Maritime Technology and Society
Vol. 4(3): 191-198, October 2025
https://doi.org/10.62012/mp.vi.45249

Regular Research Article

Assessment of the Ship Stability of the MV. Sultan Hasanuddin During Passenger Evacuation

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Abstract: The MV Sultan Hasanuddin, which was previously used solely as a training ship for cadets, is now operational as a public passenger transport vessel serving the islands and ports of South Sulawesi. This study aims to assess the impact of changes in the stability of the MV Sultan Hasanuddin during passenger evacuations in the event of a fire, under International Maritime Organization Regulation A.749 (18) Chapter 3. One significant factor influencing the vessel's stability is the distribution of cargo, which includes the movement behaviors of passengers. When passengers move freely throughout the ship, such as walking, running, or congregating in specific areas, they can cause a shift in the ship's center of gravity. In this study, the Krylov method was employed to obtain the ship's GZ stability curve by analyzing multiple cases and tank conditions. The simulation and analysis revealed that the stability of the MV Sultan Hasanuddin decreased during passenger evacuation under different circumstances: upon departure from the port, there was an 18% decrease in the GZ value; during the voyage, the GZ value decreased by as much as 58%; and upon arrival at the port, the decrease ranged from 44% to 70%.

Keywords: Ship Stability; Passengers Evacuation; MV. Sultan Hasanuddin.

1. Introduction

The weak maritime safety systems are a major potential cause of casualties in maritime accidents [1]. Accidents involving ships in ports include ship sinkings, collisions between ships, and ship fires [2], [3]. Accidents involving ships can also occur due to non-compliance with the standards set by the International Maritime Organization (IMO). Stability is one of the critical factors determining the safety of a ship at sea [4], [5]. Simply put, stability is a ship's ability to return to its original position after experiencing internal or external disturbances such as strong winds or large waves. Stability is not only important for the safety of passengers and crew but also plays a vital role in maintaining the structural integrity of the ship and its cargo. As shown in Figure 1, one of the analysis results from the National Transportation Safety Committee (KNKT) on the sinking of MV. Rafelia II concluded that the sinking of the ship was due to the ship's stability not meeting the criteria for good stability [6]. The ferry owned by PT. Surya Timur Line, which capsized and sank in the waters of Gilimanuk in 2021. The SB Evelyn Calisca passenger ship that sank in the waters of Indragiri Hilir Regency, Riau, in 2023[7]. The Dausa 02, an Indonesian-flagged passenger ship that sank in the Egron Strait in 2024 [8], and the Lorena Sari, a ship carrying dozens of people that sank in 2024 [9].

Received 2025-06-27; Accepted 2025-07-24; Published 2025-10-08

Figure 1. The evacuation process of the MV. Rafelia II during the sinking

One factor that greatly affects the stability of a ship is the distribution of cargo, including the distribution of passengers [10]. When passengers move freely on board, for example, walking from one place to another, running, or gathering in a certain area, this causes a shift in the ship's center of gravity. In a previous study on Passenger Evacuation Time Analysis during a Fire on the MV. Sultan Hasanuddin conducted several simulation scenarios of passenger evacuation, observing changes in passenger distribution during the evacuation process [11]. On the evacuation route of the MV. Sultan Hasanuddin, the assembly station is located on deck 3 (crew deck) and deck 4 (bridge deck), where in the passenger evacuation simulation process, most passengers head toward the assembly station located on deck 4 (bridge deck). This can result in an asymmetrical passenger distribution and a significant increase in the ship's center of gravity (G).

2. Materials and Methods

Ship stability is the ability of a ship to return to its original position after experiencing roll [12]. Ship stability is closely related to cargo distribution and the calculation of the righting lever (GZ) value [13]. Differences in cargo distribution under various loading conditions will result in changes to the KG value, which is the vertical distance between point K (keel) and point G (center of gravity), thereby affecting the righting lever (GZ) value that is formed [14], [15]. Ship stability depends on several factors, including ship dimensions, the shape of the ship's hull in the water, the distribution of objects on the ship, and the ship's angle of inclination relative to the horizontal plane [16]. The stability arm indicates the ship's ability to return to its original position when it tilts due to external disturbances.

