curves.

5.3 WAVE STEEPNESS FACTOR

In the analysis following the tests, a more accurate value of the wave steepness required by the weather criterion was determined 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.

5.4 ROLL ANGLE

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 5.3. The wave height used was that determined as in section 5.1.

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, and their effect on the maximum angles was within 5%.

The adjusted average roll angles are shown in Figure 4, plotted against the ratio of wave frequency to model natural frequency. In most cases the maximum angle occurred in waves of frequency similar to the model natural frequency. While 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, with an encounter frequency lower than the wave frequency.

For M928 and its variants, no clear peak roll angle was found for the range of frequencies tested, 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 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.

6. OBSERVATIONS OF ROLL MOTION

Those models which exhibited distinctly resonant behaviour, such as M929H, were characterised by a peak 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. Observations 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.

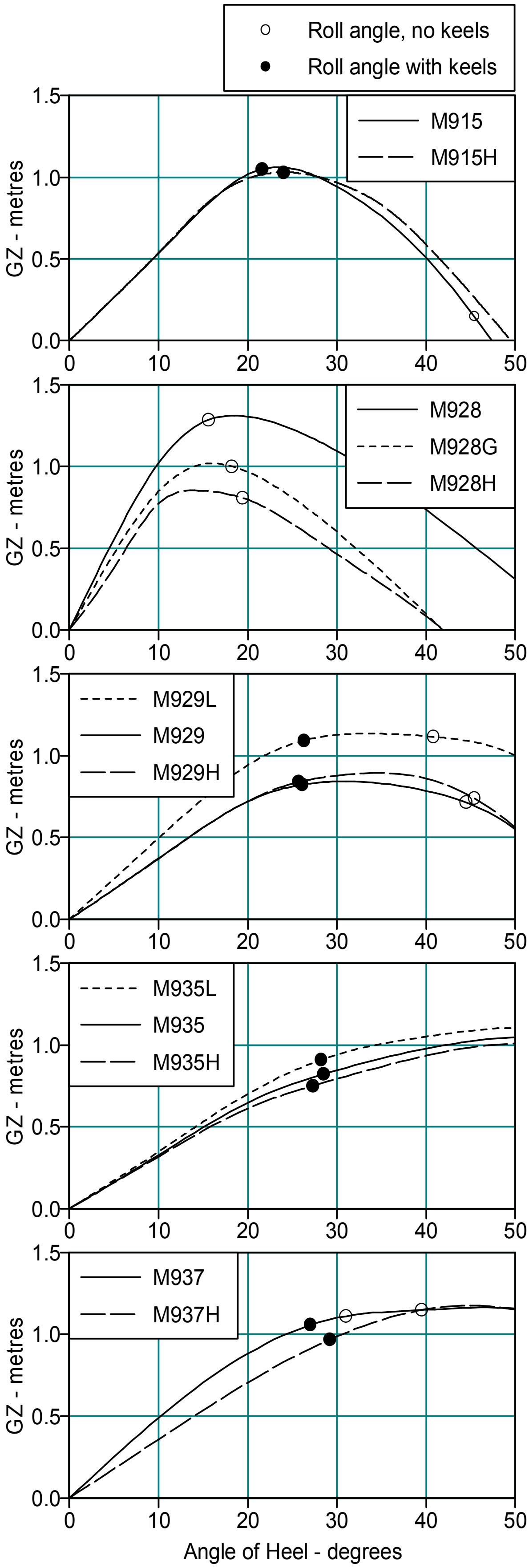


Figure 3 GZ curves of the tested models conditions, with the maximum roll angles indicated

