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Operational limitation of Indonesian traditional wooden boat in the framework of second generation intact stability criteria

D Paroka[1], **A H Muhammad**[2], **S Rahman**[1] **and M A Azis**[3]

[1] Department of Ocean Engineering, Hasanuddin University, Kampus Gowa Jl. Poros Malino Km. 6 Bontomarannu, Gowa, South Sulawesi, Indonesia
[2] Department of Marine System Engineering, Hasanuddin University, Kampus Gowa Jl. Poros Malino Km. 6 Bontomarannu, Gowa, South Sulawesi, Indonesia
[3] Department of Naval Architecture, Hasanuddin University, Kampus Gowa Jl. Poros Malino Km. 6 Bontomarannu, Gowa, South Sulawesi, Indonesia

e-mail: dparoka@eng.unhas.ac.id

Abstract. Recently, the International Maritime Organization (IMO) developed the second generation intact stability criteria for all possible capsizing scenario in seaways with performance based approach. This paper presents application of the criteria to investgate operational limitation of an Indonesian traditional woooden boat for dead ship condition. The hydrodynamic characteristics of the ship are determined by model experiment except the effective wave slope coefficient is calculated using the simplified Froude-Krylov assumption of roll exciting moment and the formula of weather criterion. The wave characteristics are described by JONSWAP spectrum based on the wave statistic of Flores sea and the gusty wind is calculated by Davenport spectrum. The results show that the Indonesian traditional wooden boat comply with the criteria when the downflooding angle is larger than 25.0 degrees. The vulnerability criteria level 1 and the vulnerability criteria level 2 of the criteria are not consistent when the effective wave slope coefficient is calculated using the formula of weather criterion but it is consistent when the simplified Froude-Krylov assumption is used. The inconsistency could appear due to the geometry characteristics of Indonesian traditional wooden boats which are different from the geometry characteristics of ships used to develop the weather criterion as the level 1 of vulnerability criteria.

1. Introduction

Traditional wooden boats are wooden ships built based on the experience of traditional boat builders without a systematic design process like in the case of modern ship. The traditional wooden boats are mostly used as cargo ships for inter-island tranportation in a relatively short distance, inland ships or operated in restricted area especially in the region with minimum port facilities. They play an important role for sea transportation in Indonesia to provide connectivity of undeveloped regions, outermost area as well as isolated area to the main route of national sea transportation system. It has been stated in the regulation of national transportion system of Indonesia [1]. Even the number of traditional boats used for national sea transportation tends to decrease in the last decade [2,3], but their role is still important in a certain region especiallly in eastern part of Indonesia.

As the boats were built traditionally without a systematic design process, the ship safety could not be measured in the beginning. Casualty report shows that capsizing accidents in Indonesian seaways are dominated by traditional wooden boat [4]. This means that the operational safety should be improved in order to minimize the accident by introducing safety criteria applicable for nonconvention ships. In order to improve the safety, the Indonesian government published regulation for nonconvention ships operating in Indonesia including stability [5]. This stability criteria was based on the general intact stability criteria of International Maritime Organization (IMO). Several parameters in this criteria seems to be difficult to be applied to ships operating in Indonesia including the traditional wooden boats. This is brought about the facts that their downflooding angle mostly smaller than 40.0 degrees and the heel angle with maximum righting arm is smaller than 25 degrees due to small freeboard and small draught compared to the ship breadth. Since this stability criteria depends only on the ringhting arm characteristics without considering the effect of external disturbance, it cannot be used to determine the operational limitation of the ships correspond to seaway condition. Information about the operational limitation is important reference to decide whether the ship is safely operated.

The lack of information about operational limitation or safety level in the stability criteria of IMO has been discussed within the last two decades. Finally the second generation of intact stability criteria of IMO is developed in order to provide safety level or safety index for any dangerous scenario of ships in seaways. The safety level in dead ship condition is measured using the capzising probability when the ship is operating in beam seas under certain sea state for exposure time of one hour. If a maximum acceptable safety level for the traditional wooden boats is available, the maximum sea state for ship safely operated in a certain loading condition can be determined. The safety index indicated by capsizing probability is calculated based on roll respon of ship under combined action of wind and waves. This method has been used to determined operational limitation of river-seas ship to obtain the range of metecentric height (*GM*) with safety index smaller than the minimum safety level according to the sea state of operational area of the ship [6].