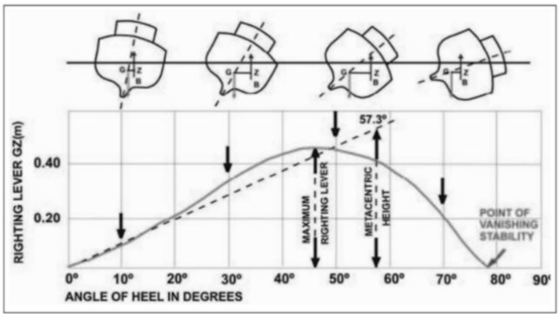

Figure 2. Curve of Ship Stability Arm (GZ)

The stability arm describes the stability characteristics of a ship. Therefore, the stability arm serves as a stability criterion parameter, where the angle of inclination caused by wave-induced disturbances is inversely proportional to the stability arm. The distance between the center of gravity line and the center of buoyancy line at an angle of inclination less than 6.0 degrees can be seen in Figure 8. The waterline section undergoes significant changes, resulting in different metacentric to buoyancy (MB) compared to when the ship is upright. The displacement of the center of pressure is no longer linear with changes in the angle of inclination; the displacement of the center of pressure must be calculated using a specific method. When the ship is upright at 0.0 degrees, the stability arm is equal to zero. The stability arm reaches its maximum (maximum righting lever) at a specific angle of inclination, as illustrated in Figure 2. At a certain angle of inclination, the stability arm returns to zero (point of vanishing stability). The moment that returns the ship to its original position when it is inclined is the stability moment, which is the product of the stability arm and the ship's displacement under specific loading conditions.

$$Ms = GZ\ x\ \Delta \quad (1)$$

Where, GZ is Stability Arm (m) and Δ is Displacement of the ship (ton). The GZ curve will vary depending on the VCG (or load condition) for the same draft [17]. Once the KN curve is obtained for a given draft, GZ can be easily calculated for any load condition using formula 2.

$$GZ = KN - KG \sin \theta \quad (2)$$

A fully loaded tank is considered a static load with its center of gravity in the middle of the tank. The load does not move when the ship tilts. Therefore, the ship's center of gravity remains unchanged. If the tank is partially filled, the initial center of gravity of the water volume in the tank is g and the center of gravity of the ship is G. When the ship tilts at an angle (θ), the water volume shifts to the lower side, the center of gravity of the water volume g shifts to position g1, causing the center of gravity of the ship to shift to G1 in a direction parallel to gg1 as shown in Figure 3.

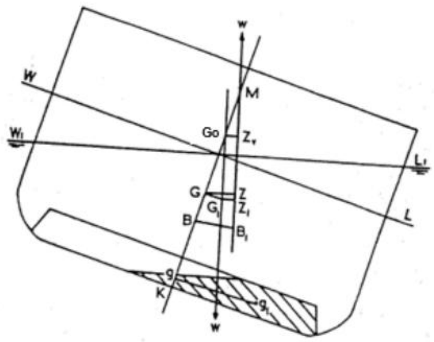

Figure 3. Fee Surface Effect

It can be easily seen that the Free Liquid Surface reduces GM to the value of G_0M. Therefore, GG_0 is the reduction in GM because of the free liquid surface on partially filled tanks. The stability of the ship will be reduced when the ship is in a tilted position. When a ship has several partially filled tanks, the formula below should be applied for GM calculations instead of:

$$GM = KM - KG - GG_0 \quad (3)$$

The determination of the angle of inclination is caused by the disturbing moment equal to the disturbing force multiplied by the distance of the line of action of the disturbing force to the center of gravity of the ship. The angle of inclination due to the disturbing moment is determined using the stability curve.