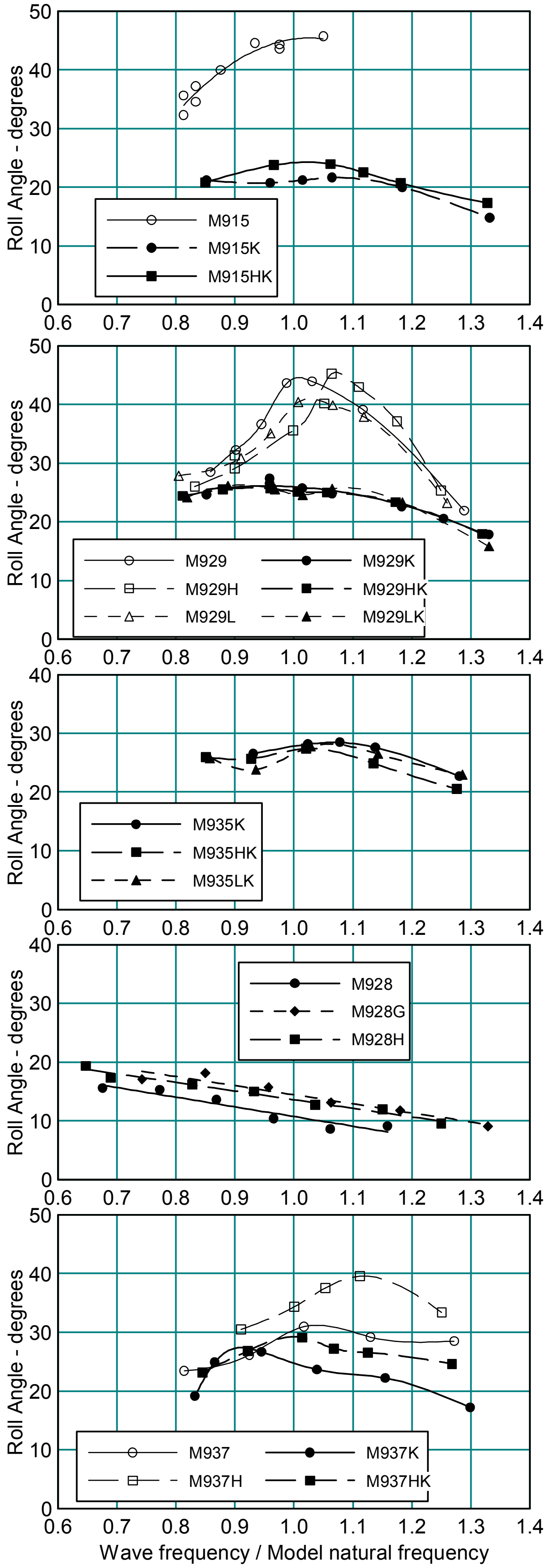


Figure 4 Variation of roll angle with wave frequency for all model configurations.

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. 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.10, 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.

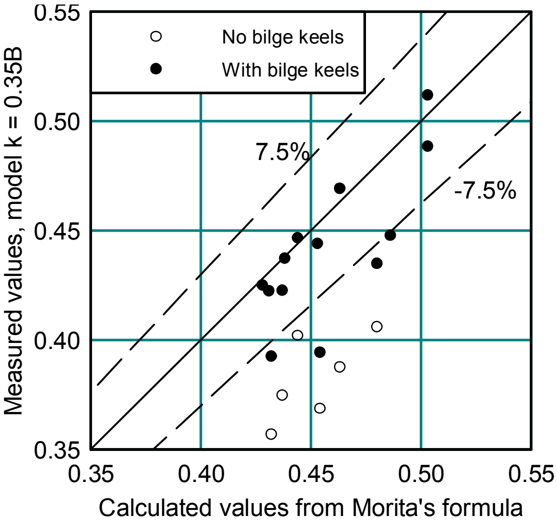
7. COMPARISON OF RESULTS WITH CRITERION PREDICTIONS

7.1 ROLL PERIOD

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, particularly for the models tested without keels.

The reliability of the roll period prediction was claimed to be good by Morita when he developed the formula. His results are presented in Ref.9, 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, Figure 5. 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 from Italy, Ref.5, that the criterion overestimated the roll period.



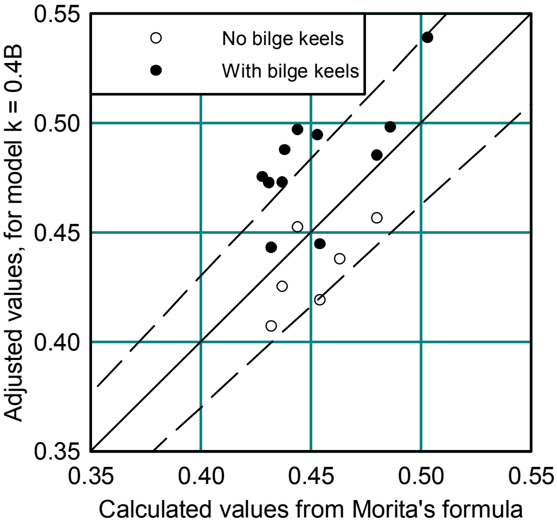


Figure 5 Comparison of calculated and measured values of the roll period coefficient, C, for two inertias.

