Capsizing Probability of an Indonesian RoRo Passenger Ship in Irregular Beam Seas
(Second Report)

by Budhi H. Iskandar*, Student Member, Naoya Umeda*, Member, Masami Hamamoto**, Member

Summary

In our first report, we presented a methodology for determining the critical metacentric height of an Indonesia RoRo passenger ship in the light of the annual capsizing probability calculated with piece-wise linear mathematical model and wave statistics. The second report follows the methodology in the first report, and provides more realistic outcomes by making use of the ship roll data from the model experiments and corrected wave statistics. As a result, it is demonstrated that the annual capsizing probability of the Indonesian RoRo passenger ship with side openings of the RoRo space almost coincides with the actual capsizing rate taken from the casualty statistics in Indonesian water areas, and can be drastically reduced by closing the side openings.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Froude’s extinction coefficient</td>
</tr>
<tr>
<td>b</td>
<td>Froude’s extinction coefficient</td>
</tr>
<tr>
<td>B</td>
<td>ship breadth</td>
</tr>
<tr>
<td>C_b</td>
<td>ship block coefficient</td>
</tr>
<tr>
<td>d</td>
<td>ship draught</td>
</tr>
<tr>
<td>f(H_{1/3}, T_{01})</td>
<td>joint probability density of significant wave height and the mean wave period</td>
</tr>
<tr>
<td>f(H_{1/3})</td>
<td>marginal probability distribution of significant wave height</td>
</tr>
<tr>
<td>f(T_{01}/H_{1/3})</td>
<td>conditional probability of mean wave period given the significant wave height</td>
</tr>
<tr>
<td>GM</td>
<td>metacentric height</td>
</tr>
<tr>
<td>GZ</td>
<td>righting arm</td>
</tr>
<tr>
<td>H_{1/3}</td>
<td>significant wave height</td>
</tr>
<tr>
<td>KG</td>
<td>height of center of gravity</td>
</tr>
<tr>
<td>L_{CA}</td>
<td>ship length over all</td>
</tr>
<tr>
<td>L_{pp}</td>
<td>ship length between perpendiculars</td>
</tr>
<tr>
<td>N</td>
<td>Bertin’s extinction coefficient</td>
</tr>
<tr>
<td>P</td>
<td>capsizing probability in a stationary wave state for a certain time duration</td>
</tr>
<tr>
<td>P_{annual}</td>
<td>annual capsizing probability</td>
</tr>
<tr>
<td>P^{*}</td>
<td>long term capsizing probability for a certain time duration</td>
</tr>
</tbody>
</table>

\( T_{01} \): mean wave period
\( T \): duration of the wave state
\( T_z \): zero crossing wave period
\( \gamma \): effective wave slope coefficient

1. Introduction

Since Indonesian area consists of many islands, RoRo passenger ships have an important role to transport people and vehicles from one island to another island. Several capsizing events of RoRo passenger ships have occurred so far and thousands of Indonesians have lost their lives and property as well in these disasters\(^1\). As it is acknowledged that until now Indonesia has no domestic stability standard, the establishment of stability standard based on the rational index, such as capsizing probability, becomes an urgent issue.

Responding such urgent problem, in the first report\(^2\), the methodology for calculating the annual capsizing probability was presented but there were following unsolved problems.

1) The used wave statistics, Global Wave Statistics\(^3\) (GWS), ignores rare but crucial waves for determining the annual capsizing probability.
2) The roll damping coefficients that used in the first report were not directly relevant to the Indonesian ship because the roll decay data were not available for the ship and then the extinction coefficients (a and b) were assumed to be identical to the ones

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recommended as standard values for a ship with bilge keel by Watanabe4).

3) The annual capsizing probability obtained from the calculation was too small to explain the frequent disasters in Indonesian water areas.

Thus, this report pursues more realistic results by improving the following elements, namely:
1) Extrapolation of the GWS data to take rare but critical waves into account;
2) Use of the roll damping coefficients measured in the experiment and actual superstructure taken from the relevant drawing.

