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# Analysis the Freeboard Effect on a Ferry Ro-Ro Ship Stability Based on the Weather Criteria

Lukman Bochary[1], Mohammad Rizal Firmansyah[2*], Syamsul Asri[3], Wihdat Djafar[4], Wahyuddin Mustafa[5], Rosmani[6], Muhammad Akbar Asis[7], Nasaruddin[8]

[1,2,3,4,5,6,7,8]Departemen Teknik Perkapalan, Fakultas Teknik, Universitas Hasanuddin, Indonesia

*Corresponding Author: mr.firmansyah@unhas.ac.id

**Abstract**

Weather criteria is one of the IMO standards that must be met before the ship operates. Ferry Ro-Ro ship, which operates in Indonesia, tends to have a small freeboard. The small freeboard affects the stability of the ship. The smaller the freeboard, the arm stability will be smaller as well and vice versa. This research analyzes the stability of a Ferry Ro-Ro ship based on the weather criteria at the design stage. Analysis was conducted by varying KG value with Breadth (B) and Draught (T) or B/T ratio and freeboard (fb) ratio with Breadth (B) or fb/B. The ship models are analyzed using two weather criteria based on IMO recommendations and the characteristics of Indonesian waters. After testing the ship stability based on the weather criteria, the maximum KG value for ship ratio B/T = 5 m and the fb/B ratio = 0.04 at 1.0H is 3.456 m. At fb/B ratio = 0.06 on 1.1H of ship height, the maximum KG value is 4.118 m. At fb/B ratio = 0,08, the maximum KG value is 4,435 m at 1.1H, while at fb/B ratio = 0.1, the maximum KG value is 4.752 m at 1.1H.

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## 1. Introduction

Ferry Ro-Ro is a ship type designed to transport motored vehicles and passengers from one destination to the other. This ship type has a bow/ramp door for vehicles to get in and out. Generally, Ferry Ro-Ro ships operating in Indonesia are designed and built in an Indonesian shipyard. It was designed with a relatively small ship draught (T) but wide ship breadth (B). These ship characteristics are determined to accommodate its special cargo. Hence, Ferry Ro-Ro ship generally has a big breadth and draught (B/T) ratio. However, this ratio needs to fulfill ship stability criteria. The ship height (H) is relatively small, with many ship openings above the area of the main deck. Besides, it has a small freeboard; hence ship buoyancy reserve is small. These conditions will make seawater easily enter the main deck's area [1],[2]. On the other hand, wind speed in some parts of Indonesian waters is lower than the IMO wind speed standard for determining ship stability criteria [3]. These two differences between Indonesian waters characteristics and Ferry Ro-Ro ship characteristics make the IMO ship stability criteria difficult to be applied to the Indonesian Ferry Ro-Ro ship design.

The main aim of this research is to determine the maximum value of KG (distance between ship keel (K) and center of gravity (G)) for the ship with the ratio of B/T = 5 and the certain ratio of freeboard (fb) against ship Breadth (B) or fb/B which fulfill the IMO weather ship stability criteria.

## 2. Weather Criteria

### 2.1 Ship Stability

Stability is the equilibrium of a ship. It represents characteristics or the tendency of a ship to return to its initial position after some force or moment causes a small change in its position. The value of ship stability is the moment resulting from the interaction between ship weight and buoyancy [4], [5]. In general, two forces influence a ship's stability which is: internal factors, referring to the layout of the ship cargo, the ship form specifically in the ship's under-water area and flooding because of grounding or collision and external factors, referring to wind, wave, current and storm [6].

### 2.2 Energy Balancing Method

The basic principle of weather criteria for ship stability is the balancing energy between inclination moment caused by wave and wind energy (external factor). It makes a ship incline to some degree into portside and heeling moment to return a ship to its initial position. Wave, wind energy, and heeling moment can be represented as an area restricted by the stability arm curve (Figure 1). The value of heeling moment must be at least the same or greater than the wave and wind energy to put the ship in a stable equilibrium.

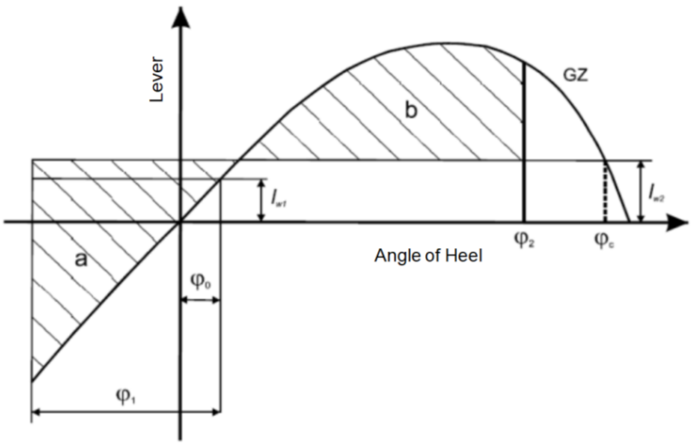


**Figure 1.** Parameter to evaluate ship stability based on the weather criteria [3]

## 3. Methods

Data were collected from 4 subjects of the Ferry Ro-Ro ship, as seen in Table 1. The B/T ratio of the ship object is 5 with four variations of fb/B from 0.01, 0.06, 0.08, up to 0.1.