7.2 MAXIMUM ROLL ANGLE

The maximum roll angles are presented in Figure 6 to show their variation with beam/draught ratio. For clarity, Figure 6 is divided into two graphs, for models with and without bilge keels.

For comparison, two calculated points are presented for each model configuration: 'Weather Criterion' values using the current formulation, and 'Proposed adjustments' values using proposals described in 2.3.

Without bilge keels the measured roll angles were greater than those predicted for all but one of the models, that with the highest B/d ratio. Its measured roll was less than that predicted by the criterion but the same as that predicted with the proposed adjustments.

With keels the correlation 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 predictions and the measured values increases as B/d ratio increases above a value of about 4.5.

Correlation with values 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.

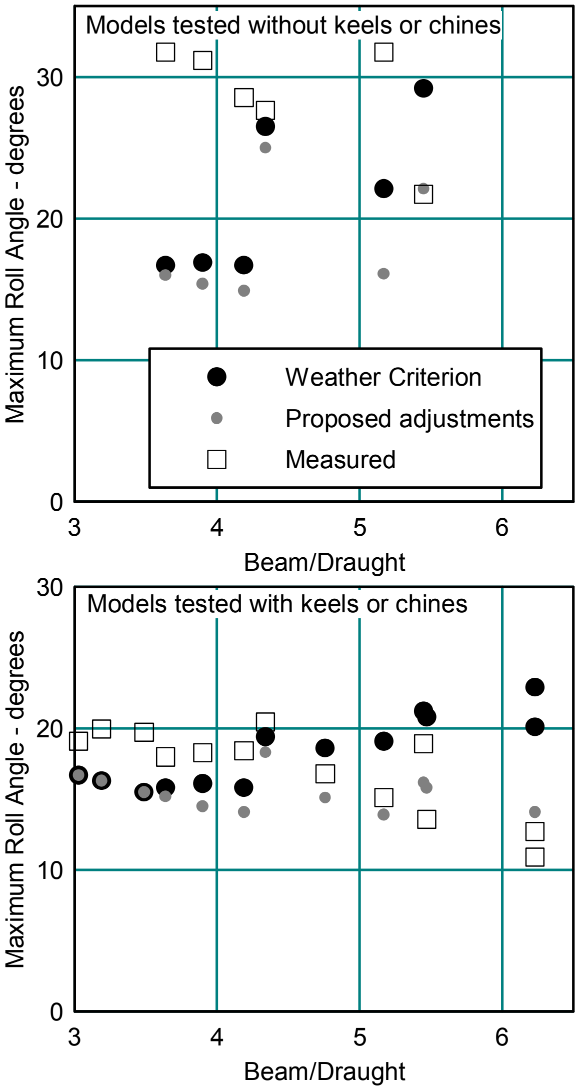


Figure 6 Maximum roll angles presented in relation to the beam/draught ratio.

7.3 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 radius of gyration.

All 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.7 refers to some modern RoRo vessels where this value is too low an estimate.

Estimates were made of the greater 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 5. The adjusted values are presented in lower graph of that figure. All 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 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 inertia. The inertias of small domestic passenger vessels are 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 inertia is not incorporated.

For some models, greater inertia 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. Where the steepness would have been lower, notably for 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. A 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.

8. POSSIBLE SCALE EFFECTS

The models were smaller than recommended in Ref.9, which suggests that models should be not less than 2m 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 1.85m long.

The guidelines also suggest that models without bilge keels or sharp chines should be at least 4 metres long.

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 were those with round bilges and no keels: M915, M929, M929H and M929L. The measured roll angles for these were all significantly greater than predicted however.

The procedure given in Ref.9 was used to correct the damping coefficient to account for frictional scale effects. The corrections were found to be small and, if applied as an adjustment to the measured 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 imprecise, 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. Support for the use of small models of chine vessels is provided by Ref.4, which 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.

