ALTERNATIVE ASSESSMENT OF WEATHER CRITERION FOR SHIPS WITH LARGE BREADTH AND DRAUGHT RATIOS BY A MODEL EXPERIMENT: A CASE STUDY ON AN INDONESIAN RO-RO FERRY

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SUMMARY

The weather criterion is one of stability criteria to verify ability of a ships to withstand the combined effects of severe wind and rolling criteria in dead ship condition. An overestimated roll angle is obtained when the weather criterion is applied to ships with breadth and draught ratios larger than 3.50 and ratios between vertical centre of gravity and draught larger than 1.50. This paper discusses the assessment of weather criterion for an Indonesian ro-ro ferry by model experiments. The drift test is performed in four wave steepnesses with wave frequencies near the roll natural frequency. The maximum roll amplitude is used to calculate the effective wave slope coefficient correponding to the wave steepness, with Bertin's coefficient obtained by the roll decay test. The damping factors correspond to the breadth and draught ratio as well as the bilge keel contribution are determined using the formula of weather criterion with the roll angle obtained by the Japanese formula with a correction factor of 0.70 due to the irregularity of waves. The obtained effective wave slope coefficient and the damping factors due to breadth and draught ratio and the bilge keel are smaller than those used in the weather criterion.

NOMENCLATURE

a	Linear damping coefficient (s^{-1})
b	Nonlinear damping coefficient ($deg.^{-1}$)
k	Damping factor due to bilge keel
r	Effective wave slope coefficient
s	Wave steepness
N	Bertin's coefficient
X_1	Damping factor due to breadth and draught ratio
X_2	Damping factor corresponds to block coefficient
ϕ_1	Maximum roll amplitude in irregular waves (m)
ϕ_{1r}	Maximum roll amplitude in regular waves (m)
ω	Wave frequency (rad/sec)
ω_0	Natural frequency of roll (rad/sec)

1. INTRODUCTION

The weather criteria were adopted as part of intact stability criteria to consider effect of wind and waves in dead ship condition especially for ships with large windage areas such as passenger ships and ro-pax ships, by the International Maritime Organization (IMO) in 1985 and are still part of the International Code on Intact Stability (IS Code 2008) (IMO, 2008). This criterion is used to ensure ability of a ship to survive against action of combined wind and waves. The parameter of this criteria is ratio between area under the righting arm curve from the static heel angle due to steady wind to the angle of vanishing stability or the down flooding angle which is the smallest and area under the righting arm curve from the static heel angle to the roll-back angle due to waves action in windward direction. This ratio should be larger than 1.0 to comply with this criteria. The empirical formula for calculating the roll-back angle on the windward side was developed by merging the Japanese and the Russian standards. The value of each formula variable was statistically determined as a function of the ship geometry, which consists of breadth and draught ratio smaller than 3.50 and block coefficient smaller than 0.70. The effective wave slope coefficient was linearly calculated as a function of the ratio between the vertical centre of gravity and the ship draught. This function was statistically developed based on ships with a ratio of the vertical centre of gravity and ship the draught between 0.70 and 1.50. The wave steepness was determined based on a natural period of roll range from 6 seconds to 20 seconds, corresponding to a wind velocity of 26 m/s. The maximum roll period was extended to 30 seconds, corresponding to a wave steepness of 0.02 (IMO, 2015). This wave steepness is 0.10 for ships with a natural roll period of 6.0 seconds or smaller.

During the last two decades, the weather criteria have been criticized by some authors because the current major ship types are different from ship types when the criteria were developed (Zbigniew, 2014; Umeda and Francescutto, 2016). The roll-back angle obtained through the weather criteria formula may be overestimated due to a larger value of X_1 indicating a smaller damping factor corresponding to the breadth and draught ratio when the ratio is larger than 3.5 (Deakin, 2008; IMO, 2003). The damping factor corresponds to bilge keel designated by k factor in the formula of weather criterion, which seems to be underestimated mainly for small ships. The bilge keel may reduce the roll amplitude more than 30.0 percent (Fesman, *et al*, 2007). The damping coefficient could increase more than twice that of a damping coefficient without a bilge keel (Gu *et al*, 2015). All terms in the formula were incorrectly estimated at the time that the original weather criteria were established (Vassalos *et al*, 2003; Francescutto, 2011). The effective wave slope coefficient could be larger than 1.0 for ships with large vertical centres of gravity (KG) and shallow draughts. However, the results of model experiments for a large passenger ship and a ro-pax ferry show that the coefficient is smaller than 1.0 (Francescutto *et al*, 2001; Ishida *et al*, 2011). A small effective wave slope coefficient was also obtained for ships with large breadth and draught ratios (Paroka, 2014; Sato *et al*, 2008). From a safety point of view, the weather criteria provide a higher safety level compared with the proposal of the Russian Federation (IMO, 2003), but the ships should be designed with lower centres of gravity to avoid large effective wave slope coefficients. This design requirement seems to be difficult for certain ship types, such as passenger ships and ro-ro passenger ferries.