Then the calculated annual capsizing probability was compared with the actual capsizing rate from the casualty statistics.

2. Outline of Calculating Method

As presented in the first report2), the methodology to calculate capsizing probability of a ship in a stationary wave state during a certain time duration, \( P(H_{1/3}, T_0; T) \) proposed by Belenky' was used. In this method, the restoring arm curve is approximated as piece-wise linear.

The probability here can be calculated as the product of the probability exceeding a threshold and the conditional probability of instability in the range over the threshold. Because of linearity of each range, these probabilities can be analytically calculated.

Once the capsizing probability for a stationary wave state is obtained, the annual capsizing probability, \( P_{\text{annual}} \), can be evaluated as follows:

\[
P_{\text{annual}} = 1 - (1 - P^*(T) \frac{365 \times 24 \times 3600}{T})
\]  

where

\[
P^*(T) = \int_{0}^{\infty} \int_{0}^{\infty} f(H_{1/3}, T_0) P(H_{1/3}, T_0; T) dH_{1/3} dT_0
\]  

3. Wave Statistics

The wave statistics for the Indonesian water areas are available in Global Wave Statistics (GWS) by British Maritime Technology Ltd3). It is noteworthy that these statistics filtered off the waves with occurrence frequency less than 0.01.

As pointed out in the first report2), however, the occurrence of such waves plays an important role in predicting the annual capsizing probability. Thus, it is necessary to extrapolate the GWS data for covering waves having small probabilities.

For such extrapolation for North Atlantic and North Pacific Oceans, Shinkai et al. presented the following formulae by using logarithmic normal distribution8):

\[
f(H_{1/3}) = \frac{1}{\sqrt{2\pi} \sigma_{H_{1/3}}} e^{-\frac{(\ln H_{1/3} - m_{\ln})(H_{1/3})^2}{2\sigma_{\ln}^2}}
\]  

where

\[
m_{\ln} = E(\ln H_{1/3})
\]

\[
\sigma_{\ln}^2 = \text{Var}(\ln H_{1/3})
\]

\[
f(T_0; H_{1/3}) = \frac{1}{T_0 \sqrt{2\pi} \sigma(H_{1/3})} e^{-\frac{(\ln T_0 - \mu(H_{1/3}))^2}{2\sigma^2(H_{1/3})}}
\]

and

\[
\mu(H_{1/3}) = E(\ln T_0(H_{1/3}))
\]

\[
\sigma^2(H_{1/3}) = \text{Var}(\ln T_0(H_{1/3}))
\]

The Indonesian areas cover by GWS data are shown in Fig. 1. In these water areas the small occurrence, less than 0.01, of significant wave height is also ignored. This appears for the significant wave height more than 7 meters. Thus, to obtain the values of \( \mu(H_{1/3}) \) and \( \sigma^2(H_{1/3}) \) it is necessary to approximate these values by following formulae as proposed by Shinkai et al.7):

\[
\mu(H_{1/3}) = a + a \ln H_{1/3}, \quad \text{and}
\]

\[
\sigma(H_{1/3}) = b, \exp b, H_{1/3}
\]

Fig. 2 shows one of the results of fitting for mean value, \( \mu(H_{1/3}) \), and standard deviation, \( \sigma(H_{1/3}) \), in the area 62 of Indonesia waters. The same method was used for two other areas as well, the area 61 and the area 70. Fig. 3 shows the graph of marginal probability distribution of wave height as a function of significant wave height as a function of significant wave height as the original data and the fitted one in the area 62 of Indonesian waters. Based on these fitting, Tables 1 - 3 show the scatter diagrams as the results of extrapolations for the 3 areas of Indonesian waters.

Fig. 1. The Indonesian areas covered by GWS data
Fig. 2. Mean values and standard deviations of zero-crossing wave period in the area 62 of Indonesian waters

Fig. 3. Comparison between probability distribution of $f(H_{1/3})$ of GWS data and the fitted one.