The characteristics of the stability arm can be reviewed as stability criteria issued by IMO A.749 (18) or known as first generation intact stability criteria based on the area under the curve up to a certain angle of inclination where the area under the curve greatly affects the ship's roll angle when the ship experiences external disturbance, as explained in Table 1 below.

Table 1. IMO A.749 (18) Intact Stability Code

No.	Criteria A.749(18) Ch.3 Parameter	Value	Units
1	3.1.2.1: Area 0 to 30	31,51	m.deg
2	3.1.2.1: Area 0 to 40	51,57	m.deg
3	3.1.2.1: Area 30 to 40	17,19	m.deg
4	3.1.2.2: Max GZ at 30 or greater	0,20	m
5	3.1.2.3: Angle of maximum GZ	25,00	deg
6	3.1.2.4: Initial GMt	0,15	m

The main dimensions and capacity of MV. Sultan Hasanuddin are as follows in Table 2:

Table 2. Principal dimension of MV. Sultan Hasanuddin

No.	Description	Detail
1	Ship Name	MV. Sultan Hasanuddin
2	Ship Type	Training Ship 1200GT (Special Purpose)
3	Length (LOA)	63.00 Meters
4	Moulded Breadth (B)	12.00 Meters
5	Moulded Depth (H)	4.00 Meters
6	Moulded Draft (T)	2.80 Meters
7	Crew	20 people
8	VVIP	4 people
9	Instructors	10 people
10	Cadets	80 people
11	Passengers	100 people
12	Total Power	2 x 759 Bkw
13	Gross Tonage	1200 GT
14	Speed	12 Knots

In this study, Maxsurf Academic software was used to simulate several ship loading conditions. In the simulation and stability analysis of the KL Hasanuddin ship, three loading conditions were used: departure, seagoing, and arrival at the port of call. There were two variations of situations: before evacuation and after evacuation, as follows:

a. Case A: The ship departs from the port (departure), with passengers in the accommodation area before evacuation, compared to the situation during evacuation, where it is assumed that all passengers are at the assembly station on the ship's 4th deck (bridge deck) as shown in Figure 4. In Case A, crew and passenger supplies, all tanks, ballast tanks are fully loaded (100%), cargo holds are fully loaded (100%), and sewage, sludge, and bilge tanks are still empty (0%).

b. Case B: The ship is underway (seagoing), and passengers are in the accommodation areas. The situation before evacuation is compared with the situation during evacuation, where it is assumed that all passengers are at the assembly station on the 4th deck (bridge deck) during evacuation. In Case B, the ship's and passengers' provisions, ballast tanks, fresh water, fuel, and other tanks are half full (50%), and the cargo hold is fully loaded (100%).

c. In Case C, the ship will arrive at the port of call (arrival), and the passenger load is in the accommodation area. The situation before the evacuation is compared with the situation during the evacuation, where it is assumed that all passengers are at the assembly station on the 4th deck of the ship (bridge deck) during the evacuation. In Case C, the ship's and passengers' provisions, ballast tanks, fresh water, fuel, and other tanks are nearly depleted (10%), while the sewage, sludge, and bilge tanks are fully loaded (95%).

