Alternative Method for Stability Assessment of Indonesian Traditional Wooden Boats

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Abstract. Due to the small down-flooding angle, the available intact stability criteria were difficult to apply to an Indonesian traditional wooden. This paper discusses the application of the dead ship criteria of Second Generation Intact Stability Criteria as an alternative method to assess the stability of the Indonesian traditional wooden boats. The hydrodynamics factors correspond to the formula to calculate the heel angle due to wave were determined by model experiments. The calculations were conducted for four different down-flooding angles consisting of 20 degrees, 25 degrees, 30 degrees and 35 degrees with scattered wave data of Lombok Strait. The results showed that the critical metacentric height decreases if the down-flooding angle increases. The minimum area under the righting arm curve up to the down-flooding angle tends to be independent of the down-flooding angle. The capsizing index corresponds to the critical metacentric height decreased when the down-flooding angle increased. These results showed that the method to assess ship stability in the Second Generation Intact Stability Criteria could be used to evaluate the stability of the Indonesian traditional wooden boats.

1. Background

The Indonesian traditional wooden boats were used for passenger and cargo transportation, mainly for short inter-island transportation, fishing vessels and cruise ship for marine tourism. The boats were built without a design process to determine the dimension of construction, main engine power, and stability correspond to the ship safety. Report of ship accidents showed that the traditional wooden boat casualty was larger than the other ships types [1]. The accidents were dominantly occurred because of bad weather and technical problems. Ship stability could be one of the majority of root causes of ship accidents due to sinking. In order to improve the stability of Indonesian traditional wooden boats, the stability criteria for the traditional wooden boats is necessary. Recently, Indonesian traditional wooden boat stability was assessed by using the criteria recommended by the Ministry of Transportation [2]. Alternatively, the general criteria of the International Maritime Organization (IMO) [3]. Those two criteria cannot be applied to a ship having a righting arm with an angle of vanishing stability or a down-flooding angle smaller than 30 degrees.
Most Indonesian traditional wooden boats have a down flooding angle smaller than 30 degrees due to a small freeboard. The construction of the main deck was not also watertight. Therefore the stability criteria for the Indonesian traditional wooden boats should consider the construction characteristics. The maximum heeling angle to be considered in the stability criteria for traditional wooden boats should be the down-flooding angle if the angle of vanishing stability is larger than the down-flooding angle. Characteristic of righting arm curve including area under the righting arm curve should be formulated as a function of the down-flooding angle or the angle of vanishing stability, which is the less. The IMO has developed a possible approach applied to an offshore supply vessel (OSV) [3], but the main consideration of this criteria was the heel angle with maximum righting arm. The heel angle with the maximum righting arm of OSV could occur on a heel angle smaller than 25 degrees due to a small freeboard. On the other hand, the minimum metacentric height can be determined using a similar formula to calculate the minimum metacentric height of fishing vessels [3]. However, this formula is valid only for a fishing vessel with a breadth-to-height ratio between 1.75 and 2.15. The Indonesian traditional wooden boats could have a breadth-to-height ratio larger than 2.15 [4]. To develop such stability criteria, a set of stability information corresponding to the stability of Indonesian traditional wooden boats is necessary for both boats to still be safely operated, and boats had been capsized. These data were challenging to obtain because the ship was built without stability assessment.

The Second Generation Intact Stability Criteria (SGISC) [5] could be used to determine the minimum required righting arm characteristics for a ship to be safely operated in a certain sea condition. The minimum value of the ratio between the area under the righting arm curve up to the down-flooding angle and the area under the righting arm curve up to the heel angle due to wave action in the opposite direction under wind conditions has been determined in the SGISC. The maximum value of the capsizing index for the vulnerability criteria level 2 of dead ship condition has also been decided by IMO [5]. A ship vulnerability level can be identified depending only on the initial metacentric height and the down-flooding angle. This criterion seems to be applicable to the Indonesian traditional wooden boats because the parameter of the criteria does not depend on a certain heel angle. However, a methodology to determine the hydrodynamic factors corresponding to the roll damping and the effective wave slope coefficient is still necessary in order to apply the criteria. The hydrodynamics factors in the formula to calculate the heel angle due to wave may not be applied to an Indonesian traditional wooden boat due to different geometric characteristics. The damping factors and the effective wave slope coefficient in the vulnerability criteria level 1 of SGISC were statistically determined based on ships data with a breadth-to-draught ratio smaller than 3.5, the ratio between the vertical centre of gravity and the ship draught between 0.7 and 1.5 and a natural roll period smaller than 30 seconds. The three-step procedure to assess the weather criterion [6] can be used to determine the damping factors corresponding to the breadth-to-draught ratio, the damping factors due to the bilge keels and the effective wave slope coefficient [7].