**Table 1.** Data of ship main dimension

| Ship Name | LOA (m) | LWL (m) | LBP (m) | B (m) | H (m) | T (m) | fb/B | Cb |
|---|---|---|---|---|---|---|---|---|
| $SA_1$ | 55.41 | 54.77 | 52.67 | 14.40 | 3.46 | 2.88 | 0.04 | 0.61 |
| $SA_2$ | 55.72 | 54.77 | 52.67 | 14.40 | 3.74 | 2.88 | 0.06 | 0.61 |
| $SA_3$ | 56.04 | 54.77 | 52.67 | 14.40 | 4.03 | 2.88 | 0.08 | 0.61 |
| $SA_4$ | 56.36 | 54.77 | 52.67 | 14.40 | 4.32 | 2.88 | 1 | 0.61 |

Where LOA = Length of Overall, LWL = Length of Water Line, LBP = Length Between Perpendicular, B = Breadth, H = Height, T = Draught, fb = freeboard, and Cb = Coefficient Block.

## 4. Result and Discussion

### 4.1 Determination of factor value for inclination angle caused by wave and wind ($\varphi_1$)

Values of $X_1$, $X_2$, k, r and s (Tables 2, 3, 4 and 5) were used to calculate the value of $\varphi_1$. Object ships were assumed to have an inclination caused by waves which form an angle ($\varphi_1$) against the wind direction.

**Table 2.** Factor value for $X_1$ and $X_2$

| Ship Name | B (m) | T (m) | B/T | Cb | $X_1$ | $X_2$ |
|---|---|---|---|---|---|---|
| $SA_1$ | 14.40 | 2.88 | 5 | 0.61 | 0.8 | 0.95 |
| $SA_2$ | 14.40 | 2.88 | 5 | 0.61 | 0.8 | 0.95 |
| $SA_3$ | 14.40 | 2.88 | 5 | 0.61 | 0.8 | 0.95 |
| $SA_4$ | 14.40 | 2.88 | 5 | 0.61 | 0.8 | 0.95 |

Table 2 shows that the relationship between B/T with factor $X_1$ is constant. On the other hand, the ratio of $X_1$ for all ship models is relatively the same, which is 0.8. The relationship of Cb with factor $X_2$ is constant as well. The value of factor $X_2$ is constant as the block coefficient (Cb) of the ships is the same, which is 0.610, while the value of $X_2$ for all ship models is relatively the same, which is 0.95.

**Table 3.** Factor value for k

| Ship Name | LOA (m) | LWL (m) | LBP (m) | B (m) | H (m) | T (m) | Keel area (Ak) | $\frac{100xAk}{LWLxB}$ | k |
|---|---|---|---|---|---|---|---|---|---|
| $SA_1$ | 55.41 | 54.77 | 52.67 | 14.40 | 3.46 | 2.88 | 0 | 0 | 1 |
| $SA_2$ | 55.72 | 54.77 | 52.67 | 14.40 | 3.74 | 2.88 | 0 | 0 | 1 |
| $SA_3$ | 56.04 | 54.77 | 52.67 | 14.40 | 4.03 | 2.88 | 0 | 0 | 1 |
| $SA_4$ | 56.36 | 54.77 | 52.67 | 14.40 | 4.32 | 2.88 | 0 | 0 | 1 |

Table 3 shows that the value of k is constant and the same because the average ship sample in this research does not have a keel bar (Equation 1).

$$\frac{Ak \ x \ 100}{Lwl \ x \ B} = 0 \quad (1)$$

Factor r's value depends on the distance between the ship's centers of gravity (KG) against ship draught (T). Table 4 shows the result of calculating the r-value on B/T ship ratio = 5 and fb/B ratio = 1.