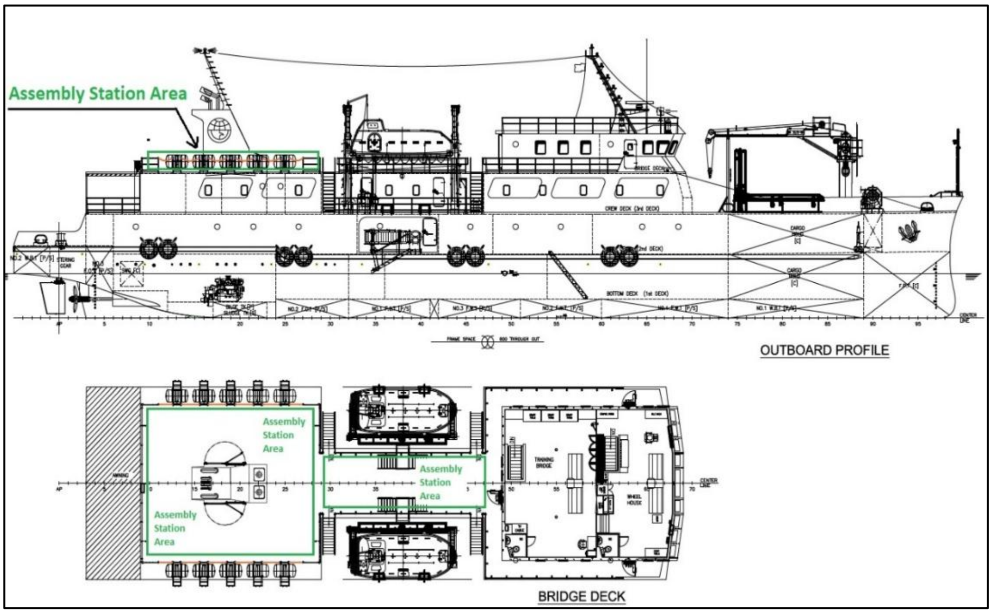

Figure 4. Location of assembly station on 4th deck

Table 3. Total Mass and distribution of MV. Sultan Hasanuddin

Item Name	Quantity	Unit Mass (ton)	Total Mass (ton)	Unit Volume (m³)	Total Volume (m³)	Long. Arm (m)	Trans. Arm (m)	Vert. Arm (m)	Total FSM (ton m)
Lightship	1	898.627	898.627			25.360	0.000	4.829	0.000
Crew & Luggage	20	0.100	2.000			36.220	0.000	7.450	0.000
Provision Store	1	3.000	3.000			5.000	-3.920	5.150	0.000
Bosun Store	1	4.000	4.000			55.990	0.000	5.572	0.000
Instructor & luggage	8	0.100	0.800			9.675	0.000	7.450	0.000
VVIP & luggage	0	0.100	0.000			14.090	0.000	7.450	0.000
Passengers (1st Deck)	0	0.100	0.000			29.100	0.000	2.730	0.000
Passengers (2nd Deck)	0	0.100	0.000			35.000	0.000	5.270	0.000
Passengers (3nd Deck)	200	0.100	20.000			21.000	0.000	11.000	0.000
Cargo on Cargo Hold	1	50.000	50.000			48.416	0.000	4.300	0.000
F.P.T(C)	0%	30.220	0.000	30.220	0.000	54.303	0.000	0.000	0.000
No.1 W.B.T (P)	50%	13.379	6.689	13.379	6.689	47.714	-1.03	0.459	23.819
No.1 W.B.T (S)	50%	13.379	6.689	13.379	6.689	47.714	1.035	0.459	23.819