However, if a reliable formula for calculating Bertin's coefficient were available, the Japanese standard could be a more appropriate method from a practical point of view because this method does not depend on the geometric characteristics of ships. The Bertin's coefficient is defined as equivalent nonlinear expression represent the damping coefficient in the Japanese standard which strongly depends on the mean amplitude of roll. This coefficient can be determined by using the extinction coefficient of relation between the average of two consecutive roll amplitude and the decrement of roll amplitude of roll decay test. This coefficient can also be determined by using the Ikeda's simplified formula as recommended by IMO for ships with the ratio between breadth and draught is smaller than 4.5 (Rukadovic and Backalov, 2017). The other method is numerical simulation using the computational fluid dynamics. The interim guidelines of IMO recommend a Bertin's coefficient of 0.02 for normal ships with a bilge keel (IMO, 2006a). This values was determined based on the maximum roll angle of 20.0 degrees. This value is too low for small passenger vessels such that the obtained roll angle could be overestimated (Fujino *et al*, 1993).

IMO decided to revise the intact stability criteria, including the weather criteria, but the semi-empirical nature of the adjusting factors introduced in the original formulation make it impossible to affect change in any detail. To accommodate the ships with geometry characteristics different from the ship used to develop the criteria, IMO provided interim guidelines for alternative assessments of weather criteria (IMO, 2006a; IMO, 2007). These guidelines provide an experimental procedure to adjust the values of each variable of the formula for calculating the roll-back angle. The two model experiments consisting of roll decay and drift tests should be conducted to estimate the damping factor represented by Bertin's coefficient and the effective wave slope coefficient, respectively. The model scale should be 1 : 75 or a model length of 2.0 metres, whichever is larger (IMO, 2006b). The initial roll angle for a decay test is at least 25.0 degrees (IMO, 2006a). For ships with small freeboard and breadth ratios, the roll decay test cannot be conducted with the recommended initial roll angle because the angle of the deck edge that is immersed is smaller than 25.0 degrees. On the other hand, the initial roll angle may affect the damping coefficients, mainly the nonlinear part (Remola *et al*, 2018).

Recently, IMO developed the second-generation intact stability criteria with a performance-based approach for each capsizing scenario of a ship in a seaway. The criteria was developed with multi-tiered approach known as the vulnerability criteria consist of the vulnerability criteria level 1, level 2 and direct assessment. The first level should be simpler and more conservative compared to the second level. This first level is meant to separate non-vulnerable ships from those supposed to be vulnerable for each stability failure mode. The second level is more complex and physics based approach considering the dynamics phenomena corresponding to the capsizing scenario. The vulnerability criteria level 2 is used to confirm the assessment made in the first level. A ship identified to be non-vulnerable in the second level should also be non-vulnerable in the first level. If the ship is found to be vulnerable in the second level, the ship should also be vulnerable in the first level. In the case of a dead ship condition, the weather criteria have been established as a first level of vulnerability criteria and a capsizing index calculated using a probability approach as the second level. These criteria have been used to assess the stability of several ship types. The results show some inconsistencies between the first and the second levels of vulnerability regarding the acceptable values of the capsizing index, especially for ships with low freeboard and large breadth and draught ratio (Umeda *et al*, 2019). This inconsistency arises due to different approach used to develop the criteria of each level of vulnerability in which the complexity of the criteria increases with the level of vulnerability. The weather criteria were deterministically calculated only for one sea state at the resonance frequency of roll motion, while the capsizing index was probabilistically calculated as the accumulation of several different sea states. A different method to estimate the damping coefficient is also used in both the weather criterion and the capsizing index. The damping factor correspond to the breadth and draught ratio in the weather criterion could be overestimate when it is applied to ships with breadth and draught ratio larger than 3.50 (Deakin, 2008). This means that the stability level of ships with large breadth and draught ratio become higher. In order to obtain more conservative stability level, an alternative method to estimate the value of parameters in the weather criterion for ships with geometry characteristics different with those used to develop the criteria become important.