This paper discusses about the operational limitation of an Indonesian traditional wooden boat based on the second generation intact stability criteria of IMO. The safety level is indicated by the capsizing index that can be obtained for different loading condition and metacentric height as well as the limitation of sea state for safety operation. The results can verify the possibility of implementation the ctriteria on Indonesian traditional wooden boats. Since the characteristics of Indonesian seaways are heterogeneous depending on the location or region, this method can be a usefull tool to evaluate the possibility of the traditional wooden boats to operate in a certain route. This paper may also becomes the starting point to determine the acceptable safety level and implemented as a part of stability criteria for traditional wooden boats operating in Indonesia.

2. Methodology

2.1 Capsizing Index

The safety standard of ship in the dead ship condition corresponds to vulnerability level 2 based on capsizing index, which is calculated as the probability of ship roll angle exceeds a certain value in seaways for a given exposure time. This probability depends on the short term capsizing probability for a determined exposure time and the occurence probability of significant wave height which can be written as in the following equation [7]:

$$CI = \sum_{i=1}^{N} C_i \, S_i \tag{1}$$

where C_i is the short term capsizing probability for a given exposure time and S_i is the occurence probability of sea state indicated by significant wave height and zero crossing period of wave, respectively. N is the number of recorded data of the wave. The short term capizing probability is calculated using the equation as follows [7]:

$$C_i = 1 - exp(-\lambda_{EA} T_{EXP}) \tag{2}$$

where the capsizing rate, λ_{EA} is calculated using the following equation:

$$\lambda_{EA} = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}\left(exp\left(-\frac{\Delta\phi_{EA^+}{}^2}{m_0}\right) + exp\left(-\frac{\Delta\phi_{EA^-}{}^2}{m_0}\right)\right) \tag{3}$$

Here, T_{EXP} is the time exposure of 1 hour as recommended by IMO [7], m_0 is the variance of roll angle and m_2 is the variance of angular velocity of roll motion under action of combined wind and waves correspond to the sea state, respectively. The variance of roll angle and the variance of roll angular velocity are obtained by solving the single degree of uncoupled roll motion equation. The wave exciting moment is calculated based on the JONSWAP spectrum and the exciting momet due to gusty wind is calculated by using the Davenport Spectrum. $\Delta\phi_{EA^+}$ is the range of positive stability in leeward direction starting from the static heel angle due to steady wind to the heel angle with the area under linearization of the righting arm the same as the the area under the original ringhting arm curve and $\Delta\phi_{EA^-}$ is that toward windward. The area under the righting arm curve is calculated from the static hell angle to the downflooding angle or the angle of vanishing stability of the ship which is one is the less. This range of heel angle could be larger than the downflooding angle or the angle of vanishing stability depending on the ringhting arm characteristics. The capsizing index is calculated by using the scatter wave data of Flores Sea for 10 years data recorded [8]. The number of occurence for each combination significant wave height and zero crossing wave period is shown in Figure 1. The maximum significant wave height of this operational area is 2.7 meters and the maximum mean wave period is 12.0 seconds.

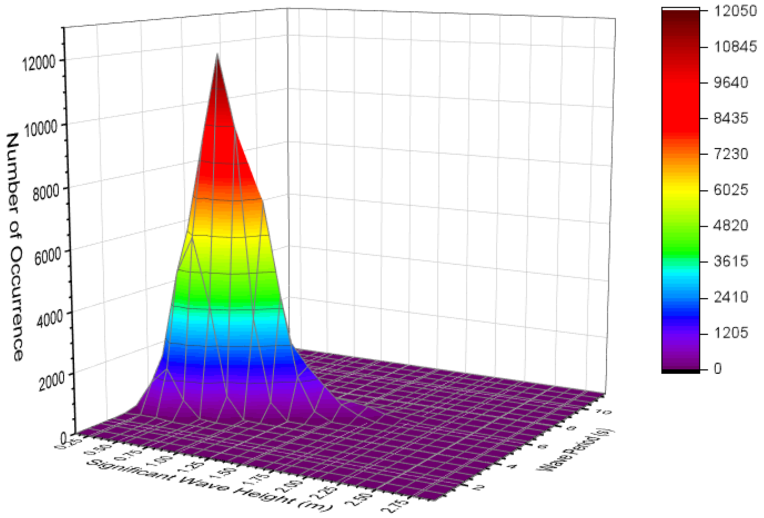

Figure 1. Scatter wave data of Flores Sea

The mean wind velocity is assumed to correlate with the significant wave height with its correlation shown in the equation (4). This equation is statictically developed based on the recorded data of Flores Sea [8]. This equation is different with that recommended by IMO, which was determined following the scatter wave data of North Atlantic Ocean [7].