The effect of righting arm on a ship’s roll motion characteristics in beam seas could also be investigated using a non-linear roll motion equation [8]. The minimum righting arm characteristics can be obtained based on a safe basin with a variation of initial condition as a combination of initial roll angle and initial roll angular velocity if the acceptable capsizing probability has been determined. Results of this method depend on the accuracy of the damping coefficients and the effective wave slope coefficient used to solve the non-linear roll equation. A large number of simulations is necessary because many combinations of the initial condition of roll angle and angular velocity of the roll could occur in ship operation.

This paper discusses the development of appropriate parameters to assess the stability of Indonesian traditional wooden boats. The formulation of the parameters should consider the construction of the traditional wooden boats, mainly the main deck. The results may be used to assess the stability of Indonesian traditional wooden boats without limitation of the down-flooding angle due to the construction characteristics. In order to develop the criteria, the effect of down-flooding angle to a minimum requirement of righting arm curve based on SGISC needs to be identified.
2. Methodology
The minimum requirement of righting arm characteristics for the stability of Indonesian traditional wooden boats is determined by using three boats built at Tanaberu Bulukumba South Sulawesi. The principal dimension of the ship is shown in Table 1, and the righting arm curve for limiting vertical centre of gravity (KG) is shown in Figure 1, respectively.

| Items                              | Dimensions |
|------------------------------------|------------|
| Length overall (Loa)               | 22.80 m    |
| Length between perpendiculars (Lbp)| 18.99 m    |
| Breadth (B)                        | 4.80 m     |
| Draught (d)                        | 1.12 m     |
| Height (H)                         | 1.60 m     |
| Metacentric height (GM)            | 0.89 m     |
| Block coefficient (Cb)             | 0.362      |
| Windage area (A)                   | 44.22 m²   |
| Centre of windage area from water surface (Z)| 1.07 m |

Figure 1. Righting arm curve

The parameter of stability criterion consists of the initial metacentric height, and the area under the righting arm up to the down-flooding angle is determined by using the vulnerability criteria level 1 for dead ship condition in the SGISC. The ratio between the area under the righting arm curve up to the down-flooding angle or the angle of vanishing stability or the angle of 40 degrees which is the less and the area under the righting arm curve up to the heel angle due to wave action in the opposite direction is calculated to determine the critical metacentric height. The heel angle due to wave action in windward is calculated by using the equation as follow [3]:

$$\phi_1 = 109 \times k \times X_1 \times X_2 \times \sqrt{r \times s}$$

(1)

where $k$ is the damping factor due to the bilge keels, $X_1$ designates the damping factor corresponds to the breadth-to-draught ratio and $X_2$ designates the damping factor corresponding to the block
coefficient. \( r \) and \( s \) indicate the effective wave slope coefficient and the wave steepness, respectively. The damping factors corresponding to the breadth-to-draught ratio and the bilge keels are determined by using the procedure proposed by Paroka, et al [7], [9]. The damping factor due to the block coefficient, the effective wave slope coefficient, and the wave steepness is determined following the values given in the vulnerability criteria level 1 [5]. The calculation is performed for variation of vertical centre of gravity to obtain the critical metacentric height corresponding to the vertical centre of gravity with area under the righting arm curve up to the angle of vanishing stability, or the down-flooding angle is the same as the area under the righting arm curve up to the heel angle due to wave action in the opposite direction. The initial metacentric height corresponds to this vertical centre of gravity is set as the minimum initial metacentric height of the ship. The area under the righting arm curve up to the angle of vanishing stability or the down-flooding angle, which is the less, is set to be the minimum required area under the righting arm curve. The same procedure is repeated for a different down-flooding angle to obtain the initial metacentric height and the area under the righting arm curve as a function of the ship’s down-flooding angle or geometric characteristics.