This paper includes a discussion about the determination of damping factors and the effective wave slope coefficient to evaluate the weather criteria for ships with breadth and draught ratios larger than 3.50 by a model experiment. This is important because many ships, especially small ro-ro passenger ferries used for short inter-island and inland transportation, have breadth and draught ratios larger than 3.50. For small ships, the effect of the bilge keel on the maximum roll angle could be more significant compared to large ships. The breadth and draught ratio and the vertical centre of gravity may also have a significant effect on the damping factor induced by the bilge keel. This is because the damping factor corresponding to the bilge keel is strongly affected by the distance between the centre of rotation and the position of the bilge keel. The obtained results can be used to determine the damping factors and the effective wave slope coefficient to evaluate the weather criteria of ships with large breadth and draught ratios. The present results may also be used to investigate the possibility of applying the second-generation intact stability criteria to small ships with large breadth and draught ratios, which had not been considered during the finalization step of the criteria.

2. METHODOLOGY

To apply the weather criteria to a ship with geometric characteristics different from the ships used to develop the criteria, the IMO recommended model experiment is conducted to adjust the values of each variable in the formula for roll-back angle calculation (IMO, 2006a; IMO, 2007). Those methods consist of a three-step procedure, including a direct method and parameter identification technique (PIT) methods. Here, a three-step procedure method is used to estimate the effective wave slope coefficient, Bertin's coefficient, and the maximum roll angle. This method is applied to an Indonesian ro-ro ferry, with the principal dimensions shown in Table 1 and the body plan shown in Figure 1. The ratio between the breadth and the draught of the ship is 5.185, and the freeboard is 1.10 metres. The vertical centre of gravity is larger than the ship height because the payload is located above the main deck. The vehicles are located on the main deck, and passenger accommodation is on a superstructure above the main deck. The righting arm curve of the ship for the full loading condition is shown in Figure 2.

Table 1: Principal dimensions of ship and model

Dimension	Ship (m)	Model (mm)
Length perpendiculars (Lpp)	50.50	1262.5
Breadth (B)	14.00	350.0
Height (H)	3.80	95.0
Draught (d)	2.70	67.5
Metacentric height (GM)	4.23	105.8
Vertical centre of gravity (KG)	4.717	117.9
Block coefficient (CB)	0.706	0.706
Length of bilge keel	18.00	450.0
Breadth of bilge keel	0.25	6.30
Displacement (Δ)	1217.58	19024.72

The model scale was 1 : 40, which is smaller than the minimum scale recommended by IMO (IMO, 2006b), but the model length is smaller than 2.0 metres in order to comply with the requirement that the towing tank width should be larger than the model length with the clearance between the model and the tank wall of 2.0 metres. The model experiment is conducted in the towing tank of Faculty of Engineering Hasanuddin University, Indonesia. The length of the towing tank is 60.0 metres, with a breadth of 4.0 metres and a depth of 3.0 metres.

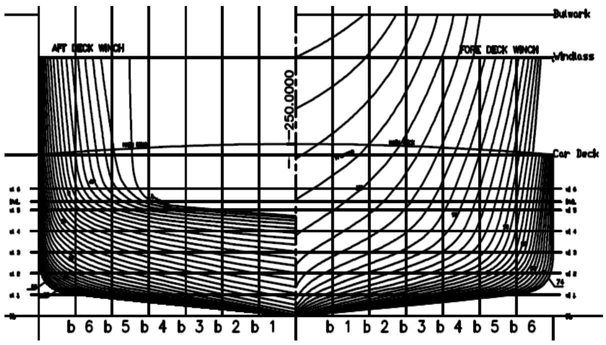

Figure 1: The ship body plan for an Indonesian Ro-ro Ferry

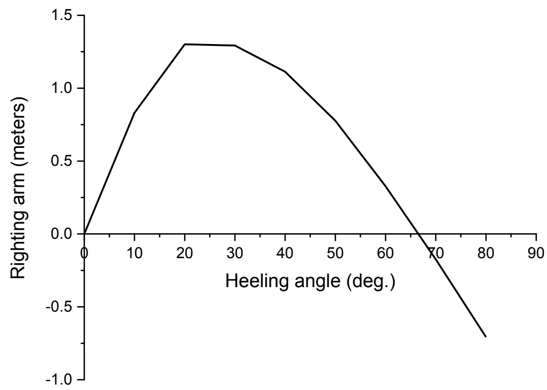

Figure 2: Righting arm curve of the subject ship

The first step of the three-step procedure is to estimate Bertin's coefficient using data from the roll decay test. To determine the damping factor corresponding to the breadth and draught ratio and the bilge keel, the roll decay test is performed for ship models with and without bilge keels. The initial roll angle for those tests is 25.0 degrees. The weight distribution is set for a radius of gyration of 0.35 of the ship breadth, following the loading plan of the vehicles on the car deck. The roll motion in the time domain is recorded using a dual-axis inclinometer. Five series of roll decay tests are conducted for ships with and without bilge keels. The linear and quadratic damping coefficients are statistically determined using curve fitting of the roll angle decrement and an average of two consecutive roll amplitudes, starting from the second roll amplitude to a roll amplitude smaller than 0.50 degrees. The Bertin's coefficient is determined based on the linear and the quadratic damping coefficients using the following equation (IMO, 2006a):

$$N(\phi_m) = \frac{a}{\phi_m} + b \tag{1}$$

The linear and the quadratic damping coefficients are determined as the average of five series decay tests. The natural frequency of roll is also determined as the average of roll natural frequencies obtained in the series roll decay tests.