**Table 4.** Factor value for r

| Ship Name | fb/B | KG | T | OG | OG/T | r |
|---|---|---|---|---|---|---|
| $SA_1$ | 0.1 | 2.160 | 2.88 | -0.720 | -0.25 | 0.580 |
| | | 2.592 | 2.88 | -0.288 | -0.10 | 0.670 |
| | | 3.024 | 2.88 | 0.144 | 0.05 | 0.760 |
| | | 3.456 | 2.88 | 0.576 | 0.20 | 0.850 |
| | | 3.888 | 2.88 | 1.008 | 0.35 | 0.940 |
| | | 4.320 | 2.88 | 1.440 | 0.50 | 1.030 |
| | | 4.752 | 2.88 | 1.872 | 0.65 | 1.120 |
| | | 5.184 | 2.88 | 2.304 | 0.80 | 1.210 |

In Table 4, it can be seen the relationship between OG/T and factor r. The values are relatively linear and tend to increase. The increasing value of r follows the increasing value of OG/T. The last factor that needs to be considered to determine the value of $\varphi_1$ is factor s. Factor s depend on the ship inclination period (Ts). Table 5 shows the result of some calculations of value s on ship ratio B/T = 5 and the ratio of fb/B = 0.1.

**Table 5.** Factor value for s

| Ship Name | fb/B | KG (m) | B (m) | T (m) | MG (m) | B/T | C | Ts | S |
|---|---|---|---|---|---|---|---|---|---|
| $SA_1$ | 0.1 | 2.160 | 14.4 | 2.88 | 6.884 | 5.0 | 5.370 | 5.894 | 0.1 |
| | | 2.592 | 14.4 | 2.88 | 6.452 | 5.0 | 5.370 | 6.089 | 0.099 |
| | | 3.024 | 14.4 | 2.88 | 6.020 | 5.0 | 5.370 | 6.303 | 0.099 |
| | | 3.456 | 14.4 | 2.88 | 5.588 | 5.0 | 5.370 | 6.542 | 0.099 |
| | | 3.888 | 14.4 | 2.88 | 5.156 | 5.0 | 5.370 | 6.811 | 0.099 |
| | | 4.320 | 14.4 | 2.88 | 4.724 | 5.0 | 5.370 | 7.116 | 0.098 |
| | | 4.752 | 14.4 | 2.88 | 4.292 | 5.0 | 5.370 | 7.465 | 0.098 |
| | | 5.184 | 14.4 | 2.88 | 3.860 | 5.0 | 5.370 | 7.872 | 0.098 |

## 4.2 Inclination angle caused by wave and wind ($\varphi_1$)

Ship inclination angle caused by wave and wind is represented by symbol φ1. The inclination angle is the relationship among effective wave slope coefficient (r), factor k, $X_1$, $X_2$ and CJR. CJR value or tuning factor is 190 based on the IMO rules. Based on information on the ship's main dimension and factor value of $X_1$, $X_2$, k, r and s in Table 1 up to Table 5, the value of $\varphi_1$ can be obtained. One sample of the calculation result of $\varphi_1$ on the ship sample with B/T = 5 and fb/B = 0.04 can be seen in Table 6.

**Table 6.** Inclination angle caused by wave and wind ($\varphi_1$) for fb/B = 0.04

| Ship Name | fb/B | KG | k | $X_1$ | $X_2$ | s | r | $\varphi_1$ |
|---|---|---|---|---|---|---|---|---|
| $SA_4$ | 0.1 | 1.728 | 1.0 | 0.8 | 0.954 | 0.1 | 0.490 | 18.415 |
| | | 2.074 | 1.0 | 0.8 | 0.954 | 0.1 | 0.562 | 19.721 |
| | | 2.419 | 1.0 | 0.8 | 0.954 | 0.1 | 0.634 | 20.946 |
| | | 2.765 | 1.0 | 0.8 | 0.954 | 0.099 | 0.706 | 21.993 |
| | | 3.110 | 1.0 | 0.8 | 0.954 | 0.099 | 0.778 | 23.078 |
| | | 3.456 | 1.0 | 0.8 | 0.954 | 0.099 | 0.850 | 24.132 |
| | | 3.802 | 1.0 | 0.8 | 0.954 | 0.099 | 0.922 | 25.006 |
| | | 4.147 | 1.0 | 0.8 | 0.954 | 0.099 | 0.994 | 25.964 |

## 4.3 Analysis of b/a factor for each KG and fb/B variation based on the IMO weather criteria

The b/a factor was analyzed based on the wind speed from 0-30 m/s. KG change was varied from 0.5H up to 1.2H on some fb/B values from 0.04, 0.06, 0.08 and 0.1. Tables 7, 8, 9 and 10 show the result of the b/a calculation up to the maximum KG value on each fb/B variation.

Figure 2 shows the relationship chart between wind speed and b/a factor for fb/B = 0.04 from KG = 0.5H – 1.2H. It can be seen that the increasing wind speeds make the b/a value decrease. Generally, the ship stability test for Indonesian waters is calculated on the wind speed from 0 to 30 m/s because only in this range of wind speed where the b/a area can be fulfilled. In this research, the wind speed parameter used is 26 m/s.

