Evaluation of the Weather Criterion by Experiments and its Effect to the Design of a RoPax Ferry

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ABSTRACT

The guidelines of experiments for alternative assessment of the weather criterion in the intact stability code were established in IMO/SLF48, 2005. Following the guidelines, wind tunnel tests and drifting tests for evaluating wind heeling lever, l_{w1}, and roll tests in waves for evaluating the roll angle, ϕ_1, were conducted. The results showed some difference from the current estimation, for example the wind heeling moment depended on heel angle and the centre of drift force existed higher than half draft. The weather criterion was assessed for allowable combinations of these results and the effect of experiment-supported assessment on the critical KG and so forth was discussed.

Keywords: *intact stability, weather criterion, safety standard, IMO*

1. INTRODUCTION

In 2005, the IMO Sub-Committee on Stability, Load Lines and Fishing Vessels Safety (SLF) restructured the Intact Stability Code (IS Code, IMO, 2002), and the weather criterion (Severe wind and rolling criterion), defined in section 3.2 of the code, was included in the Mandatory Criteria (Part A) of the revised code (IMO, 2006). The necessity of the criterion has been recognized to ensure ship stability safety in “dead ship condition”, in which the ability to control the ship is lost. However, the applicability of the criterion to some types of ships (e.g. modern large passenger ships), which did not exist at the time of development of the criterion, have been questioned. In order to solve the problem, the alternative assessment with model experiments is mentioned in the revised code.

To ensure uniform applicability of model experiments, which evaluate the wind heeling lever and the resonant roll angle, the guidelines were developed and included as Annex 1 in the revised code. However, they were set as “interim guidelines” because the feasibility, reliability and so forth are not fully clarified and it is recognized that a considerable accumulation of the experimental experience is required to correctly evaluate the safety.

Some effects of this assessment were already discussed (Bulian et al., 2004, Francescutto et al., 2004). However, they were not based on full experiments included in the guidelines. With this background the authors conducted experiments with a Ro-Pax ferry model following the guidelines and examined the above mentioned items. The previous paper (Taguchi et al, 2005, hereafter just referred as “previous paper”) reported the results except the wind tunnel tests. In this paper, the effects of this experiment-supported assessment by full experiments are reported. In the following chapters the items explained in the previous paper are mentioned concisely.

2. THE WEATHER CRITERION AND ITS ALTERNATIVE ASSESSMENT

The weather criterion evaluates the ability of a ship to withstand the combined effects of beam wind and waves. The criterion requires that area "b" should be equal to or greater than area "a" (see Figure 1), where

l_{w1} : steady wind heeling lever at wind speed of 26 m/s

l_{w2} : gust wind heeling lever (l_{w2} = 1.5 l_{w1})

ϕ_1 : roll amplitude in beam waves specified in the code

ϕ_2 : downflooding angle or 50 degrees or angle of second intercept between l_{w2} and GZ curves, whichever is less.

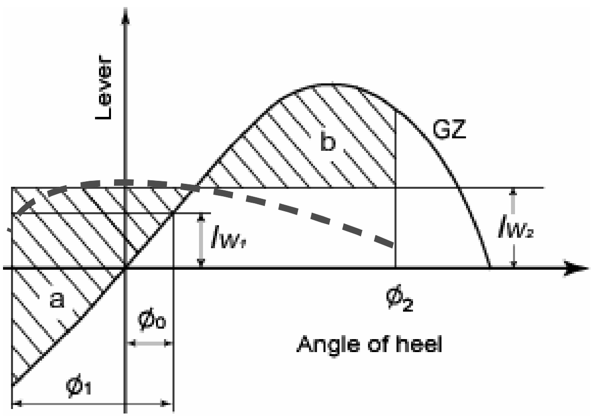

Figure 1 Weather criterion

In the revised code, l_{w1} and ϕ_1 can be evaluated by model experiments in the following conditions and it is allowed to consider the heeling lever as dependent on the heeling angle like the broken line in Figure 1,

l_{w1} : to the satisfaction of the Administration

ϕ_1 : when the parameters of the ship are out of the following limits or to the satisfaction of the Administration;

- B/d smaller 3.5
- (KG/d-1) between -0.3 and 0.5
- T smaller than 20 seconds

where B, d and KG are the breadth, draft and the height of CG above keel of the ship respectively, and T is the natural rolling period.

