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A Comparative Analysis of the Stability of Open-Deck River Boats Using Righting Moment and GM_0 Based Criteria

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Abstract

The Musi River is an important transportation route in Indonesia, where traditional boats such as Jukungs and Keteks are widely used. Both are open-deck vessels, making stability a crucial factor for safety and operability. This study analyses and compares the stability of a Jukung and a Ketek in order to provide insights for safer traditional boat design. The methodology involves calculating the stability moment (M_{GZ}) at a given heel angle and the heeling moment (M_{KR}) due to turning and passenger distribution, based on Biro Klasifikasi Indonesia (BKI) and the GM_0 value specified by International Maritime Organization (IMO). Numerical simulations based on hull geometry are also applied for a more detailed assessment. Although similar in size, the Jukung has greater displacement owing to its flat U-shaped hull extending from top to bottom. Reducing passenger loads lowers the centre of gravity and increases the height of the righting lever. Both boats satisfy stability criteria across loading cases; however, the Jukung consistently demonstrates higher M_{GZ} values, which increases further as the load decreases. Findings show that both vessels remain stable with M_{GZ} exceeding M_{KR}. The Jukung maintains a positive GM_0 under all loading conditions, whereas the Ketek fails to meet stability requirements at higher loads but is acceptable at reduced passenger levels. Overall, the Jukung proves more stable and safer, with its hull form providing a larger righting lever and greater safety margin than the Ketek. This highlights the critical role of hull design in ensuring traditional boat safety along the Musi River.

1. Introduction

Due to inadequate land infrastructure, traditional boats remain a vital mode of transportation in South Sumatra. The Musi River is a vital waterway for daily commutes and commerce, though boat accidents are a concern [1] [2]. Traditional boats, such as the Jukung and the Ketek, have evolved into critical modes of transportation in a geographical setting characterized by vast rivers and waters. They facilitate travel for residents of isolated places by connecting various points along these waterways. Large boats, with their large hulls and flat bottoms, are handy for exploring areas that are difficult for land vehicles to reach, such as isolated rural locations [3]. On the other hand, their width allows them to carry more passengers on longer trips. Due to their significant contribution to South Sumatra's economic activity and population mobility, these boats are an essential component of daily life, serving as a means of transportation for agricultural products and a tool for fostering social cohesion among various communities [4].

Recent research suggests that river transportation is hazardous, particularly for traditional boats. On Indonesia's Musi River, adverse weather conditions, natural barriers, and human errors are the leading causes of accidents. Stability issues, particularly with modified double-deckers, are the primary cause of boat accidents [5]. Accidents involving river transportation are mainly caused by human causes, such as inexperienced crews [6]. According to data from the South Sumatra Land Transportation Management Centre (BPTD), stability problems were the leading cause of 43 incidents on the Musi River between 2019 and 2024, with 13 of these incidents involving conventional passenger boats. These incidents, which encompass capsizing, sinking, and grounding, result from internal and external factors, including inclement weather, waves from larger ships, and excessive overloading that compromises stability [7]. The consequences include cargo loss, vessel damage, and fatalities. As a result, it is imperative to improve boat safety, such as monitoring the weather and ensuring that the cargoes are within their capacity, to reduce the probability of catastrophes [8].

Numerous previous studies have confirmed the usefulness and safety of traditional boats when assessing their capacity and stability, two critical components of boat operations on the water [9]. The purpose of evaluating the carrying capacities of conventional boats is to determine their maximum allowable weight, ensure the safety and comfort of passengers, and ensure that they can function efficiently while providing a safe and enjoyable experience for users [5] [10]. M. M. Kandelous and P. Ghadimi investigate the influence of weight distribution, loads, and the height of the centre of gravity on the boat's ability to balance in the water [11]. M. Moshref-Javadi and M. Gandomkar emphasize in this study the need to understand how weight distribution and centre of gravity location interact with the boat's dynamic stability, especially when the ship carries fluctuating loads [12]. These factors can significantly impact the boat's performance and safety. Because water conditions can change and directly affect the stability of vessels, a thorough understanding of these aspects is crucial for both boat design and construction, as well as for safe and effective field operations. Jiang has introduced a numerical methodology for conducting ship stability analysis, which is applied in this paper [13]. There has been no research in Indonesia addressing the stability of traditional vessels under 24 meters in length under various loading conditions, making this a research gap that needs to be filled. These boats are common in coastal and inland areas but do not have clear and standard rules for checking stability, even though they are important for local transport and fishing. Studying stability specifically for boats under 24 meters, especially how different loads affect them, would give better information about their safety. This research is necessary to establish safety rules and design guidelines that ensure these small boats remain stable and prevent accidents caused by overloading or imbalance. Filling this gap helps us understand how loading affects stability and protects the people and goods on these boats.