The drift tests in beam seas for ship models without and with bilge keels are conducted for four different wave steepness (0.01, 0.02, 0.03, and 0.04), with wave frequencies of 0.9, 1.0, and 1.1 of the natural roll frequency obtained in the roll decay tests. If the maximum roll amplitude is not obtained in those frequencies, the test should be conducted in a wider frequency range between 0.80 and 1.20 of natural roll frequency or larger as recommended by the interim guidelines of IMO (IMO, 2006a). The model is free for sway, heave, and roll motions, respectively. The yaw motion is restricted by a flexible wire rope at the vertical centre of gravity in both the stern and bow of the model connected to a pair of fixed arm in the carriage, as shown in Figure 3.

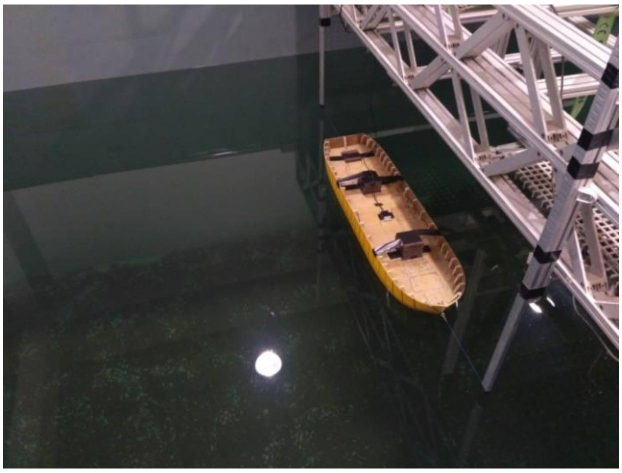

Figure 3: Setting model for a drift test in beam seas

The effective wave slope coefficient is calculated based on the maximum roll amplitude for each wave steepness unit using equation (2) (IMO, 2006a).

$$\phi_{1r} = \sqrt{\frac{90\pi rs}{N(\phi_{1r})}} \quad (2)$$

where, ϕ_{1r} is the maximum amplitude of roll motion for the corresponding wave steepness. Here, Bertin's coefficient corresponds to the maximum roll amplitude, as calculated using equation (1).

The obtained effective wave slope coefficient is used to calculate the maximum roll angle for the actual wave steepness, following the adjusted value of the weather criteria based on the natural roll period by iteratively solving equation (2) with an initial roll angle of 20.0 degrees. The maximum roll angle in irregular seas is determined as 70% of the roll angle obtained in equation (2) with the actual wave steepness. If the maximum roll angle in irregular seas is the same as the roll-back angle in the weather criterion, the damping factor corresponding to the breadth and draught ratio can be determined using the following equation (IMO, 2008):

$$\phi_1 = 109kX_1X_2\sqrt{rs} \quad (3)$$

Here, the roll angle, ϕ_1, is the maximum roll angle in an irregular wave; the damping factor corresponding to the bilge keel, k, is 1.0 because the ship is without a bilge keel and the damping factor due to the block coefficient is adjusted following the IMO weather criteria. The damping factor due to the bilge keel can be determined with the same procedure using the roll-back angle of ship with bilge keel and the damping factor corresponds to breadth and draught ratio is the same as that obtained from the experiment without a bilge keel.

3. RESULTS AND DISCUSSION

The linear damping coefficients of ships with and without bilge keels obtained from roll decay test are shown in Figure 4 for the linear part, and those for the quadratic parts shown in Figure 5, respectively. The error bars indicate the confidence interval of the damping coefficients. This confidence interval is obtained based on the results of five roll decay tests conducted for both the ship with and without bilge keels with confidence level of 0.95, respectively. The linear damping coefficient without a bilge keel is 0.08 s^{-1}, and that for ships with bilge keels is 0.234 s^{-1}. The nonlinear part of the damping coefficient increases from 0.022 deg^{-1} to 0.051 deg^{-1} due to the bilge keel.