Item Name	Quantity	Unit Mass (ton)	Total Mass (ton)	Unit Volume (m³)	Total Volume (m³)	Long. Arm (m)	Trans. Arm (m)	Vert. Arm (m)	Total FSM (ton m)
No.1 F.W.T (S)	100%	40.223	40.223	40.223	40.223	39.912	2.431	0.641	0.000
No.1 F.W.T (P)	100%	40.223	40.223	40.223	40.223	39.912	-2.43	0.641	0.000
No.2 F.W.T (S)	100%	35.430	35.430	35.430	35.430	33.289	2.755	0.624	0.000
No.2 F.W.T (P)	100%	35.430	35.430	35.430	35.430	33.289	-2.75	0.624	0.000
No.3 F.W.T (S)	100%	35.842	35.842	35.842	35.842	27.903	2.793	0.624	0.000
No.3 F.W.T (P)	100%	35.842	35.842	35.842	35.842	27.903	-2.79	0.624	0.000
No.1 F.O.T (S)	98%	33.186	32.522	35.143	34.440	21.915	2.780	0.626	0.000
No.1 F.O.T (P)	98%	33.186	32.522	35.143	34.440	21.915	-2.78	0.626	0.000
No.2 F.O.T (S)	98%	27.046	26.505	28.641	28.068	16.873	2.643	0.654	0.000
No.2 F.O.T (P)	98%	27.046	26.505	28.641	28.068	16.873	-2.64	0.654	0.000
Sludge	0%	5.470	0.000	5.792	0.000	11.982	0.000	0.000	0.000
Bilge Tank	0%	5.470	0.000	5.792	0.000	11.982	0.000	0.000	0.000
No.3 F.O.T (S)	98%	21.352	20.925	22.611	22.159	2.730	2.406	3.254	0.000
No.3 F.O.T (P)	98%	21.352	20.925	22.611	22.159	2.730	-2.40	3.254	0.000
SWG (C)	0%	3.600	0.000	3.600	0.000	4.800	0.000	2.000	0.000
No.2 W.B.T (S)	100%	18.164	18.164	18.164	18.164	-1.761	2.200	3.696	0.000
No.2 W.B.T (P)	100%	18.164	18.164	18.164	18.164	-1.761	-2.20	3.696	0.000
F.O.D.T (P)	98%	3.662	3.589	3.878	3.801	15.608	-4.95	2.692	0.000
F.O.D.T (S)	98%	3.662	3.589	3.878	3.801	15.608	4.951	2.692	0.000
Total Loadcase			1418.203	512.026	449.632	25.835	0.00	3.769	47.638
FS correction								0.034	
VCG fluid								3.802	

3. Results

The GZ curve is a powerful visual representation of a ship's stability characteristics, providing important information about the ship's ability to withstand tilting and return to a safe position. Figure 5 shows the stability curve of the MV. Sultan Hasanuddin in Case A, where the ship departs from the port (departure). That illustrates how the ship's GZ curve behaves during departure under normal conditions compared to the GZ curve during evacuation conditions, where all passengers are at the assembly station. As seen in the figure, there is a change in the ship's stability value, as indicated by the decrease in the GZ curve. In analyzing the GZ stability curve, the “Range of Stability” is one of the most critical parameters indicating the ship's ability to return to an upright position after tilting. Simply put, the Range of Stability is the range of tilt angles where the righting arm (GZ) has a positive value. The Range of Stability of the MV. Sultan Hasanuddin during passenger evacuation decreased by 2.9%.

Figure 5 shows the decrease in GZ value before evacuation (normal condition) and during passenger evacuation, where this decrease begins at a small angle (initial stability) with a change of 3.64% and increases to a decrease of 18% at an angle of 90 degrees. Passenger movement or, more generally, mass movement within the ship has a direct and significant effect on the GZ value (stability arm). This effect occurs because mass movement causes changes in the ship's center of gravity (G).

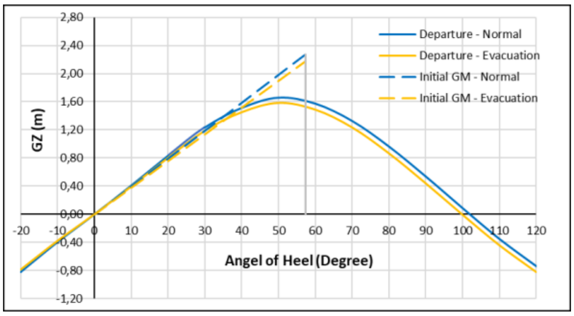

Figure 5. Stability of MV. Sultan Hasanuddin's condition, Case A

An adequate GM value ensures that the ship can return to an upright position from a small inclination that may occur due to waves or small shifts in cargo. Although GM only applies to small angles of inclination, it provides an initial indication of how responsive the ship is to disturbances. That shows the change in the Initial GM value before evacuation (normal) and during passenger evacuation, with a 3.9% decrease in the GM value from the initial condition.