Table 1. Scatter diagram of the extrapolated GWS for the area 61 of Indonesian waters

<table>
<thead>
<tr>
<th>$H_{1/3}$ (m)</th>
<th>6.5</th>
<th>7.5</th>
<th>8.5</th>
<th>9.5</th>
<th>10.5</th>
<th>11.5</th>
<th>12.5</th>
<th>13.5</th>
<th>14.5</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{2}$ (s)</td>
<td>0.751</td>
<td>0.751</td>
<td>0.751</td>
<td>0.751</td>
<td>0.751</td>
<td>0.751</td>
<td>0.751</td>
<td>0.751</td>
<td>0.751</td>
<td>0.751</td>
</tr>
</tbody>
</table>

Table 2. Scatter diagram of the extrapolated GWS for the area 62 of Indonesian waters

<table>
<thead>
<tr>
<th>$H_{1/3}$ (m)</th>
<th>6.5</th>
<th>7.5</th>
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<td>0.751</td>
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<td>0.751</td>
<td>0.751</td>
<td>0.751</td>
<td>0.751</td>
</tr>
</tbody>
</table>
4. Tested ship

4.1 Principal dimensions and the restoring arm curves

A 500 gross tonnage (GRT) RoRo passenger ship was selected among the Indonesia fleet because this is a typical example of the fleet and her design drawings are available. This ship is owned by a government shipping company providing ferry connection between Indonesian islands, and was designed and built locally. The recent statistical data of Indonesian RoRo passenger ships are presented in Figs. 4-6. In January of 2000, Indonesia has 185 RoRo passenger ships and their principal dimensions have a single peak distributions except for a longer ship group. The arrow signs in the figures indicate the tested ship. These figures well explain that the tested ship is a good example of Indonesian RoRo passenger ships that are currently used in Indonesian water areas.
The principal particulars and drawings of the tested ship are shown in Table 4 and Figs. 7-9. The ship has several side openings at the RoRo space with scuppers. Since these openings are not water tight, the superstructure above the RoRo deck, except for fore castle and poop, should be excluded for stability calculation. Here the restoring arm curves for its design condition, without side openings and with side openings, are shown in Fig. 10.

Table 4. Principal particulars of the 500 GRT RoRo passenger ship at the design condition

<table>
<thead>
<tr>
<th>Items</th>
<th>Ship</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{WA}$</td>
<td>45.50 m</td>
<td>2166.6 mm</td>
</tr>
<tr>
<td>$L_{beam}$</td>
<td>40.15 m</td>
<td>1911.9 mm</td>
</tr>
<tr>
<td>$B$</td>
<td>12.00 m</td>
<td>571.4 mm</td>
</tr>
<tr>
<td>Height of ear deck</td>
<td>3.20 m</td>
<td>152.4 mm</td>
</tr>
<tr>
<td>Height of Passenger deck</td>
<td>7.00 m</td>
<td>333.3 mm</td>
</tr>
<tr>
<td>Mean draught</td>
<td>2.20 m</td>
<td>104.8 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>750.0 ton</td>
<td>80.98 kg</td>
</tr>
<tr>
<td>$C_{p}$</td>
<td>0.708</td>
<td>0.708</td>
</tr>
<tr>
<td>$K_{G}$</td>
<td>4.29 m</td>
<td>204.3 mm</td>
</tr>
<tr>
<td>$G_{M}$</td>
<td>3.69 m</td>
<td>175.7 mm</td>
</tr>
<tr>
<td>Natural roll period</td>
<td>6.09 s</td>
<td>1.33 s</td>
</tr>
</tbody>
</table>