3. THE SUBJECT SHIP

The subject ship is a Japanese Ro-Pax ferry. Table 1, Figures 2 and 3 show the principal particulars, the general arrangement and GZ curve respectively. Compared to general European Ro-Pax ferries this ship has finer shape. From Figure 3 it is found that up to about 40 degrees the GZ curve has a very small nonlinearity to heel angle.

Table 1 Principal particulars

Length between perpendiculars: Lpp [m]	170.0
Breadth: B [m]	25.0
Depth: D [m]	14.8
draft: d [m]	6.6
Displacement: W [ton]	14,983
Blockage coefficient: C_b [-]	0.521
B/d [-]	3.79
Area of Bilge Keels: A_{bk} [m^2]	61.32
Vertical center of gravity: KG [m]	10.63
Metacentric height: G_0M [m]	1.41
Flooding angle: ϕ_f [deg]	39.5
Rolling Period: Tr [sec]	17.90
Lateral projected area: A_L [m^2]	3433.0
Height to centre of A_L above WL: Hc [m]	9.71

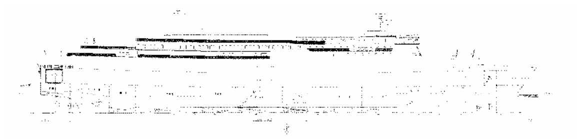

Figure 2 General arrangement

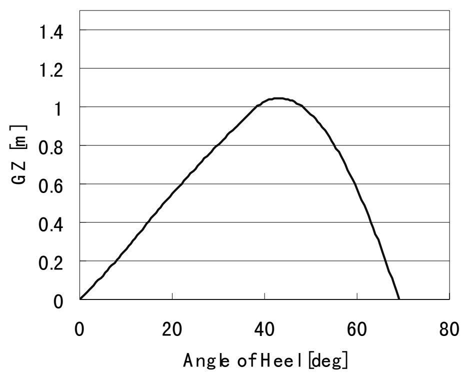

Figure 3 GZ curve

4. WIND HEELING LEVER l_{w1}

The wind heeling lever is estimated from the heeling moment when the ship is drifting laterally by beam wind. Therefore, wind tunnel tests and drifting tests are necessary.

4.1 Wind Tunnel Tests

The wind tunnel tests were conducted at "pulsating wind tunnel with water channel" of NMRI (National Maritime Research Institute), with wind section of 3m in width and 2m in height. The test arrangement is shown in Figure 4. The connection between the model and load cell had a rotating device for testing the model in heeled conditions. In heeled conditions, the height of the model was adjusted by the adjusting plate to keep the displacement constant when floating freely. By using the model of 1.5m in length, the blockage ratio was kept less than 5%, which is requested by the guidelines. The gap between the model and the floor plate was kept within approximately 3mm and covered by soft sheets for avoiding the effect of downflow through the gap.

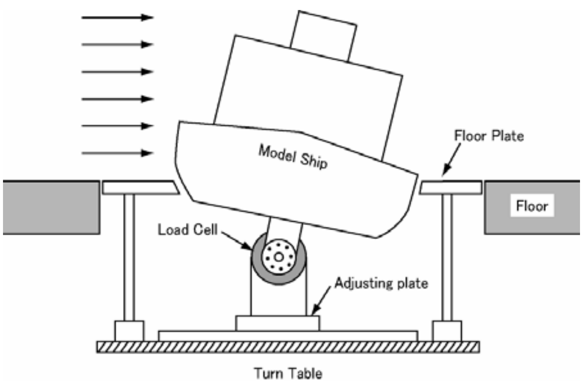

Figure 4 Arrangement for wind tunnel tests

The wind speed was varied from 5m/s to 15m/s in upright condition and confirmed that the drag coefficient is almost constant in this speed range. For the full tests a wind speed of 10m/s was used, corresponding to the Reynolds' number of 1.52×10^5, as defined by the following equation:

$$Re = \frac{U_\infty B}{\nu} \tag{1}$$

where U_∞ is the uniform wind speed outside the boundary layer, B is the breadth of the model and ν is the kinematic viscosity coefficient of air.

The horizontal force F_{wind}, the heeling moment M and the lift force L were measured by the load cell. The heeling moment M was converted to the one with respect to point O, defined as M_{wind} in the guidelines, by the following equation:

$$M_{wind} = M - F_{wind} l\cos\phi + L\cdot l\sin\phi \tag{2}$$

where l is the distance from the centre of the load cell to the point O, which is defined as the cross point of the centre line of the ship and waterline in upright condition.