**Table 7.** Value of b/a factor for fb/B = 0.04 with KG = 1.1H

| Model | KG | Vwind (m/s) | Wind pressure (Pa) | φ1 (deg) | Lw1 (m) | Lw2 (m) | φ0 (deg) | φ Lw2 (deg) | Φc (deg) | a (m.deg) | b (m.deg) | b/a |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| fb/B 0.04 | 3.456 | 0 | 0.000 | 24.132 | 0.000 | 0.000 | 0.000 | 0.000 | 43.400 | 13.845 | 19.640 | 1.419 |
| | | 2 | 2.982 | 24.132 | 0.000 | 0.001 | 0.000 | 0.000 | 43.300 | 13.852 | 19.625 | 1.417 |
| | | 4 | 11.929 | 24.132 | 0.002 | 0.003 | 0.000 | 0.000 | 43.300 | 13.874 | 19.579 | 1.411 |
| | | 6 | 26.840 | 24.132 | 0.004 | 0.006 | 0.000 | 0.000 | 43.300 | 13.909 | 19.503 | 1.402 |
| | | 8 | 47.716 | 24.132 | 0.007 | 0.011 | 0.000 | 0.100 | 43.200 | 13.958 | 19.397 | 1.390 |
| | | 10 | 74.556 | 24.132 | 0.011 | 0.016 | 0.100 | 0.100 | 43.100 | 14.021 | 19.261 | 1.374 |
| | | 12 | 107.361 | 24.132 | 0.016 | 0.024 | 0.100 | 0.200 | 43.000 | 14.098 | 19.095 | 1.354 |
| | | 14 | 146.130 | 24.132 | 0.022 | 0.032 | 0.100 | 0.200 | 42.800 | 14.190 | 18.900 | 1.332 |
| | | 16 | 190.864 | 24.132 | 0.028 | 0.042 | 0.200 | 0.200 | 42.700 | 14.295 | 18.676 | 1.306 |
| | | 18 | 241.562 | 24.132 | 0.036 | 0.053 | 0.200 | 0.300 | 42.500 | 14.414 | 18.423 | 1.278 |
| | | 20 | 298.225 | 24.132 | 0.044 | 0.066 | 0.300 | 0.400 | 42.300 | 14.546 | 18.143 | 1.247 |
| | | 22 | 360.852 | 24.132 | 0.053 | 0.080 | 0.300 | 0.500 | 42.100 | 14.639 | 17.835 | 1.214 |
| | | 24 | 429.444 | 24.132 | 0.063 | 0.095 | 0.400 | 0.600 | 41.800 | 14.853 | 17.500 | 1.178 |
| | | 26 | 504.000 | 24.132 | 0.074 | 0.111 | 0.400 | 0.700 | 41.600 | 15.027 | 17.139 | 1.141 |
| | | 28 | 584.521 | 24.132 | 0.086 | 0.129 | 0.500 | 0.800 | 41.300 | 15.214 | 16.753 | 1.101 |
| | | 30 | 671.006 | 24.132 | 0.099 | 0.148 | 0.600 | 0.900 | 41.000 | 15.414 | 16.342 | 1.060 |

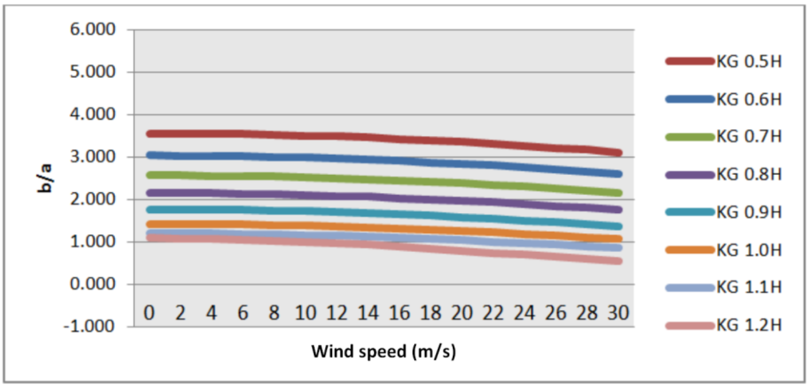


**Figure 2.** Relationship between wind speed and b/a factor for fb/B = 0.04

IMO recommendation for Ferry Ro-Ro ship requires the b area must be at least the same or greater than the a area [3]. For Ferry Ro-Ro ships with fb/B = 0.04 and KG = 0.5G – 0.9H, the result of the ratio b/a in a ship speed 0- 30 m/s is fulfilled by the weather criteria. The b/a ratio is greater than one and in the range of 1.060 – 3.552. For KG = 1.1H – 1.2H, the ratio of b/a value when the wind speed is more than 26 m/s is less than 1 in the range of 0.930 – 0.637, which means it does not fulfill the weather criteria. For the Ferry Ro-Ro ship with the ratio B/T = 5 and fb/B = 0.04, the KG maximum, which fulfilled the weather criteria, is 1.0H.