$$U_w = \left(\frac{H_s}{0.13}\right)^{0.85} \tag{4}$$

where U_w is the mean wind velocity and H_s is the significant wave height. The correlation between the significant wave height and the wind velocity based on the data in Flores Sea and that from the wave data of North Atlantic Ocean are shown in Figure 2. The present formula result in mean wind velocity larger than that obtained by formula of IMO when the significant wave height larger than 1.50 meters. A smaller mean wind velocity by using the present formula is obtained for the significant wave height smaller than 1.50 meters. A different formula can be obtained for different operational area of the ship depend on the wave characteristics of the location.

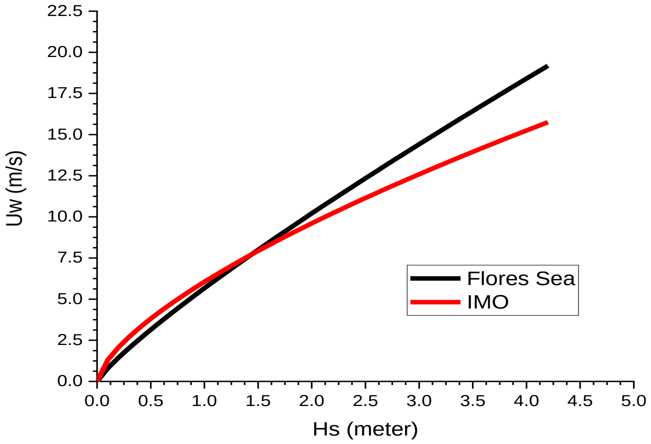

Figure 2. Mean wind velocity as function of significant wave height

2.2 Ship Data

The ship data used in this study is a wooden boat built in Bulukumba, South Sulawesi, with principle dimensions as shown in Table 1. The damping coefficients consist of linear dan quadratic damping coefficients as well as the natural frequency of roll motion are determined by model experiment. The effective wave slope coefficient as function of wave frequency is calculated by using simplified strip theory under assumption of Froude-Krylov exciting moment [9]. Alternatively the effective wave slope coefficient can be determined by using the formula of weather criterion of IMO [10] with assumption that this coefficient is independent of the wave frequency and it becomes zero when the wave length is smaller than a half of ship breadth. For ships with large vertical center of gravity and small draught, the formula of weather criterion may result in overestimate of the effective wave slope coefficient. Some experimental results show that the maximum value of the effective wave slope coefficient is 1.0 [11,12].

Table 1. Principle dimensions of subject ship

Items	Dimension
Length overall (*Loa*)	22.80 m
Length of waterline (*Lwl*)	19.00 m
Breadth (*B*)	4.80 m
Height (*H*)	1.60 m
Draught (*T*)	1.12 m
Design metacentric height (*GM*)	0.92 m
Windage area (*A*)	40.79 m^2
Center of windage area from waterline (*Z*)	1.56 m
Downflooding angle	30.0 deg.

The capsizing index is calculated for full loading condition with several different metacentric height under assumption that the virtual moment of inertia in roll direction is independent of the metacentric height. As a result, the natural frequency of roll in upright position will change with the variation of metacentric height. The righting arm of the ship for vertical center of gravity of 3.0 meters is shown in Figure 3. The righting arm for different vertical center of gravity is calculated based on the bouyancy lever arm from the ship keel which is constant as long as the ship draught does not change.