4.2 Results of Wind Tunnel Tests

The measured drag coefficient C_D, lift coefficient C_L and heeling moment coefficient C_M are shown in Figure 5. They are nondimensionalized by the following equations:

$$\begin{pmatrix} C_D \\ C_L \end{pmatrix} = \begin{pmatrix} F_{wind} \\ L \end{pmatrix} \Bigg/ \left(\frac{1}{2}\rho_{air}U^2 A_L\right) \tag{3}$$

$$C_M = M_{wind} \Bigg/ \left(\frac{1}{2}\rho_{air}U^2 \frac{A_L^2}{L_{pp}}\right) \tag{4}$$

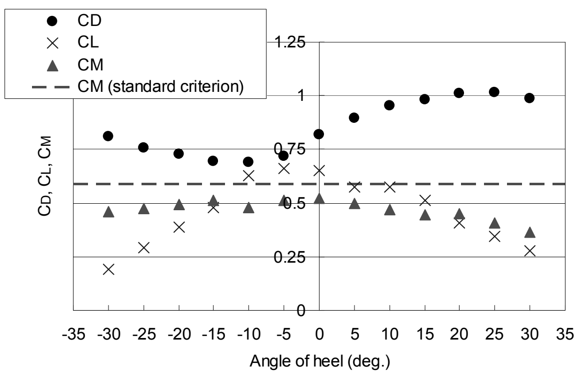

Figure 5 Results of wind tunnel tests

In the figure the angle of heel is defined as positive when the ship heels to lee side as shown in Figure 4. The broken line is the heeling moment coefficient calculated from the current weather criterion (IMO, 2002, called standard weather criterion hereafter).

It is characteristic in Figure 5 that at all the quantities (C_D, C_L and C_M) vary significantly with heel angle. As for the heeling moment, it is smaller than the standard criterion and further reduces when the ship heels, especially to lee side. The lift force is not so small and close to the drag force when the heeling angle is -5 degrees (weather side). However, the adjustment of the vertical position of the model is not necessary since the lift force is 0.7% of the displacement of the ship in the assumed wind speed of 26m/s.

The result is also shown in Figure 6 as the height of the centre of wind force above waterline , l_{wind}, by the following equation. It can be observed that the centre of wind force is also a function of heel angle.

$$l_{wind} = M_{wind} / F_{wind} \tag{5}$$

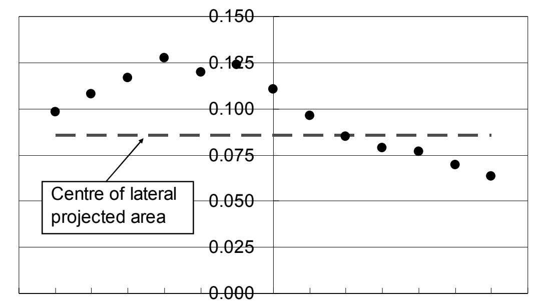

Figure 6 Height of the centre of wind force above waterline (model scale)

Although it is not requested in the guidelines, the effect of encounter angle, φ, was investigated. Figure 7 shows the wind heeling moment coefficient, C_M. Here φ <90 means following wind. The figure shows that the wind heeling moment is almost at the maximum in beam wind condition (φ =90 degrees). This fact supports the assumption of existing regulations. However, for developing performance based, physics based criteria, the information on the effect of encounter angle to heeling moment might be necessary.