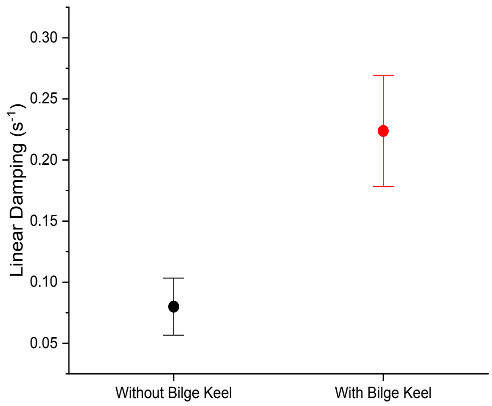

Figure 4: Linear damping coefficients of the ship without and with bilge keels.

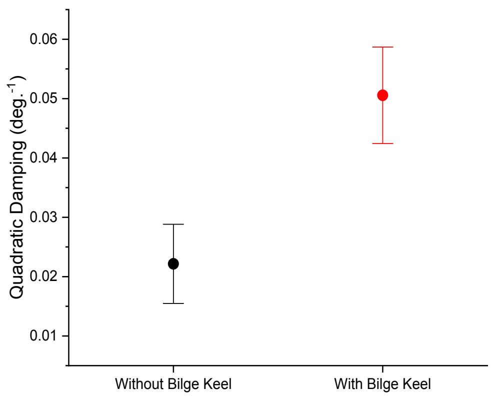

Figure 5: Quadratic damping coefficients of the ship without and with bilge keels.

A similar result has been obtained by Gu *et al* (2015) for an FPSO using CFD and model experiment. The damping moment induced by the bilge consists of the moment due to the drag force acting on the surface of the bilge keel and the moment due to pressure on the ship hull induced by the bilge keel. The damping moment induced by the bilge keel for a ship with a shallow draught and a large vertical centre of gravity is larger than that for normal ships (Katayama *et al*, 2018). Therefore, the adjusted damping factor in the weather criteria could be overestimated for ships with large breadth and draught ratios larger than 3.50 and ratios between the vertical centres of gravity and draughts larger than 1.50. The natural roll period obtained by the roll decay test is 4.454 seconds in full scale for the ship without a bilge keel, and that for the ship with a bilge keel is 4.652 seconds. The natural roll period is smaller than that obtained using the IMO weather criteria formula. The radius of gyration of the ship obtained by the model experiment is smaller than that calculated by using Morita's empirical formula that was used in the weather criteria to estimate the natural roll period. The formula to calculate the coefficient "c" in the weather criterion was developed based on ship data with breadth and draught ratio smaller than 3.5. A significant error of the formula may appear when it is applied to a ship with larger breadth and draught ratio and metacentric height (Borisov and Luzyanin, 2015). The formula does also not take into account the vertical centre of gravity as well as the bilge keel effect. The different between the roll period calculated by formula of weather criterion and that obtained by roll decay test is 26.4 percent for ship without bilge keel and that of 23.1 percent for ship with bilge keel.

Similar results have been found for ships with radius gyration of 0.35 of ship breadth (Deakin, 2008). For ships with large breadths and shallow draughts, the value of "c" in the formula of natural roll period could be larger than that obtained by the model experiment because the formula is proportional to those ship dimensions mainly the breadth and draught ratio as well as the ship length. The increase in the natural roll period due to bilge keel was also found by Gu *et al* (2015). However, the formula to calculate the natural roll period in the weather criteria is independent of bilge keel geometry. The bilge keel reduces the angular velocity of roll so that the period of motion becomes larger. These natural roll periods result in the application of the maximum wave steepness because they are smaller than the minimum natural roll period given in the weather criteria. This wave steepness could be unrealistic for ships operated for short inter-island and river-sea transportation. The wave characteristics in such operation area could be different from open seas.

The increasing damping coefficients induced by bilge keel can be verified from the roll amplitude obtained by drift tests in beam seas, as shown in Figure 6, for ships without bilge keels and those with bilge keels, as shown in Figure 7. The bilge keel reduces the roll amplitude by 43.73 percent from 10.878 degrees for a ship without a bilge keel to 6.121 degrees for a ship with a bilge keel in a wave steepness of 0.04. The bilge keel area of the subject ship is 9.0 m^2, corresponding to a 3.60 percent reduction of damping factor in the weather criteria. This result shows that the reduction of damping factor due to bilge keels for small ships with large breadth and draught ratios in the weather criteria is smaller compared to the present results. The reduction of roll amplitude due to bilge keels of the present results is similar with the bilge keels effect on roll motion found by Fesman *et al* (2007). The decreasing roll angle could be larger for a ship with a larger breadth and draught ratio and a large vertical centre of gravity, as found by Katayama *et al* (2018).