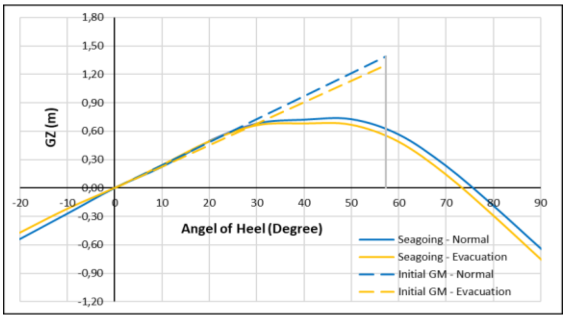

Figure 6. Stability of MV. Sultan Hasanuddin's condition, Case B

Figure 6 shows the stability curve of MV. Sultan Hasanuddin in Case B, where the ship is underway (seagoing), assuming that the ship's supplies and passengers, ballast tanks, fresh water, fuel, and other tanks are half full (50%). Figure B illustrates how the ship's righting arm curve (GZ) during normal seagoing conditions compares to the GZ curve during evacuation conditions, where all passengers are at the assembly station. The figure shows the stability range of the MV. Sultan Hasanuddin during passenger evacuation decreases by 3.7% from normal conditions. Figure 6 illustrates the decrease in GZ values before evacuation (normal) and during passenger evacuation, where the decrease begins at a small angle (initial stability) with a change of 3.22% and increases at the advanced stability angle until the ship reaches a 70-80-degree angle, resulting in a decrease of 40% to 58%. Figure 6 shows the change in the Initial GM value before evacuation (normal) and during passenger evacuation, with a decrease in the GM value of 6.6% from the initial condition.

Figure 7 shows the stability curve of MV. Sultan Hasanuddin in Case C, where the ship arrives at the port (arrival), assuming that the ship's supplies and passengers, ballast tanks, fresh water, fuel, and other tanks are nearly depleted (10%). Figure A illustrates how the ship's righting arm curve (GZ) arrives at the port (arrival) under normal conditions compared to the GZ curve of the ship during evacuation when all passengers are at the assembly station. The figure shows the stability range of the MV. The Sultan Hasanuddin ship's passenger evacuation decreases by 4.5% from normal conditions.

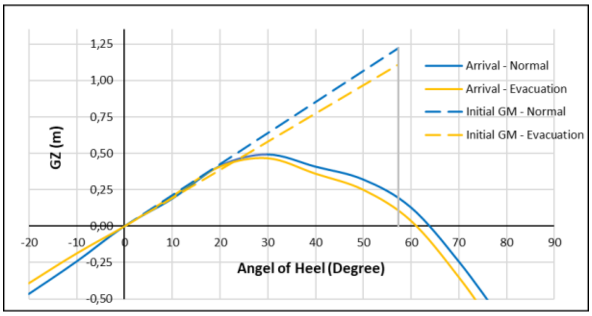

Figure 7. Stability of MV. Sultan Hasanuddin's condition, Case C

Figure 7 illustrates the decrease in GZ values before evacuation (normal) and during passenger evacuation, where the decrease begins at a small angle (initial stability) with a change of 9.5% and increases at the advanced stability angle (60 to 70 degrees) to a decrease of 44% to 70%. As shown in Figure 7, the change in the Initial GM value before evacuation (normal) and during passenger evacuation resulted in a decrease in the GM value of 9.0% from the initial condition.