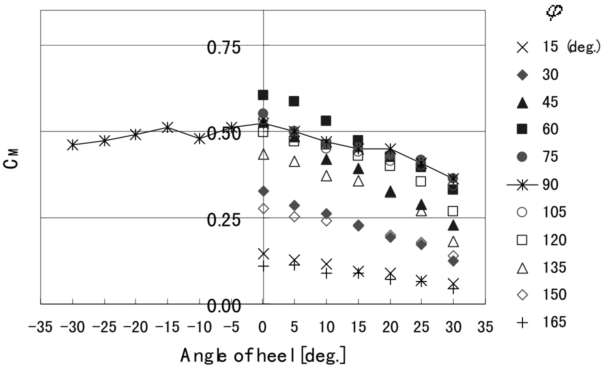

Figure 7 Wind heeling moment coefficient for various encounter angles

4.3 Drifting Tests

The detail of drifting tests was reported in the previous paper. Here, the height of the centre of drift force above waterline, l_{water}, is shown in Figure 8. l_{water} was calculated in the same manner as equation (5). The angle of heel is positive when the ship heels to the drift direction. The drift speed (towing speed) was decided, as requested in the guidelines, to make the measured drift force equal to the wind force at the wind speed of 26m/s in ship scale. Because drifting tests were conducted before wind tests, the wind drag coefficient, C_D, was assumed to be from 0.5 to 1.1. In upright condition and C_D=0.8 the drift speed was 0.195m/s (1.80m/s in ship scale).

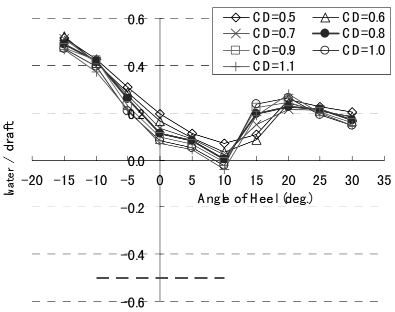

Figure 8 Height of the centre of drift force above waterline

Figure 8 shows that the centre of drift force is above half draft (which is assumed in the standard criterion) and is generally above the waterline for this ship. This phenomenon was reported by Hishida and Tomi (1960), Ishida (1993), Ishida and Fujiwara (2000) and referred in IMO/SLF (2003). This is due to the more dominant effect of the bottom pressure distribution than the side pressure when breadth/draft ratio is large. For the cross sections with this proportion, high position of the centre of sway force can be easily found in hydrodynamic tables of Lewis Form. This fact suggests that potential theory would explain this phenomenon. However, the effect of separated flow, e.g. from bilges, was also pointed out (Ishida and Fujiwara, 2000). It was confirmed experimentally in the previous paper that l_{water} reduces when the draft is enlarged.

4.4 Determination of l_{w1}

The heeling moments by wind, M_{wind}, and by drifting, M_{water}, both around point O, were divided the displacement, Δ, and the wind heeling lever, l_{w1}, was calculated as a function of heel angle (equation (6)). Figures 9 and 10 show the results.

$$l_{w1} = \frac{M_{wind} + M_{water}}{\Delta} \tag{6}$$

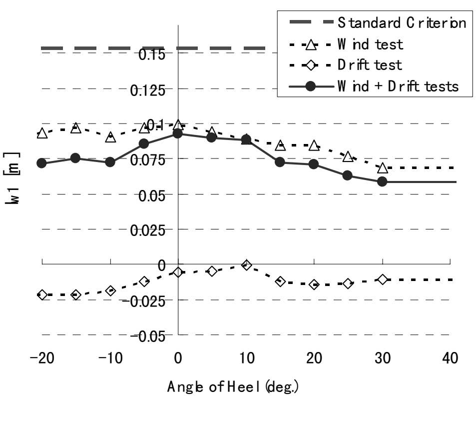

Figure 9 Wind heeling lever, l_{w1}, evaluated by the tests

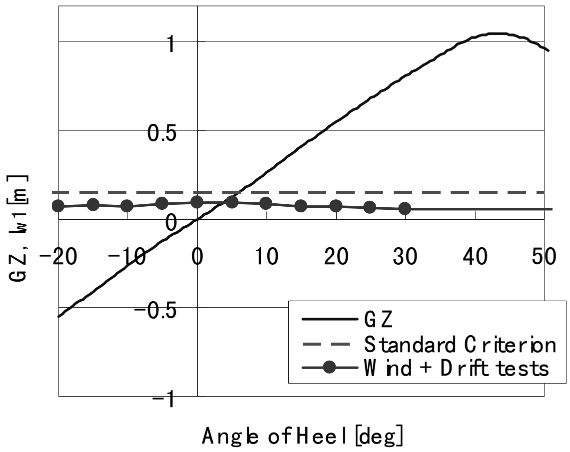

Figure 10 Wind heeling lever, l_{w1}, compared with the GZ curve

In Figure 9, the heeling levers due to wind (M_{wind}/Δ) and drift motion (M_{water}/Δ) are also included. In both figures, l_{w1} at angles greater than 30 degrees (tested range) is assumed to keep the same value as at 30 degrees as prescribed in the guidelines. Figure 9 and 10 show that, in the considered case, the wind heeling lever estimated by wind and drift tests is sensibly smaller than that required by the standard weather criterion.