This study aims to assess the survivability level of intact stability in traditional passenger boats on the Musi River. The research explicitly discusses the comparison of stability criteria between the vessel's rolling moment due to turning and the number of passengers as loads, as well as the vertical center of gravity criterion MG. The results of the study present the stability conditions for each load case at full passenger, 80% passenger, 60% passenger, and 40% passenger. Furthermore, a discussion is conducted to compare the two types of boats: the Jukung and the Ketek boats. This research is expected to establish safe load capacity limits, thereby reducing the likelihood of accidents caused by overloading. The study's benefits include providing boat operators and relevant authorities with practical guidance on regulating passenger load capacities, promoting safety during navigation, and increasing public comfort and confidence in local river transportation.

2. Method

The flowchart aims to provide a comprehensive and organized overview of the research process, from the preliminary to the concluding phase. The research query formation is the initial step in the flowchart, as it establishes the basis for the investigation. The next step is to conduct a thorough literature review to identify deficiencies in the current body of knowledge and refine the research objectives. Figure 1, a flowchart, illustrates the sequence of work for this investigation.

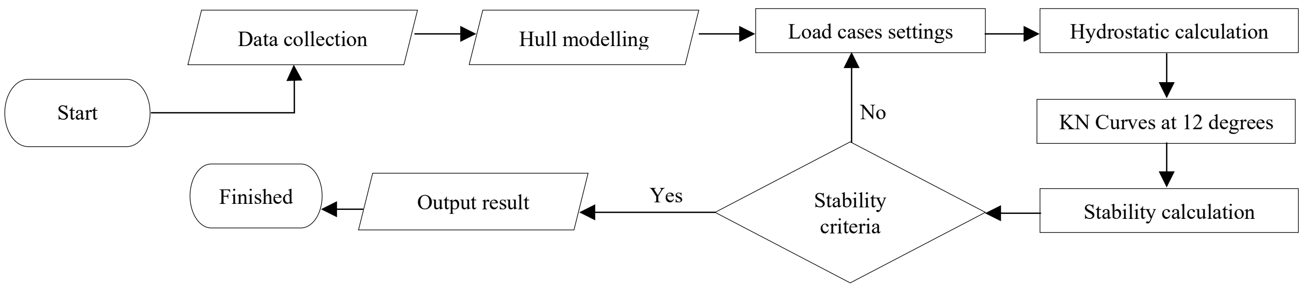

Figure 1. Methodology framework

The research commences with a preparatory phase that involves identifying the objectives and scope of the study. Consequently, surveys are being conducted at various locations in South Sumatra to gather pertinent information about the aquatic ecology and traditional vessels. Subsequently, the data is processed by modelling the hulls of the vessels and containers on the boats to understand their physical characteristics. Hydrostatic calculations be performed to determine the forces acting below the waterline. The modelling process organizes load cases, encompassing a variety of operational scenarios that the vessels may encounter. The KN curve at a heel angle of 12is calculated for use in open deck ship stability calculations. Then, stability calculations are conducted for each load case to assess the boats' efficacy under various conditions. The stability is calculated using a numerical panel method, where the hull below the waterline is divided into small panels to compute the volume and centre of gravity, followed by the calculation of the stability arm [14]. Then, the stability criteria are assessed to confirm that all necessary parameters are satisfied, including the righting moment (M_{GZ}) at 12°, and the heeling moments (M_{KR}) due to turning and passenger movement, in accordance with the Rules for Small Vessels up to 24 m – Section 5C.1.2.1.1 established by Biro Klasifikasi Indonesia (BKI) [15], as well as the GM_0 value specified by the 2008 Intact Stability Code of the International Maritime Organization (IMO) [16]. The process reverts to the load case arrangement stage if the stability criteria are not met, allowing for the necessary adjustments to be made. However, when the stability criteria are satisfied, the research is considered complete, indicating that the traditional boat has undergone testing and is ready for safe operation.

2.1. Boats Data

The subject boats of this investigation are a Jukung and a Ketek boat type that operates in the Musi River, South Sumatra. The selection of these two boat types was based on their substantial role as traditional modes of transportation extensively used by the local community. The line plans of the vessels operating in these waters were redrawn to obtain data for analysis. Furthermore, the fundamental dimensions of the vessels, such as overall length, beam, and hull depth, were recorded. This data lays the groundwork for future research on the operational features, stability, and capacity of conventional vessels in the Musi River. The data obtained from the field survey was collected in coordination with officers of the river officer in the Musi River, Palembang. The selection of ship samples in this study is based on their involvement in a study conducted by the Ministry of Transportation of the Republic of Indonesia. The study aims to accelerate and simplify the ship stability inspection process for small traditional vessels. The use of these samples is expected to support the development of a more efficient and easily implemented ship stability inspection method in the field, without compromising compliance with established maritime safety standards.