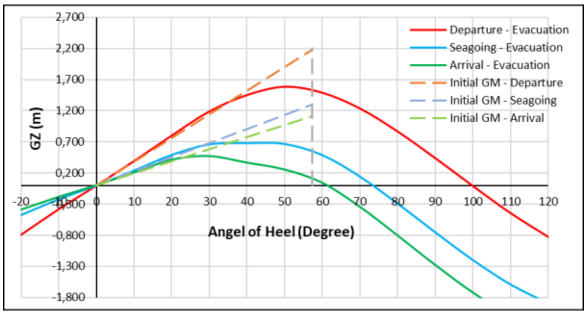

Figure 8. Stability of MV. Sultan Hasanuddin in cases A, B, and C

A comparison has been made with another study discussing the differences in stability curves when sailing and arriving, where the results of this study are in line with previous studies [18], [19]. Figure 8 shows the stability curve of MV. Sultan Hasanuddin during passenger evacuation in Case A when the ship departed, Case B when the ship was at sea, and Case C, when the ship arrived at the port. It is visible in the diagram that the comparison of the GZ and GM values of the MV. Hasanuddin ship under three different conditions. Loading and unloading of tanks on the ship have a significant impact on the ship's stability, particularly because they affect the position of the ship's center of gravity (G) and the “free surface effect” phenomenon. When tanks are loaded or unloaded, the mass of the liquid inside changes, directly altering the ship's total weight (displacement) and, more importantly, the vertical and lateral location of the center of gravity (G). These changes affect the GM value (initial metacenter) and the shape of the GZ curve (righting arm), which are primary indicators of ship stability. The change in the righting arm value of the MV. Sultan Hasanuddin's ship in initial stability shows a decrease ranging from 36% to 49% from condition A to condition B and condition C. The change in the righting arm value of the MV. Sultan Hasanuddin's stabilizer arm value in advanced stability decreased by approximately 61% at a 30-degree angle, 128% at a 70-degree angle, and 271% at a 90-degree angle from condition A to condition B and condition C.

One of the most critical effects of tank loading is the effect on the ship's center of gravity (CG). When tanks are loaded in the upper part of the ship (e.g., fuel tanks on the upper deck), the ship's CG will increase (the G point moves higher). This increase in CG reduces the GM value and lowers the GZ curve, making the ship more “tender” or less stable. Conversely, if tanks are filled in the lower part of the ship (e.g., ballast tanks in the double bottom), the ship's CG decreases, increasing the GM and raising the GZ curve, thereby enhancing the ship's stability. Therefore, strategic tank loading arrangements are crucial for maintaining optimal stability. As shown in Figure 8, the change in the Initial GM value during passenger evacuation varies across different cases, with a decrease in GM value ranging from 40% to 49% from the initial condition of Case A to Case B and Case C.

4. Discussion

Based on the analysis results of the ship's condition departing from the port (departure) in case A, the ship en route (seagoing) in case B, and the ship arriving at the port (arrival) in case C, the stability curve results obtained meet all the criteria in IMO A.749 (18) Chapter 3. Based on the simulation results, changes in the stability of the KL ship. Sultan Hasanuddin during passenger evacuation when the vessel departed from the port (departure) experienced a decrease in GZ value of 18%, during the vessel's voyage (seagoing) experienced a decrease in GZ value of up to 58%, and upon arrival at the port (arrival) experienced a decrease ranging from 44% to 70%. The initial GM of the MV. Sultan Hasanuddin vessel during passenger evacuation when the vessel departs from the port (departure) experiences a decrease in GM value of 3.9%, when the vessel is underway (seagoing) experiences a decrease in GM value of up to 6.6%, and when the vessel arrives at the port (arrival) experiences a decrease of 9.0% from normal conditions.

5. Conclusions

Based on the results of the stability simulation of the KL Sultan Hasanuddin ship under various conditions, it is recommended that the ship's crew not evacuate passengers to the Assembly Station on the 4th deck (bridge deck) when the ship's tanks are nearly empty (10%), as the GZ righting arm value and the ship's GM value decrease by 49% to 61%, which significantly impacts the ship's safety. For further research, stability analysis should be conducted with the addition of disturbing moments on the ship, particularly the addition of moments on the davits and lifeboats during passenger evacuation.

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