Figure 3 shows the relationship between the wind speed and b/a factor with fb/B = 0.06 and KG value from 0.5H – 1.2H. The increasing value of wind speed will make the ratio of b/a to be decreased.

**Table 8.** Value of b/a factor for fb/B = 0.06 with KG = 1.1H

| Model | KG | Vwind | Wind pressure | φ1 | Lw1 | Lw2 | φ0 | φ Lw2 | Φc | a | b | b/a |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | m/s | Pa | deg | m | m | deg | deg | deg | m.deg | m.deg | |
| fb/B 0.06 | 4.118 | 0 | 0.000 | 26.017 | 0.000 | 0.000 | 0.000 | 0.000 | 42.100 | 17.014 | 22.465 | 1.320 |
| | | 2 | 2.982 | 26.017 | 0.000 | 0.001 | 0.000 | 0.000 | 42.100 | 17.022 | 22.448 | 1.319 |
| | | 4 | 11.929 | 26.017 | 0.001 | 0.002 | 0.000 | 0.000 | 42.000 | 17.048 | 22.398 | 1.314 |
| | | 6 | 26.840 | 26.017 | 0.003 | 0.005 | 0.000 | 0.000 | 42.000 | 17.091 | 22.314 | 1.306 |
| | | 8 | 47.716 | 26.017 | 0.006 | 0.009 | 0.000 | 0.100 | 41.900 | 17.152 | 22.196 | 1.294 |
| | | 10 | 74.556 | 26.017 | 0.009 | 0.014 | 0.100 | 0.100 | 41.900 | 17.230 | 22.046 | 1.280 |
| | | 12 | 107.361 | 26.017 | 0.013 | 0.020 | 0.100 | 0.200 | 41.800 | 17.324 | 21.862 | 1.262 |
| | | 14 | 146.130 | 26.017 | 0.018 | 0.027 | 0.100 | 0.200 | 41.600 | 17.436 | 21.646 | 1.241 |
| | | 16 | 190.864 | 26.017 | 0.024 | 0.035 | 0.200 | 0.300 | 41.500 | 17.565 | 21.398 | 1.218 |
| | | 18 | 241.562 | 26.017 | 0.030 | 0.045 | 0.200 | 0.300 | 41.400 | 17.711 | 21.118 | 1.192 |
| | | 20 | 298.225 | 26.017 | 0.037 | 0.055 | 0.300 | 0.400 | 41.200 | 17.874 | 20.807 | 1.164 |
| | | 22 | 360.852 | 26.017 | 0.045 | 0.067 | 0.300 | 0.500 | 41.000 | 18.054 | 20.465 | 1.134 |
| | | 24 | 429.444 | 26.017 | 0.053 | 0.079 | 0.400 | 0.600 | 40.800 | 18.250 | 20.094 | 1.101 |
| | | 26 | 504.000 | 26.017 | 0.062 | 0.093 | 0.500 | 0.700 | 40.600 | 17.463 | 19.693 | 1.067 |
| | | 28 | 584.521 | 26.017 | 0.072 | 0.108 | 0.500 | 0.800 | 40.300 | 18.692 | 19.264 | 1.031 |
| | | 30 | 671.006 | 26.017 | 0.083 | 0.124 | 0.600 | 0.900 | 40.100 | 18.938 | 18.808 | 0.993 |

For Ferry Ro-Ro ships with fb/B = 0.06 and KG = 0.5G – 1.1H, the result of the ratio b/a in a ship speed 0 - 30 m/s fulfilled the weather criteria. The b/a ratio is greater than one and in the range of 1.031 – 3.647. For KG = 1.2H, the ratio b/a value when the wind speed is more than 26 m/s is less than one, which is 0.919, meaning it does not fulfill the weather criteria. For Ferry Ro-Ro ship with the ratio B/T = 5 and fb/B = 0.06, the KG maximum, which fulfilled the weather criteria, is 1.1H.