Table 1. Main Dimensions of the Boats

Dimension	Symbol	Unit	Type of boat	
			Jukung	Ketek
Length	L	meter	14.0	14.0
Breadth	B	meter	2.5	2.5
Height	H	meter	1.1	0.8
Draft	T	meter	0.7	0.5

A Jukung and a Ketek are two traditional vessels, with their primary dimensions illustrated in Table 1. This table shows the length, Width, Height, and draft of both boats. Jukung is 14.0 m in length, 2.5 m in Breadth, 1.1 m in height, and has a draft of 0.7 m, while Ketek is 14.0 m in length, 2.5 m in Breadth, 0.8 m in height, and has a draft of 0.5 m. These size differences reflect the operational characteristics and functions of the two boats used as research objects. Data on the size of the boats obtained from the operational location indicates the number of boats in those waters. This size information provides essential insights into the characteristics of traditional boats on the Musi River, tailored to operational needs and local water conditions.

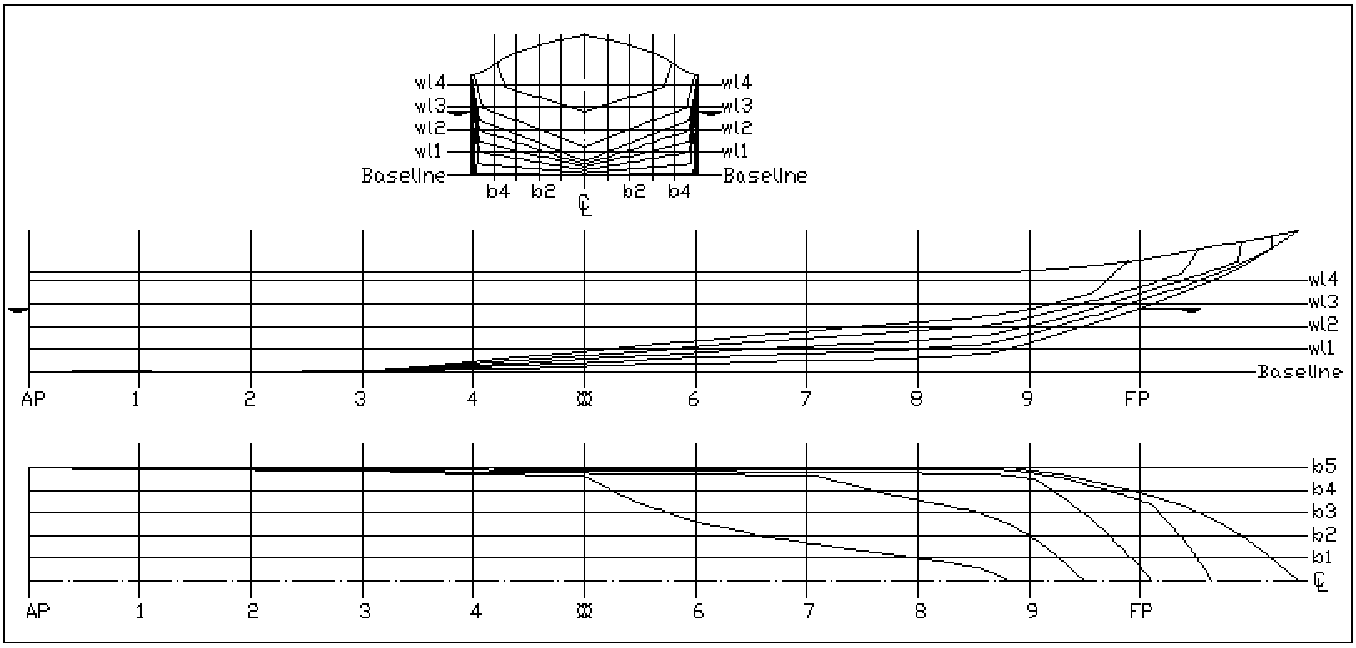

Figure 2. Lines plan of the Jukung

As illustrated in Figure 2, the Jukung is distinguished by a pointed superstructure at the front and a flat bottom. This vessel is designed with a modest draft, making it particularly well-suited for use in shallow waters, such as rivers, where water depths are frequently restricted. This design enables the Jukung to travel with exceptional mobility, even when transporting substantial cargo, and to travel steadily and efficiently. The pointed U-hull design of the canoe enables more efficient navigation through the water, thereby reducing resistance and increasing speed. The boat's flat bottom also provides supplementary stability, reducing the probability of capsizing in adverse weather conditions.