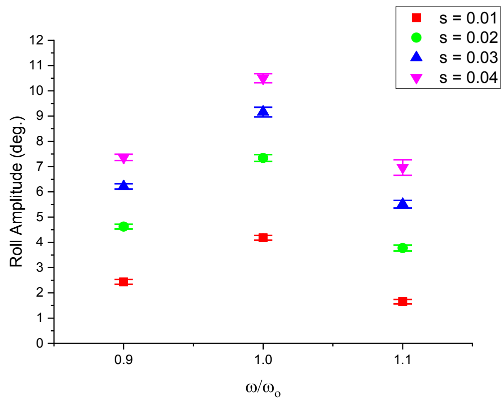

Figure 6: Roll amplitude obtained by the model experiment in beam seas for ship without bilge keels

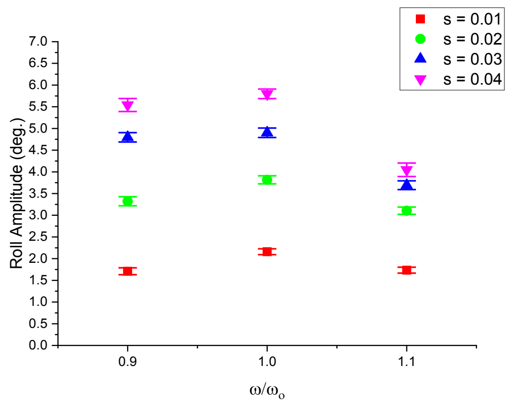

Figure 7: Roll amplitude obtained by the model experiment in beam seas for ship with bilge keels

The effective wave slope coefficient for each wave steepness unit is calculated using the equation (2), with the maximum roll amplitude shown in Figure 6 and Figure 7. The obtained effective wave slope coefficients of ships with and without bilge keels are shown in Figure 8. The effective wave slope coefficients of ships with bilge keels tend to decrease due to increases in wave steepness when the wave steepness is larger than 0.02. At the same wave steepness, this coefficient tends to be constant for ships without bilge keels. The effective wave slope coefficient for a ship with a bilge keel is larger than that for a ship without a bilge keel, but the difference is not significant. This result indicates that the bilge keel does not have a significant effect on the effective wave slope coefficient.

Those coefficients are smaller than those obtained by the weather criteria formula (1.178) because the ship has a large vertical centre of gravity. Sato *et al* (2008) ascertained that ships with large breadth and draught ratios have effective wave slope coefficients smaller compared to ships with smaller breadth and draught ratios. Their results have a good agreement with strip theory. This means that the effective wave slope coefficients of ships with large breadth and draught ratios can be estimated using strip theory if experimental data is not available. A similar result for a chemical tanker with a small freeboard has been obtained, but here, a small effective wave slope coefficient is supposed to occur due to water on deck phenomena when the wave steepness is larger than 0.01 (Umeda *et al*, 2019).

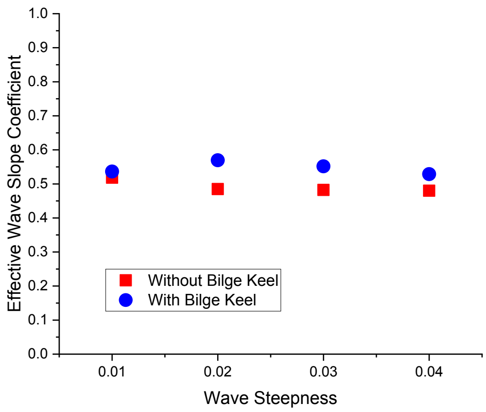

Figure 8: Effective wave slope coefficient

Some researchers have recommended an effective wave slope coefficient of 1.0 if a larger coefficient is obtained using the IMO formula (Francescutto, 2011; Francescutto *et al*, 2001). However, the present results and the results obtained by Sato *et al* (2008) show that the effective wave slope coefficient does not depend only on the vertical centre of gravity, especially for ships having breadth and draught ratios larger than 3.50. A more accurate formula for estimating the effective wave slope coefficient is necessary in order to implement the weather criteria for ships with shallow draughts and large breadths in the future.

The maximum roll angles using the weather criteria formula with the effective wave slope coefficient obtained by the model experiment are shown in Figure 9 for ships with and without bilge keels, respectively. Here, the damping factor corresponds to the breadth and draught ratio and the bilge keel given in the weather criteria are used. These results indicate that the bilge keel does not have a significant effect on the roll-back angle. The effective wave slope coefficient of a ship with a bilge keel is larger than a ship without a bilge keel. However, the damping factor due to the bilge keel of 0.964 corresponding to a bilge keel area of 9.0 m^2 reduces the roll angle. Therefore, the maximum roll angles of ship without and with bilge keel obtained by the formula of weather criterion are not to be significantly different.