5. ROLL ANGLE ϕ_1

The formula of roll angle ϕ_1 in the weather criterion implies the maximum amplitude out of 20 to 50 roll cycles in beam irregular waves. And ϕ_1 is related to the resonant roll amplitude, ϕ_{1r}, in regular waves, whose height and period are equal to the significant wave height and mean wave period of the assumed irregular waves (IMO, 2006, Watanabe et al., 1956). The reduction factor is 0.7 (see equation (7)) and this alternative assessment estimates ϕ_{1r} instead of ϕ_1 by model experiments.

$$\phi_1 = 0.7\phi_{1r} \tag{7}$$

5.1 Direct Measurement Procedure

In the guidelines, this procedure is called "Direct measurement procedure" because the resonant roll angle, ϕ_{1r}, is measured directly in waves with the steepness specified in the IS Code and the period equal to the natural roll period.

The results of experiments were mentioned in the previous paper. Here, Figure 11 is shown again. In the figure, "*s*" is the wave steepness, which is tabled in the Code as a function of the natural roll period. For this ship *s*=0.0383 (1/26.1), but lower steepnesses were also used. Due to the linearity of the GZ curve the amplitudes reach the maxima at the vicinity of the natural roll frequency in all steepnesses. From this result, ϕ_1 was decided as 19.3 degrees (=0.7 ϕ_{1r}).

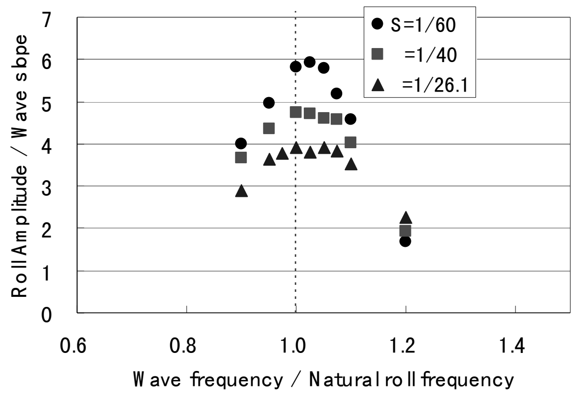

Figure 11 Roll amplitude in regular waves

5.2 Alternative Procedures

In the guidelines, alternatives procedures are included, i.e. "Three steps procedure" and "Parameter identification technique (PIT)". In the "Three steps procedure", the roll damping coefficient N is estimated by roll decay tests. And, the effective wave slope coefficient r is estimated by roll motion tests in waves with smaller value of s. Finally, ϕ_{1r} (degrees) is calculated by the following equation:

$$\phi_{1r} = \sqrt{\frac{90\pi rs}{N(\phi_{1r})}} \tag{8}$$

This method was adopted when the standard weather criterion was developed and is based on linear theory except roll damping. The previous paper showed that the estimated value of ϕ_1 is 19.5 degrees when the resonant roll amplitude at *s*=1/60 is used. This value of ϕ_1 is very close to that by the "Direct measurement procedure" due to the linear feature of GZ curve.

The PIT is a methodology to determine the parameters included in the equation of roll motion. Once all the parameters are decided by test data at small wave steepness, the roll amplitude at prescribed *s* can be extrapolated. In the guidelines, an equation with 9 parameters is presented, in which nonlinear features of roll damping, GZ curve and wave exciting moment are included. PIT analysis is not carried out in this paper. However, the difference of ϕ_1 by PIT from other 2 procedures is expected to be limited because of the linearity of GZ curve.

6. ALTERNATIVE ASSESSMENT OF THE WEATHER CRITERION

In the guidelines, simplified procedures on the wind heeling lever, l_{w1}, are also mentioned for making the assessment practically easier. For wind tunnel tests, the lateral horizontal force F_{wind} and the heeling moment M_{wind} can be obtained for the upright condition only and considered as constants (not depending on heeling angle). Instead of drifting tests, the heeling moment M_{water} due to drift can be considered as given by a force equal and opposite direction to F_{wind} acting at a depth of half draft in upright condition, as assumed in the standard criterion. And the combinations of complete procedures and simplified procedures are to the satisfaction of the Administration.