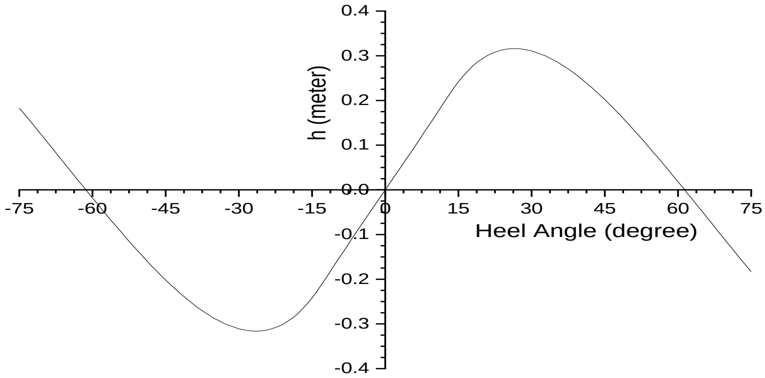

Figure 3. Righting arm of ship for vertical center of gravity of 3.0 meters

In order to determine the operational limitation which consists of the range of metacentric height for several different sea state, the safety level recommended by IMO even it is not final index is used [7]. The results should be verified with the weather criterion as the vulnerability criteria level 1 because several ships show inconsitency between the weather criterion and the acceptable maximum capsizing index [7]. A ship comply with the weather criterion should also comply with the vulnerability level 2 of the second generation intact stability criteria for dead ship condition.

3. Results and Discussions

Capsizing index of the subject ship for range of metacentric height starting from 0.20 meters to 2.0 meters is shown in Figure 4 for the case oxf downflooding angles 35.0 degrees, 30.0 degrees and 25.0 degrees with the effective wave slope coefficient calculated by simplified Froude-Krylov assumption. The capsizing index increases as the downflooding angle decreases. It indicates that the range stability and the area under the righting arm has significant effect on the stability of ship in beam seas. The traditional wooden boats mostly have sufficiently large stability range but have small downflooding angle because the weather deck is lower due to small freeboard. The opening on deck such as hatch coaming and the door cannot properly be closed with watertight hatch cover and doors, respectively.

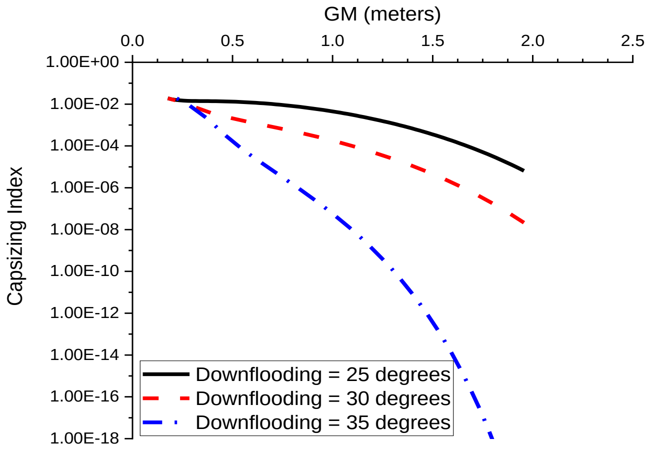

Figure 4. Capsizing index with effective wave slope coefficient obtained by simplified Froude-Krylov assumption

For the sake of comparison, the capsizing index was also calculated by using the effective wave slope coefficient obtained by the formula of weather criterion. Here, the effective wave slope coefficient is assumed to be independent of wave frequency but it becomes zero when the wave length is smaller than a half of the ship breadth [13]. It is also assumed that the maximum effective wave slope coefficient is 1.0 [11]. The calculation results for the three different downflooding angle are shown in Figure 5. The same phenomena with the capsizing index obtained by using the effective wave slope coefficient calculated by using the Froude-Krylov assumption of roll exciting moment is found but the present capsizing index is larger. This is because the effective wave slope coefficient obtained by the formula of weather criterion is larger than that obtained by the Froude-Krylov assumption. The formula of weather criterion was developed for ships with vertical center of gravity to draught ratio between 0.70 to 1.50 with ship length of 100.0 meters or larger. Therefore, an alternatif method for estimation of effective wave slope coefficient for non convention ships is necessary for practical point of view in the fututre.