9. POSSIBLE ADJUSTMENTS TO THE CRITERION

9.1 EFFECTIVE WAVE SLOPE COEFFICIENT

The formula used for this factor, r, in the weather criterion is an approximate one. The Froude-Krylov formula, Ref.4, was used to calculate the effective wave slope coefficients for the model configurations to assess the validity of the weather criterion approximation. See Figure 7.

It is apparent that the approximate formula gives an overestimate of the coefficient. This supports the findings presented in Ref.4, 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.

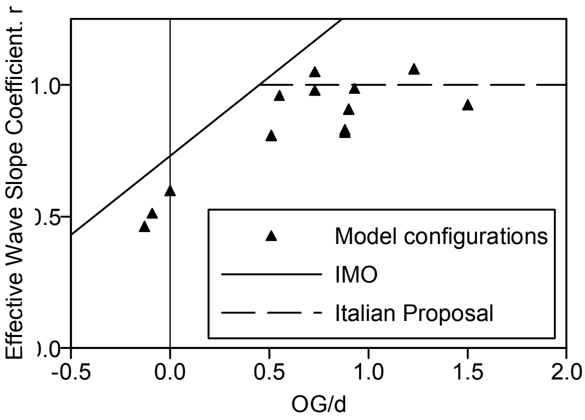


Figure 7 Effective wave slope coefficients for the models compared with the predicted values

9.2 DAMPING FACTOR X1

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 8. The data for models without keels or chines have not been included here. Much greater X_1 values would be required to correlate their measured and calculated roll angles.

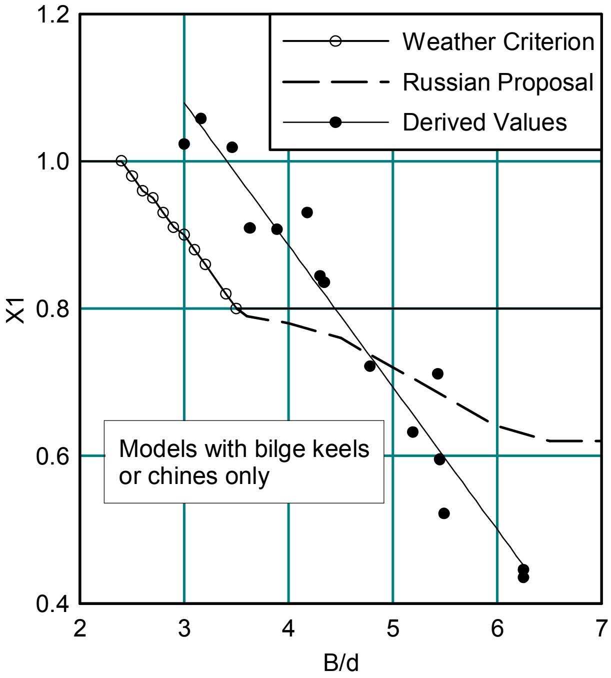


Figure 8 Values of X_1 required for accurate prediction of the model results

It is interesting to note that the data fit intersects the line for the Russian proposal near the middle of its B/d range, but is parallel with the IMO line. 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.11. This includes a graph similar to Figure 8, but with very little scatter of the data points through which their curve was fitted. A translation of the paper has not been obtained so the details of their testing and analysis are unclear.

10. OTHER EXPERIMENTERS' DATA

Other experimenters have conducted similar tests to study the weather criterion, Refs.5 and 12. Their results are presented in Figure 9, in the same format as Figure 6 for ease of comparison. The Italians found that the 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 present data for only one model, and in this case the criterion gave a substantial under prediction at a B/d ratio of 4.12, which compares closely with the findings of this study. In general, the correlation between measured and predicted values was weaker than found in this study.