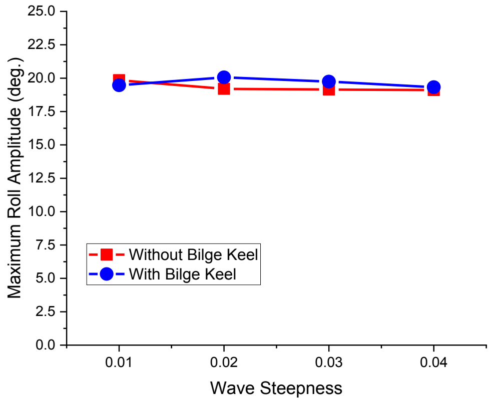

Figure 9: Maximum roll angle obtained by the weather criteria for ship with and without bilge keels

Figure 10 shows the maximum roll angle calculated by using the three-step procedure recommended by IMO. These maximum roll angle are smaller than those obtained by the formula of weather criterion shown in Figure 9. The smaller roll angles in the three-step procedure for both the ship without and with bilge keels occur due to a large Bertin's coefficient, which is 0.039 for the ship without a bilge keel and 0.112 for the ship with a bilge keel. Therefore, the maximum roll angle of the ship without a bilge keel is larger than that for the ship with a bilge keel. These results show that the damping factor corresponding to the breadth and draught ratio and to the bilge keel of the ship is smaller than the adjusted factor in the IMO weather criteria. This fact could be one of the reasons for the inconsistency between the first level and the second level of vulnerability in the second generation of intact stability criteria. For a certain ship type and geometric characteristics, the adjusting values of those parameters are underestimated, and for others ship types, they are overestimated compared to those used in the second level of vulnerability.

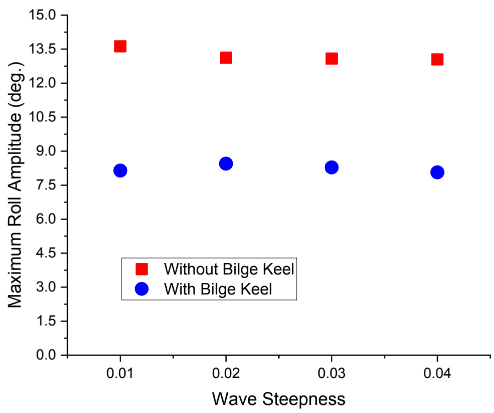

Figure 10: Maximum roll amplitude based on the three-step procedure of IMO (IMO, 2006a)

The damping factor corresponding to the breadth and draught ratio is calculated using the equation (3), with the maximum roll angle shown in Figure 10 for the ship without a bilge keel. The obtained damping factor due to the breadth and draught ratio is smaller than that adjusted in the weather criteria for a ratio of 3.5 or larger, as shown in Figure 11. Deakin (2008) also showed that the damping factor corresponding to the breadth and draught ratio in the weather criteria is overestimated when this ratio is larger than 3.5. The Russian standard (IMO, 2003) also recommended a smaller damping factor for ships with breadth and draught ratios larger than 3.5. Moreover, the present results are still smaller than that based on the Russian standard but the different is smaller compared to the weather criterion as shown in Figure 12. These results show that the damping factor due to breadth and draught ratio given by the Russian Federation can be an alternative to be used when the weather criterion is applied to ships with breadth and draught ratio larger than 3.50.

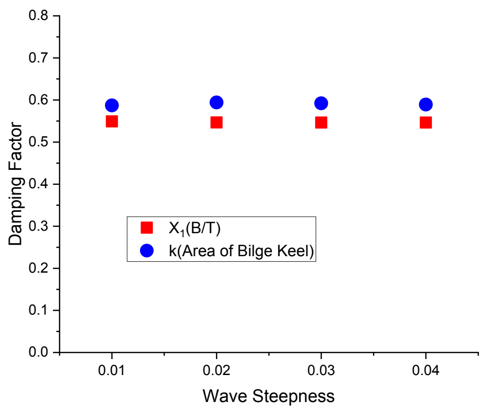

Figure 11: Damping factor corresponding to B/T and the area of the bilge keel

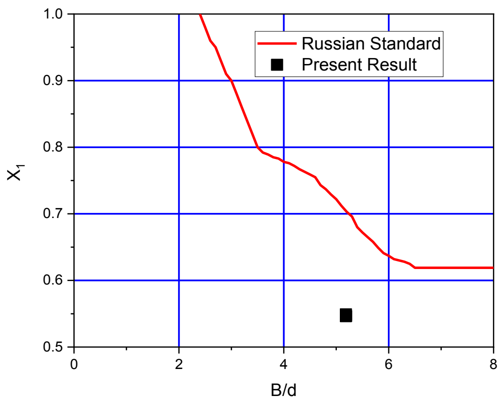

Figure 12: Damping factor correspond to breadth and draught ratio of Russian standard (IMO, 2003) and present result