Fig. 7. General Arrangement of the tested ship

Fig. 8. The body plan of the tested ship with side openings

Table 5. The comparison between IMO criteria and the ship

<table>
<thead>
<tr>
<th>Norm</th>
<th>IMO code</th>
<th>The ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.055 m.rad</td>
<td>0.272 (+)</td>
</tr>
<tr>
<td>B</td>
<td>0.09 m.rad</td>
<td>0.315 (+)</td>
</tr>
<tr>
<td>C</td>
<td>0.03 m.rad</td>
<td>0.043 (+)</td>
</tr>
<tr>
<td>D</td>
<td>0.20 m</td>
<td>0.706 (+)</td>
</tr>
<tr>
<td>E</td>
<td>&gt;25°</td>
<td>15 (-)</td>
</tr>
<tr>
<td>F</td>
<td>≥ 0.15 m</td>
<td>3.69 (+)</td>
</tr>
</tbody>
</table>

Remarks:
A : Area under the GZ curve until 30°.
B : Area under the GZ curve until 40°.
C : Area under the GZ curve between 30° - 40°.
D : Maximum righting arm.
E : Angle of maximum stability.
F : Metacentric height.
Obviously, even at the design condition the ship with side openings does not comply with the Intact Stability Code (IS code) of the International Maritime Organization (IMO) as shown in Table 5. The angle of maximum restoring arm at the design condition is about 15°, while the IS code requires more than 25°. The main reason of this poor stability is the small freeboard.

4.2 Ship roll data

The roll damping coefficients, a and b, and the effective wave slope coefficient, γ, were estimated with data of different but standard ships in the first report. To exclude this uncertainty of these coefficient estimation, the authors and Bahreisy carried out the roll experiments with a scaled model of the tested ship in a seakeeping and maneuvering basin of Indonesian Hydrodynamic Laboratory. The measured coefficients for the design condition are as follows:

\[ a = 0.1017, \]
\[ b = 0.0133, \]
\[ N = 0.0184, \text{ at 20 degrees}, \]
\[ γ = 0.452. \]

These coefficients were used for the calculation of capsizing probability in this report.

5. Numerical results and discussion

The results of calculation are shown in Figs. 11 - 13. These figures describe the capsizing probability in the areas of Indonesian waters that covered by GWS data in different metacentric height values for the ship with side openings and without side openings. The effect of side openings on the annual capsizing probability is significant. Capsizing probability of the ship with side openings is much higher than one without side openings.

As confirmed in the first report, it is possible to determine the critical metacentric height by specifying the acceptable probability. This is because the annual capsizing, in most cases, decreases with the increasing metacentric height. To specify the acceptable probability level, actual capsizing rate per ship per year from casualty statistics can be a useful index. In case of Indonesian RoRo passenger ship fleet, 7 capsizes occurred these 6 years. Thus the actual capsizing rate is obtained as

\[ \frac{7}{(6 \times 185)} = 0.00631. \]

This value is also plotted in the figures.

Fig. 11. The annual capsizing probability in the area 61 of Indonesian waters

Fig. 12. The annual capsizing probability in the area 62 of Indonesian waters

The comparison between the calculated probabilities and the actual one demonstrates that the calculated probability for the ship with side openings is almost comparable to the actual capsizing rate. This means that the frequent capsizes of Indonesian RoRo passenger ships can be explained by the present mathematical modeling. At the same time, it can be presumed that the main cause of the capsizes is the existence of side openings of the RoRo spaces. Therefore, it is suggested that the side openings should be closed to avoid further capsizing of the Indonesian RoRo passenger ships. It is also true that the effect of trapped-water-on-deck that is ignored in this mathematical model should be examined in the future.
Among the three water areas, the capsizing probability in the area 62 is the largest. This is because the wave statistics only in this area include high and short waves as shown in Table 2. It is noteworthy that longer waves such as swell appeared in Indian Ocean are not so crucial to capsizing of the Indonesian RoRo passenger ship.

6. Concluding Remarks

The following conclusions can be drawn from this work:
1. The calculated annual capsizing probability of the Indonesian RoRo passenger ship with side openings is comparable to the actual capsizing rate from the casualty statistics.
2. The effect of side openings on the annual capsizing probability is very significant. By closing the side openings, the annual capsizing probability can be drastically reduced.
3. Critical metacentric height value can be specified by the present procedure.
4. Among the three water areas, the area 62 has the highest annual capsizing probability.

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References