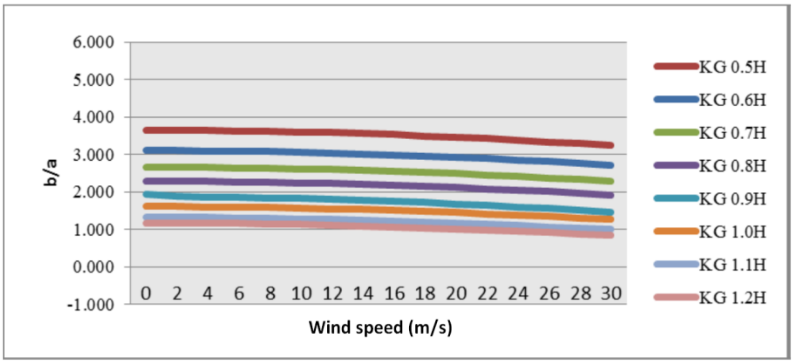


**Figure 3.** Relationship between wind speed and b/a factor for fb/B = 0.06

**Table 9.** Value of b/a factor for fb/B = 0.08 with KG = 1.1H

| Model | KG | Vwind m/s | Wind pressure Pa | φ1 deg | Lw1 m | Lw2 m | φ0 deg | φ Lw2 deg | Φc deg | a m.deg | b m.deg | b/a |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| fb/B 0.08 | 4.435 | 0 | 0.000 | 26.872 | 0.000 | 0.000 | 0.000 | 0.000 | 46.300 | 46.300 | 29.035 | 1.439 |
| | | 2 | 2.982 | 26.872 | 0.000 | 0.001 | 0.000 | 0.000 | 46.300 | 46.300 | 29.014 | 1.437 |
| | | 4 | 11.929 | 26.872 | 0.002 | 0.002 | 0.000 | 0.000 | 46.200 | 46.200 | 28.949 | 1.432 |
| | | 6 | 26.840 | 26.872 | 0.004 | 0.005 | 0.000 | 0.000 | 46.200 | 46.200 | 28.842 | 1.423 |
| | | 8 | 47.716 | 26.872 | 0.006 | 0.010 | 0.100 | 0.100 | 46.100 | 46.100 | 28.692 | 1.411 |
| | | 10 | 74.556 | 26.872 | 0.010 | 0.015 | 0.100 | 0.100 | 46.000 | 16.000 | 28.500 | 1.396 |
| | | 12 | 107.361 | 26.872 | 0.015 | 0.022 | 0.100 | 0.200 | 45.900 | 45.900 | 28.265 | 1.377 |
| | | 14 | 146.130 | 26.872 | 0.020 | 0.030 | 0.200 | 0.300 | 45.800 | 45.800 | 27.989 | 1.355 |
| | | 16 | 190.864 | 26.872 | 0.026 | 0.039 | 0.200 | 0.300 | 45.700 | 45.700 | 27.672 | 1.331 |
| | | 18 | 241.562 | 26.872 | 0.033 | 0.049 | 0.300 | 0.400 | 45.500 | 45.500 | 27.314 | 1.304 |
| | | 20 | 298.225 | 26.872 | 0.040 | 0.061 | 0.300 | 0.500 | 45.400 | 45.400 | 26.917 | 1.274 |
| | | 22 | 360.852 | 26.872 | 0.049 | 0.073 | 0.400 | 0.600 | 45.200 | 45.200 | 26.480 | 1.241 |
| | | 24 | 429.444 | 26.872 | 0.058 | 0.087 | 0.500 | 0.700 | 44.900 | 44.900 | 26.006 | 1.207 |
| | | 26 | 504.000 | 26.872 | 0.068 | 0.102 | 0.600 | 0.900 | 44.700 | 44.700 | 25.494 | 1.170 |
| | | 28 | 584.521 | 26.872 | 0.079 | 0.119 | 0.700 | 1.100 | 44.500 | 44.500 | 24.945 | 1.132 |
| | | 30 | 671.006 | 26.872 | 0.091 | 0.136 | 0.800 | 1.200 | 44.200 | 44.200 | 24.362 | 1.092 |

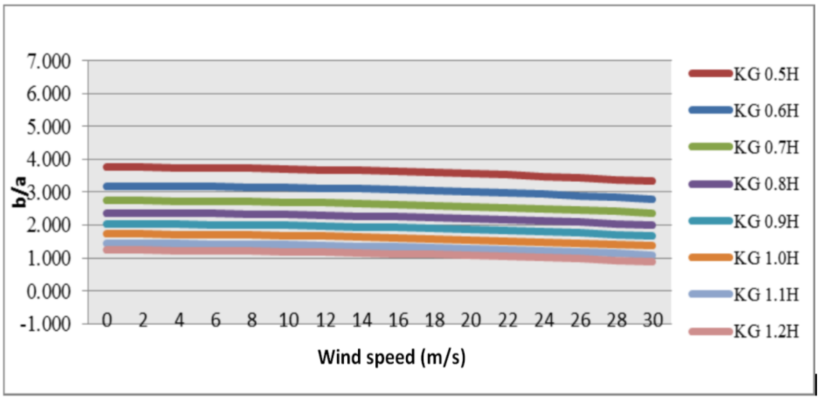


**Figure 4.** Relationship between wind speed and b/a factor for fb/B = 0.08

Figure 4 shows the relationship between the wind speed and the b/a factor with fb/B = 0.06 and KG value from 0.5H – 1.2H. The increasing value of wind speed will make the ratio of b/a to be decreased.