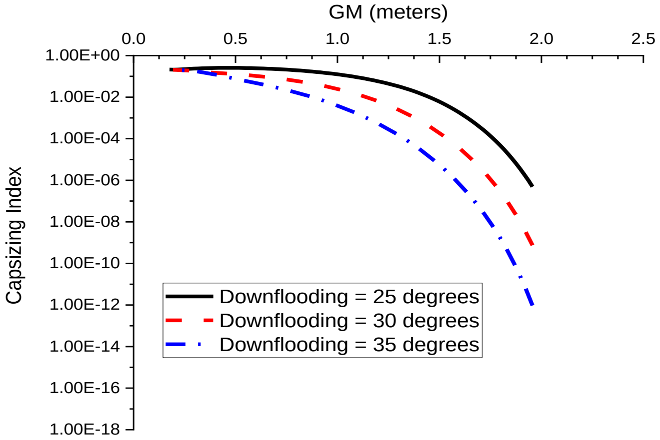

Figure 5. Capsizing index with effective wave slope coefficient obtained by formula of weather criterion

Following the safety index recommended by IMO for dead ship condition of 0.04 or 0.06 (still under discussion), the effective wave slope coefficient obtained by the simplified Froude-Krylov assumption give safety index smaller than the safety standard of IMO even for very small metacnetric height. This is unrealistic result because the roll motion become unstable when the roll angle is larger than the angle of vanishing stability. This result due to the Froude-Krylov assumption results in under estimate effective wave slope coefficient especially in the wave frequency having the same value as the roll natural frequency. The minimum metacentric height of the subject ship for downflooding angle of 25.0 degrees is 1.276 meters. Those are 0.916 meters for the downflooding angle of 30.0 degrees and 0.636 meters for the downflooding angle of 35.0 degrees when the effective wave slope coefficient is calculated by using the formula of weather criterion. When the safety index of 0.06 is used, the minimum metacentric height for the downflooding angle of 25.0 degrees is 1.196 meters, then 0.796 meters for the downflooding angle of 30.0 degrees and 0.556 meters for the downflooding angle of 35.0 meters. In case of the actual metacentric height of the subject ship, the capsizing index for the downflooding angle of 25.0 degrees is 0.156 and 0.038 for the downflooding angle of 30.0 degrees. When the downflooding angle is 35.0 degrees, the capsizing index is 0.008. The smaller capsizing indexes correspond to the actual metacentric height are obtained if the effective wave slope coefficient is determined by simplified Froude-Krylov assumption. Those calculation results show that the minimum metacentric height for the downflooding angle of 25.0 degrees is larger than the critical metacentric height for both effective wave slope coeffcient obtained by weather criterion formula and Froude-Krylov assumption of roll exciting moment. The safety of traditional wooden boat can be improved by increasing the downflooding angle by way of minimizing the number of opening or using watertight cover for the opening in the weather deck.

In order to verify the concistency of the safety standard from the obtained capsizing index with the stability limitation based on the weather criterion, the minimum metacentric height is also calculated based on the weather criterion for three different downflooding angle. Here, the wind pressure is corrected to be 170 Pa following the maximum wind velocity in the ship route of 15.0 m/s. The calculation results for the three different downflooding angle are shown in Figure 6. The minimum metecentric height for the downflooding angle of 25.0 degrees is 1.556 meters correspond to the vertical center of gravity of 0.90 meters. The minimum metacentric height decreases to be 0.316 meters if the downflooding angle becomes 30.0 degrees. The same minimum metacentric height is obtained for the downflooding angle of 35.0 degrees. Inconsistency between the safety index of vulnerability level 1 (weather criterion) and that for the vulnerability level 2 of the second generation intact stability citeria appears when the safety index for the vulnerability level 2 (capsizing index) is calculated by using the effective wave slope coefficient based on the formula of weather criterion. The other parameters in the weather criterion such as the damping factors correspond to the breadth to draught ratio as well as due to the block coefficient could be not appropriate to be applied for ship with geometry characteristic the same as the traditional wooden boats. It has been found that the damping factor correspond to breadth to draught ratio of ship with shallow draught and large breadth is smaller than that given in the weather criterion [14]. Therefore the minimum metacentric height obtained in the vulnerability criteria level 1 (weather criterion) is larger than that obtained in the vulerability criteria level 2.