The comparison of the assessments of the weather criterion using experimental results is summarized in Table 2. In the table all the possible combinations of the wind tests and the drifting tests, complete procedures and simplified procedures are included. As for ϕ_1, the standard criterion and the result of "Direct measurement procedure" are included. The results of "Three steps procedure" can be omitted here since the estimated ϕ_1 was almost equal to the one of "Direct measurement procedure" for this ship.

Table 2 Assessments of weather criterion by experiments

l_{w1}	Standard Weather Criterion	Wind test + Drift test	Wind test + draft/2	Wind test (upright) + Drift test	Wind test (upright) + draft/2	Standard Weather Criterion	Wind test + Drift test	Wind test + draft/2	Wind test (upright) + Drift test	Wind test (upright) + draft/2
ϕ_1	Standard Weather Criterion					Direct Procedure (or Three Steps Procedure)				
l_{w1} [m]	0.153	Function of heel angle			0.125	0.153	Function of heel angle			0.125
r [-]	1.096					0.759 (Three Steps Procedure)				
T_r [sec]	16.3					17.9				
s [-]	0.0431					0.0383				
ϕ_1 [deg]	15.4					19.3				
ϕ_0 [deg]	6.1	3.7	4.9	3.8	5.0	6.1	3.7	4.9	3.8	5.0
$\phi_0-\phi_1$ [deg]	-9.3	-11.7	-10.4	-11.6	-10.4	-13.2	-15.7	-14.4	-15.5	-14.3
ϕ_f [deg]	39.5									
Area a [rad-m]	0.075	0.063	0.069	0.063	0.070	0.111	0.096	0.103	0.095	0.106
Area b [rad-m]	0.224	0.295	0.259	0.276	0.247	0.224	0.295	0.259	0.276	0.247
b/a [-]	2.99	4.71	3.76	4.41	3.51	2.02	3.09	2.51	2.90	2.34
Crit. KG [m]	11.48	11.88	11.68	11.79	11.62	11.35	11.82	11.59	11.73	11.52

The last line of Table 2 shows the critical values of the vertical centre of gravity (KG), in which the ratio of area b/a=1 (see Figure 1). These last results are to be taken with some caution, since the effects of changing the vertical centre of gravity on T_r (natural roll period) and on the other quantities related to roll motion, including ϕ_1, have been neglected.

Table 2 shows that the alternative assessment by model experiments can change b/a significantly with respect to the standard criterion. For this ship, b/a's of the right side of the table are smaller than those of the left side. This tendency comes from the increased ϕ_1 obtained by experiments and it was suggested in the previous paper that ϕ_1 was enlarged by the small damping coefficient (N=0.011 at 20 degrees). On the other hand, the l_{w1} evaluated through all the combinations of the wind tests and drifting tests, complete procedures and simplified procedures, tends to make b/a larger than the standard criterion. It has to be noted that the leading cause of the fluctuations is the large variation in the vertical centre of hydrodynamic pressure when evaluated through the drifting tests.

Figure 12 shows the critical values of KG. From Table 2 and Figure 12, it is recognized that the changes in the critical value of the vertical centre of gravity are more contained than b/a, but as much as 0.4m at the maximum from the standard criterion.

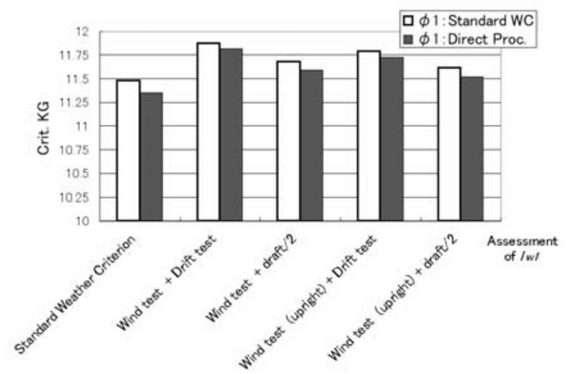

Figure 12 Variation of critical KG

7. CONCLUSIONS

In this paper, the results of the alternative assessment of the weather criterion by model experiments are reported. Almost full tests, included in the interim guidelines, were conducted. Considerable fluctuations of the assessment and their reasons are clarified. In order to make the assessment more uniform and to remove the word of "interim" from the guidelines, more extensive confirmation from the experience gained through the application of the guidelines is needed.

8. ACKNOWLEDMENTS

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