The capsizing index as the parameter of the vulnerability criteria level 2 for the dead ship condition was calculated to verify the safety level due to variation of the vertical centre of gravity. The safety level corresponding to the critical metacentric in the vulnerability criteria level 1 is verified against the maximum capsizing index given by IMO [5]. The minimum metacentric height complies with the vulnerability criteria level 2 could also be identified in this calculation. The capsizing index is calculated by using the scatter wave data of the Flores Sea based on recorded data provided by Berrisford, et al [10]. The linear and quadratic damping coefficients were estimated with logarithmic roll-decrement curve [11] based on the results of roll decay test with radius gyration coefficient the same as that obtained by using the formula in the weather criterion [3]. The effective wave slope coefficient for the corresponding vertical centre of gravity as a wave frequency function was calculated using the Froude-Krilov wave exciting moment with a rectangular assumption of the ship’s cross-section [12]. Several methods to calculate the effective wave slope coefficient have been proposed [13], but the Froude-Krylov approach seems simpler from a practical point of view. Therefore the IMO recommends this method to calculate the capsizing index for the vulnerability criteria level 2 for the dead ship condition in the SGISC. The JONSWAP spectrum was used to model the irregular waves.

The critical metacentric height and the area under the righting arm curve up to the down-flooding angle or the angle of vanishing stability for different down-flooding angles are used to develop the stability criteria for the Indonesian traditional wooden boats. The initial metacentric height can be formulated as a function of the breadth-to-draught ratio and the ratio between the freeboard and the breadth of the ship. Then, the area under the righting arm curve would be developed as a function of the heel angle and the down-flooding angle or the angle of vanishing stability.

3. Results and Discussion
The vulnerability criteria level 1 and the vulnerability criteria level 2 of dead ship condition in the SGISC had been calculated for an Indonesian traditional wooden boat used as subject ship in this paper. The \( b/a \) ratio in the vulnerability criteria level 1 for metacentric height ranges from 0.06 meters to 2.16 meters with four different down-flooding angles is shown in Figure 2. The area under the righting arm curve up to the down-flooding angle increases with the down-flooding angle for a constant vertical centre of gravity. Conversely, the heel angle to windward due to wave action was independent of the vertical centre of gravity. As a result, the area under the righting arm curves up to the heel angle to windward due to wave decrease when the vertical centre of gravity increases. Therefore, the \( b/a \) ratio in the vulnerability criteria levels 1 for the ship with a larger down-flooding angle is larger than the ship with a smaller down-flooding angle. The critical metacentric height decreases if the down-flooding angle increases. This means that the required minimum metacentric height to comply with the vulnerability criteria level 1 of SGISC decreases if the down-flooding angle increases.
Figure 2. The vulnerability criteria level 1 for different down-flooding angles.

The critical metacentric height corresponds to the down-flooding angles, and the minimum area under the righting arm curve up to the down-flooding angle are shown in Figure 3 and Figure 4, respectively.

Figure 3. The critical metacentric height
A ship with a smaller down-flooding angle needs a larger metacentric height and an area under the righting arm curve to comply with the vulnerability criteria level 1 of SGISC. The critical metacentric heights for the four down-flooding angles are larger than the recommended initial metacentric height in the general criteria of IMO and minimum metacentric height obtained based on the formula applied to fishing vessels with lengths smaller than 30 meters [3]. The minimum initial metacentric height in the general criteria for an intact ship of IMO was 0.2 meters, and that for the fishing vessels was 0.615 meters. The smallest critical metacentric height for the present results was 0.73 meters, corresponding to the down-flooding angle of 35 degrees. The critical metacentric height obtained from the vulnerability criteria level 1 could be smaller for a larger ship even though the down-flooding angle should be considered in the determination of the minimum metacentric height of a traditional wooden boat. The formula for minimum initial metacentric height as a function of the down-flooding angle using a linear regression can be written as follows:

$$GM_0 = 2.602 - 0.056\phi_f$$  \hspace{1cm} (2)

where $\phi_f$ is the down-flooding angle in degree. This equation will result in a negative initial metacentric height for a large down-flooding angle. Therefore, the minimum initial metacentric height should be limited to be the same as that obtained by the formula for fishing vessels if the initial metacentric height obtained by using equation (2) is smaller. The breadth-to-draught ratio and the ratio between the freeboard and ship breadth may have a significant effect on the initial metacentric height. Several ships data are necessary to identify the effect of those parameters.

The area under the righting arm curve up to the down-flooding angle was not significantly different due to alteration of the down-flooding angle. The minimum area under the righting arm curve corresponding to the down-flooding angle of 20 degrees was 0.096 m.rad, larger than the area up to the heel angle of 30 degrees in the general criteria of IMO [3] and that for the down-flooding angle of 35 degrees was 0.107 m.rad. These areas under the righting arm curve were larger than the area up to 30 degrees or 40 degrees in the general criteria of IMO [3]. The stability range of Indonesian traditional wooden boats is mostly larger than 40 degrees. However, the down-flooding angle was even smaller than 30 degrees due to open deck construction for the main deck. The area under the righting arm curve tends to increase due to the increase in the down-flooding angle. The righting arm of the ship reduces as the vertical centre of gravity increases (reducing metacentric height). Increasing
of the area under the righting arm curve could occur due to the increasing of the equilibrium angle due to wind when the vertical centre of gravity increases. The minimum area under the righting arm (m.degree) for the subject ship can be written as follows:

$$A_0 - \phi_f = 4.8778 + 0.0367\phi_f$$

(3)

The capsizing index corresponds to the vulnerability criteria level 2 of SGISC for the dead ship condition is shown in Figure 5. The horizontal axis in this figure is the $b/a$ ratio as shown in Figure 2. The capsizing index of the ship decreases due to the increase in the down-flooding angle. These results indicated that the effect of the down-flooding angle is more significant compared to the effect of the righting arm. The righting arm for the larger down-flooding angle is smaller than that for the smaller down-flooding angle, but the capsizing index for the larger down-flooding angle is smaller than that for the smaller down-flooding angle.

![Figure 5. Capsizing index](image)

The capsizing index corresponds to the critical $b/a$ ratio is $2.63 \times 10^{-4}$ for the down-flooding angle of 20 degrees, $1.51 \times 10^{-5}$ for the down-flooding angle of 25 degrees, $1.34 \times 10^{-6}$ for the down-flooding angle of 30 degrees and $2.23 \times 10^{-7}$ for the down-flooding angle of 35 degrees. These capsizing indexes are smaller than the standard value given in the SGISC of 0.06. The very small values of the capsizing index are obtained because the wave data used for the calculation was smaller compared to the recommended wave data by IMO [5]. On the other hand, the vulnerability criteria level 1 and the vulnerability criteria level 2 recently obtained showed consistency.

4. Conclusion
The stability of an Indonesian traditional wooden boat has been evaluated by using the Second Generation Intact Stability Criteria with four different down-flooding angles. The results showed that the minimum metacentric height for the ship to comply with the vulnerability criteria level 1 decreases due to increase the down-flooding angle. The minimum metacentric height correspond to the down-flooding angle of 20 degrees was 1.57 meters with the area under the righting arm curve up to the down-flooding angle of 0.096 meters. The alternations of the area under the righting arm due to increase of the down-flooding angle was not significant compared to the alternation of the minimum metacentric height. The minimum metacentric height and the area under the righting arm curve up to
the down-flooding angle can be linearly modeled as function of the down-flooding angle. The calculations for several ships with different principle dimension are necessary in order to generally determine the minimum metacentric height and the minimum area under the righting arm curve as intact stability criteria for the Indonesian traditional wooden boats.

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