For Ferry Ro-Ro ships with fb/B = 0.08 and KG = 0.5G – 1.1H, the result of the ratio b/a in a ship speed 0 - 30 m/s fulfilled the weather criteria. The b/a ratio is greater than one and in the range of 1.092 – 3.754. For KG = 1.2H, the ratio b/a value when the wind speed is more than 26 m/s is less than one, which is 0.970 means that it does not fulfill the weather criteria. For Ferry Ro-Ro ship with the ratio B/T = 5 and fb/B = 0.08, the KG maximum, which fulfilled the weather criteria, is 1.1H.

**Table 10.** Value of b/a factor for fb/B = 0.1 with KG = 1.1H

| Model | KG | Vwind | Wind pressure | $\varphi_1$ | $Lw_1$ | $Lw_2$ | $\varphi_0$ | $\varphi$ $Lw_2$ | $\Phi_c$ | a | b | b/a |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | m/s | Pa | deg | m | m | deg | deg | deg | m.deg | m.deg | |
| fb/B 0.1 | 4.32 | 0 | 0.000 | 26.564 | 0.000 | 0.000 | 0.000 | 0.000 | 54.200 | 23.033 | 40.812 | 1.772 |
| | | 2 | 2.982 | 26.564 | 0.000 | 0.001 | 0.000 | 0.000 | 54.100 | 23.042 | 40.785 | 1.770 |
| | | 4 | 11.929 | 26.564 | 0.002 | 0.003 | 0.000 | 0.000 | 54.100 | 23.069 | 40.706 | 1.765 |
| | | 6 | 26.840 | 26.564 | 0.004 | 0.006 | 0.000 | 0.100 | 54.100 | 23.115 | 40.575 | 1.755 |
| | | 8 | 47.716 | 26.564 | 0.007 | 0.010 | 0.100 | 0.100 | 54.000 | 23.178 | 40.390 | 1.743 |
| | | 10 | 74.556 | 26.564 | 0.011 | 0.016 | 0.100 | 0.200 | 53.900 | 23.259 | 40.154 | 1.726 |
| | | 12 | 107.361 | 26.564 | 0.015 | 0.023 | 0.100 | 0.200 | 53.800 | 23359 | 39.865 | 1.707 |
| | | 14 | 146.130 | 26.564 | 0.021 | 0.031 | 0.200 | 0.300 | 53.700 | 23.476 | 39.524 | 1.684 |
| | | 16 | 190.864 | 26.564 | 0.027 | 0.040 | 0.300 | 0.400 | 53.500 | 23.611 | 39.132 | 1.657 |
| | | 18 | 241.562 | 26.564 | 0.034 | 0.051 | 0.300 | 0.500 | 53.400 | 23.763 | 38.688 | 1.628 |
| | | 20 | 298.225 | 26.564 | 0.042 | 0.063 | 0.400 | 0.600 | 53.200 | 23.933 | 38.193 | 1.596 |
| | | 22 | 360.852 | 26.564 | 0.051 | 0.077 | 0.500 | 0.700 | 52.900 | 24.120 | 37.647 | 1.561 |
| | | 24 | 429.444 | 26.564 | 0.061 | 0.091 | 0.600 | 0.900 | 52.700 | 24.324 | 37.051 | 1.523 |
| | | 26 | 504.000 | 26.564 | 0.071 | 0.107 | 0.700 | 1.000 | 52.500 | 24.545 | 36.402 | 1.483 |
| | | 28 | 584.521 | 26.564 | 0.083 | 0.124 | 0.800 | 1.200 | 52.200 | 24.783 | 35.709 | 1.441 |
| | | 30 | 671.006 | 26.564 | 0.095 | 0.142 | 0.900 | 1.400 | 51.900 | 25.037 | 34.965 | 1.397 |

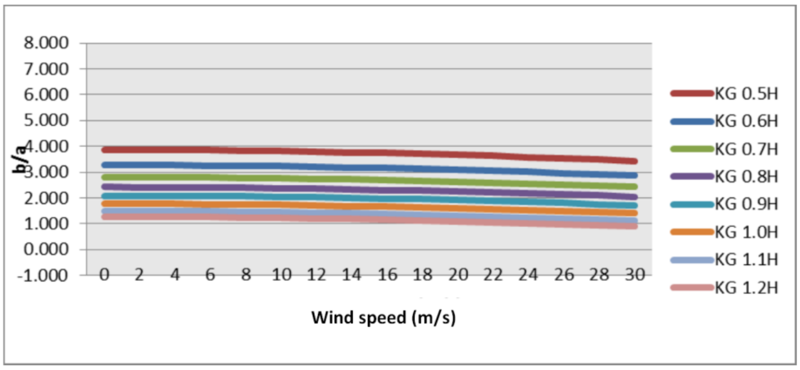


**Figure 5.** Relationship between wind speed and b/a factor for fb/B = 0.1

Figure 5 shows the relationship between the wind speed and the b/a factor with fb/B = 0.1 and KG value from 0.5H – 1.2H. The increasing value of wind speed will make the ratio of b/a to be decreased.