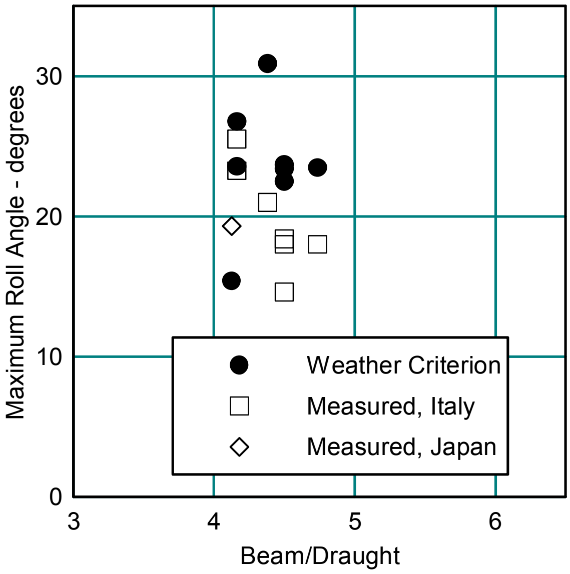


Figure 9 Correlation of other model test results with the weather criterion

11. COMMENTS AND RECOMMENDATIONS

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 its natural roll period. That is, the worst possible wave conditions in terms of roll behaviour. The waves represented are extremely severe. 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, but there 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 author 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. It is my belief that a more realistic criterion could be developed that would prove less restrictive for designers, whilst enabling regulators to ensure that vessels retain an adequate level of safety in severe weather.

Notwithstanding this opinion, it is recognised that, in the short term, the criterion will be retained by IMO. Taking a pragmatic view, therefore, the author recommended that the Maritime & Coastguard Agency support the proposals previously submitted to IMO for adjustments to the criterion, and recommend their application in EC Directive 98/18. In general this study supported those proposals because, as shown in Figure 6, they provide a more consistent assessment of the level of safety of vessels, albeit an inaccurate one.

Since completion of this project, further consideration has been given to the weather criterion, and other aspects of the Intact Stability Code, at IMO. The latest developments are described in Ref.13. Some valuable advances are being made in our understanding of ship survivability and safety, but it is the author's opinion that the large number of unpredictable factors involved in accidents precludes accurate prediction of capsize, even with complex models. Rather, it is recommended that authorities should strive for simple criteria and methods of assessment with which to judge the relative vulnerability of ships. Equivalence in safety is an important consideration, and methods should be developed which relate vessel stability and size to the anticipated seastate, as described in Refs.10 and 14 for example. Such an approach is relevant to this project, which concerned small vessels on short voyages, where exposure to extreme conditions is avoided.

12. CONCLUSIONS

1. Five ship models were tested in a total of 19 configurations. The results provided roll period and 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, however, 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.

13. REFERENCES

1. European Council. Directive 98/18/EC on Safety Rules and Standards for Passenger Ships. 1998L0018 - EN - 04.06.1998 - 000.001. 2006.
2. IMO. Code on Intact Stability for All Types of Ships, Res.A.749(18) as amended by Res. MSC.75(69). 2002.
3. Japan. Proposal on Draft Explanatory Notes to the Severe Wind and Rolling Criterion. SLF 48/4/5. 2005. IMO.
4. Fujino M, et al. Examination of Roll Damping Coefficients and Effective Wave Slope Coefficients for Small Passenger Craft. Proc.USCG Vessel Stability Symposium. 1993. US Coast Guard Academy.
5. Francescutto A, Serra A. Experimental Tests on Ships with Large Values of B/T, OG/T and Roll Period. Proceedings of the 6th International Ship Stability Workshop. 2002. Webb Institute.
6. Italy. Weather Criterion for Large Passenger Ships. SLF 45/6/5. 2002. IMO.
7. Germany. Remarks Concerning the Weather Criterion. SLF 45/6/3. 2002. IMO.
8. Russia. Severe Wind and Rolling Criterion (Weather Criterion). SLF 46/6/10. 2003. IMO.
9. Germany. Revised Intact Stability Code prepared by the Intersessional Correspondence Group. SLF 49/5. 2006. IMO.
10. Wolfson Unit: Maritime & Coastguard Agency Research Project 509: HSC – Evaluation of Existing Criteria. 2005. Maritime & Coastguard Agency, UK.
11. Lugovsky VV, Luzyanin AA. The Main Principles of Reconciliation Calculation Methods for the Roll Amplitude in the RS Rules and the IMO Code on Stability Requirements. Trans of Russian Maritime Register of Shipping 23. 2000. (In Russian)
12. Japan. Comments on draft guidelines for alternative assessment of weather criterion based on trial experiment results. 2005. IMO.
13. Francescutto A. Intact Stability of Ships – Recent Developments and Trends. PRADS 2007, Houston.
14. Deakin, B. An Experimental Evaluation of the Stability Criteria of the HSC Code. FAST 2005. St Petersburg, Russia.

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