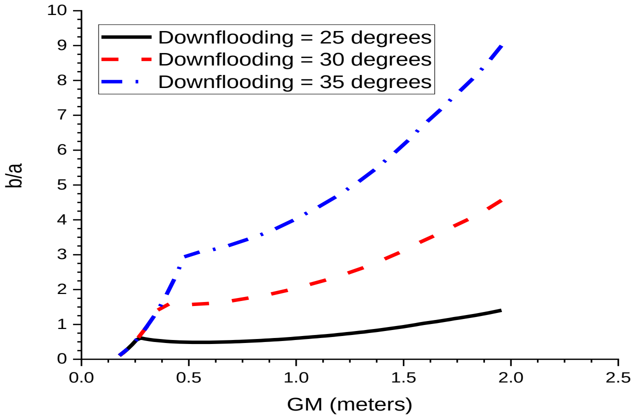

Figure 6. The vulnerability criteria level 1 for three different downflooding angle

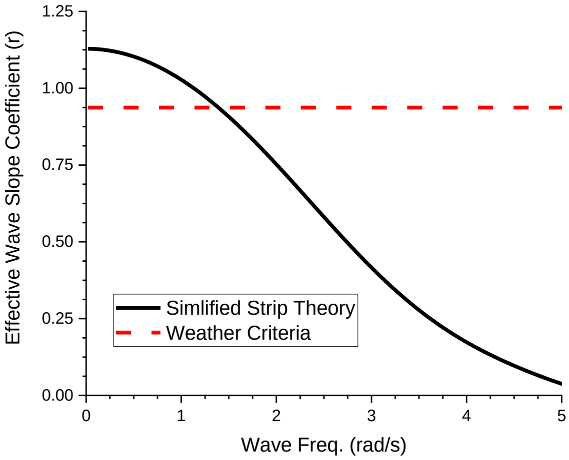

Figure 7. The effective wave slope coefficient

The consistency of the second generation intact stability criteria is achieved when the effective wave slope coefficient is calculated by using the simplified Froude-Krylov assumption of roll exciting moment but unrealistic capsizing index is obtained for very large vertical center of gravity. This is because the effective wave slope coefficient in the resonance frequency is small so that the roll angle is small as a result of small roll exciting moment. Figure 7 shows the effective wave slope coefficient obtained by the simplified Froude-Krylov assumption for the vertical center of gravity of 1.541 meters. The obtained effective wave slope coefficient is larger than that obtained by the formula of weather criterion. Oppositely, the weather criterion result in a larger effective wave slope coefficient for higher wave requency. The natural frequency of roll of the subject ship is 1.98 rad/s which is the largest roll amplitude so that the weather criterion result in higher capsizing index. Some experimental results shown that the effective wave slope coefficient of ships with small freeboard and large breadth is smaller than those obtained by the weather criterion. However, it is impossible to conduct model experiment for large variation of wave frequency in practical point of view [15]. Alternative method to estimate the effective wave slope coefficient is using numerical simulation such as computational fluid dynamics (CFD).

4. Conclussions

The second generation intact stability criteria for dead ship condition is applied to an Indonesian traditional wooden boat to determine her operational limitation based on the scatter wave data of Flores Seas. Based on the obtained results and discussions, some conclusions can be described as follows:

1. The minimum metacentric height of the traditional wooden boat has been determined based on the second generation intact stability criteria of IMO consists of the weather criterion as the vulnerability criteria level 1 and the capsizing index as the vulnerability criteria level 2. The subject ship does not comply with the criteria if the downflooding angle is 25.0 degrees or smaller. Therefore, the deck opening in the weather deck should be designed to be watertight in order to increase the downflooding angle.
2. Both vulnerability criteria level 1 and level 2 show inconsistency following the structure of the second generation intact stability criteria for dead ship condition when the effective wave slope coefficient is calculated by using the formula of waether criterion. But it is consistent when the simplified Froude-Krylov assumption is used for both safety standard of 0.04 and 0.06. This is because the formula of weather criterion does not consider effect of wave frequency.
3. Damping factors correspond to the breadth to draught ratio as well as the block coefficient in the vulnerability criteria level 1 should be investigated in advance because the values correspond to those parameters in the weather criteria of IMO could be overestimate when applied to the traditional wooden boats. The geometry characteristics of Indonesian traditional wooden boats are out of the range of the geometry characteristics used to determine the values of parameters in the criteria.

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