For Ferry Ro-Ro ships with fb/B = 0.1 and KG = 0.5G – 1.1H, the result of the ratio b/a in a ship speed 0 - 30 m/s is fulfilled the weather criteria. The b/a ratio is greater than one and in the range of 1.118 – 3.864. For KG = 1.2H, the ratio b/a value when the wind speed is more than 26 m/s is less than one, which is 0.984, meaning it does not fulfill the weather criteria. For Ferry Ro-Ro ship with the ratio B/T = 5 and fb/B = 0.1, the KG maximum, which fulfilled the weather criteria, is 1.1H.

## 4.4 Discussion

Indonesian waters have different characteristics, with the recommendation from IMO to calculate weather criteria of ship stability [1],[7]. The r coefficient (the effective wave slope coefficient) of Indonesian waters is 0.43 + 0.631 (OG/T) with the s function value (wave steepness) is 0.0975, and the wind speed is 16 m/s which is equal to 190.864 Pa. These characteristics are less valuable than IMO requirements for calculating the weather criterion. In the IMO recommendation, the r coefficient is 0.73 + 0.6 ( OG/T), the s function value is 0.1, and the wind speed is 26 m/s, equal to 504 Pa (Table 11).

**Table 11.** The comparison between KG maximum value of IMO and Indonesian waters based on the ship weather criteria of B/T = 5

| Ship Name | KG | IMO Recommendation | | | | Indonesian waters | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | r | s | P (Pa) | KGmax (m) | r | s | P (Pa) | KGmax (m) |
| $SA_1$ | 0.04 | 0.850 | 0.099 | 504 | 3.456 | 0.084 | 0.076 | 190.864 | 3.802 |
| $SA_2$ | 0.06 | 0.988 | 0.098 | 504 | 4.118 | 0.097 | 0.063 | 190.864 | 4.493 |
| $SA_3$ | 0.08 | 1.054 | 0.098 | 504 | 4.435 | 0.103 | 0.056 | 190.864 | 4.838 |
| $SA_4$ | 0.1 | 1.120 | 0.098 | 504 | 4.752 | 0.110 | 0.054 | 190.864 | 5.184 |

Table 11 shows the comparison between the result of the calculation using Indonesian waters characteristics and IMO recommendation. In Indonesian waters, the maximum value of KG is greater than the value according to IMO recommendations. The difference caused by the value of r (effective wave slope coefficients), s (wave steepness) and wind speed of Indonesian waters is smaller than the value in the IMO recommendation. The increasing value of KG will increase the value of r. Consequently, the ship inclination angle caused by wind and wave (φ1) will also be increased [8].

The graph in Figure 6 shows that the ship sample with B/T = 5, based on weather criteria of Indonesian waters, fulfilled the requirements to operate with KG value more significantly than the IMO recommendation.

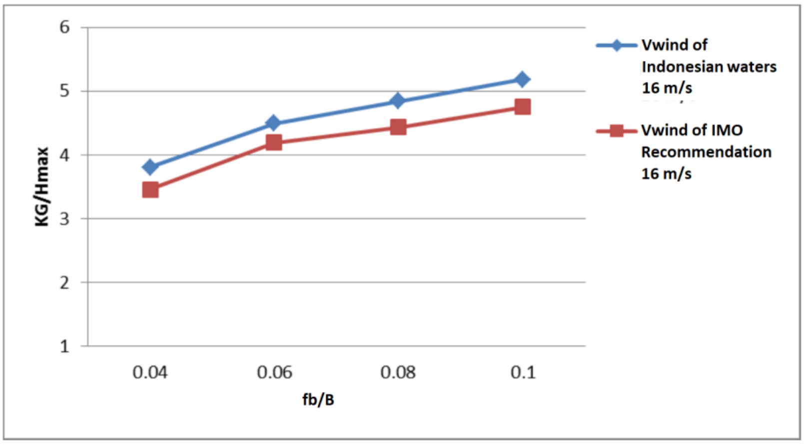


**Figure 6.** Relationship between fb/B and maximum KG value on weather criteria based on the IMO Recommendation and Indonesian water characteristics

## 5. Conclusion

Based on the analysis, some conclusions can be drawn to figure out the influence of freeboard and centre of gravity on Ferry Ro-Ro ship stability based on the weather criteria of IMO. Maximum KG for Ferry Ro-Ro ship with B/T = 5 on some fb/B ratio of 0.04, 0.06, 0.08 and 0.1 are increasing from 3.456 m, 4.118 m, 4.435 m, and 4.752 m. Further, on the same fb/B ratio, the KG values that fulfil IMO weather criteria are at 1.0H for fb/B = 0.04 and 1.1H for the rest of the other fb/B ratios.

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