The damping factor corresponding to the bilge keel is also calculated by using the equation (3) with the damping factor due to breadth and draught ratio shown in Figure 11, based on the maximum roll amplitude of a ship with a bilge keel (Figure 10). Here, the damping factor due to the bilge keel is 0.59, which is smaller than the adjusted amount in the weather criteria for a bilge keel area of 9.0 m^2, which is 0.96. This means that the bilge keels increases the roll damping about 40 percent, coincides with the results obtained by Fesman *et al* (2007). A larger increasing of the damping coefficient due to bilge keels was found by Gu *et al* (2015). Rudakovic and Backalov (2018) show that the increasing of damping coefficient due to bilge keel can decrease the capsizing index of a river-sea ships of 10^{-2}. This means that the bilge keel can significantly reduce the roll angle so that it's probability to exceed the maximum acceptable heeling angle become smaller.

The damping factors due to the breadth and draught ratio and the bilge keel are estimated under the assumption that the damping factor corresponds to the block coefficient is the same as that in the weather criteria. Deakin (2008) obtained different damping factors corresponding to the breadth and draught ratios for ships with the same ratios. This means that the damping factor corresponding to the breadth and draught ratio does not only depend on this ratio but also other factors that should be identified in the future. Regarding the bilge keel effect, attention should be given to the effect of the vertical centre of gravity and the breadth and draught ratio. These two parameters affect the distance between the bilge keel and the centre of roll rotation, which have a significant effect on the damping factor induced by the bilge keel. Therefore, more effort regarding the implementation of weather criteria to ships with shallow draughts and large breadths is necessary in the future.

For comparison means, the ratio between the area under the righting arm curve from the static heeling angle due to steady wind to the down flooding angle and the area from the static heeling angle to the roll-back angle shown in Figure 10 (index b/a) is calculated for both using the values in the weather criterion and those obtained based on the model experiment. The results obtained from the weather criterion is 1.176 and that based on the model experiment is 17.467. The critical metacentric height for the b/a index calculated using the values in the weather criterion is 3.9 metres and that is 1.3 metres when the experimental based values are used. Those critical metacentric height are smaller than the design metacentric height of the ship. The weather criterion provides higher stability level compared to the experimental based calculation.

4. CONCLUSIONS

The weather criteria have been applied to evaluate the stability of an Indonesian ro-ro ferry, supported by model experiments consisting of roll decay tests to estimate damping coefficients represented by Bertin's coefficients and drift tests in beam seas to obtain maximum roll amplitudes. The results of the model experiments are used to estimate the values of each variable in the formula to calculate the maximum roll angle in the weather criteria.

The effective wave slope coefficient obtained by the model experiments is smaller than that obtained by the weather criteria formula. This means that the formula for calculating the effective wave slope coefficient of the weather criterion overestimates when it is applied to a ship with a breadth and draught ratio larger than 3.50. The strip theory could be an alternative method to calculate the effective wave slope coefficient for ships with geometry characteristics similar with the present subject ship if experimental data does not available. The damping factor corresponding to the breadth and draught ratio agrees with the Russian Federation proposal. Therefore, the breadth and draught ratio range of the table should be extended, especially for ratios larger than 3.50, to adjust the corresponding damping factor. The same phenomenon is found regarding the bilge keel effect on the damping factor. The effect of the bilge keel on the maximum roll angle obtained by our experiments is more significant compared to the damping factor in the weather criteria. The bilge keel effect not only depend on the ratio between the bilge keel area and the product of the length of waterline and the breadth but could also depend on the breadth and draught ratio and the vertical centre of gravity of the ship. For small ships, the bilge keel effect could be more significant compared to large ships for the same ratios of bilge keel area and the product of the length of waterline and the breadth. An alternative method to estimate the damping factor correspond to the bilge keel should be developed mainly for ships with large breadth and draught ratio as well as large vertical centre of gravity. These results show that the maximum roll angle obtained by the weather criteria is overestimated when it is applied to a ship with a large breadth and draught ratio and a large vertical centre of gravity. The index b/a obtained by using the values in the weather criterion is smaller than that obtained the results of present model experiment. The critical metacentric height based on the parameters values given in the weather criterion is 3.9 metres and that based on the results of model experiments is 1.3 metres.

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