One of the numerous applications of a Jukung is transporting products and individuals. Due to their practical design, they are an exceptional option for examining challenging rivers. Figure 3 illustrates the hull shape of a Ketek boat, which is distinguished by its rounded shape and the V tapering of both extremities. The Ketek boat can operate reliably in adverse weather conditions due to the design's ability to maintain stability in various water conditions. Due to their slightly higher draft, boats are more adept at traversing slightly deeper waters or minor swells than a Jukung. The convex hull shape improves the boat's durability, ensuring the load is distributed uniformly. This design serves as an illustration of the operational and functional distinctions that exist between these two categories of traditional vessels. Ketek boats are being used more frequently to transport passengers and merchandise in larger bodies of water.

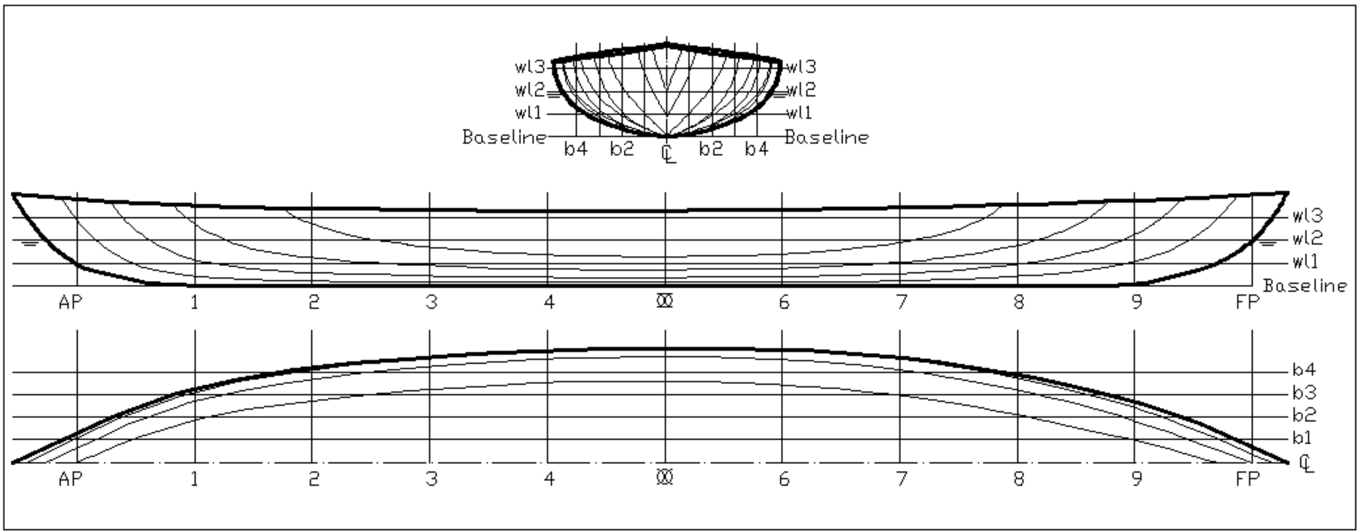

Figure 3. Lines plan of the Ketek

2.2. Minimum Passenger Area

These limits serve as an essential reference to ensure that the boats have a capacity that meets safety and comfort standards for passengers. Table 2 shows the minimum area limits used to determine the number of passengers on traditional boats: a Jukung and a Ketek. The characteristics and functions of these traditional vessels are incorporated into SNI 10-4834-1998 [17]. This minimum area was selected because the criteria for conventional vessels, which are the focus of this study, are likely to be consistent with these provisions. This standard enables the boat to maintain stability while accurately calculating its passenger capacity. This is crucial because of the distinctive design features of boats, including Keteks, which are typically more expansive, and a Jukung, which has a long and narrow vessel shape. Consequently, it is imperative to employ prudence when estimating the passenger capacity of these vessels.

Table 2. Minimum Passenger Area

Position	Duration of Voyage	Minimum Deck Area Per Passenger
Weather Deck (only during good weather season)	≤ 24 hours	0.74 m²
	24 ≤ hours ≤ 72	1.12 m²
Upper Deck	≤ 24 hours	0.74 m²
	24 ≤ hours ≤ 72	1.12 m²
Middle Deck	≤ 24 hours	0.88 m²
	24 ≤ hours ≤ 72	1.12 m²
Lower Deck	≤ 24 hours	0.88 m²
	24 ≤ hours ≤ 72	1.40 m²

Jukung and Ketek are traditional boats with no upper deck; thus, they are only equipped with a middle deck that allows passengers to enjoy the surrounding views while sailing. These boats are generally designed for relatively short journeys, such as river crossings or explorations along the riverbanks, with travel times typically less than 24 hours. This moment presents the optimal application of Jukung and Ketek for local transportation, where speed and efficiency are crucial. Therefore, the minimum area allocated for each passenger is 0.74 m², which is considered adequate according to the criteria set for the duration of these boat trips. With this sufficient space allocation, passengers are comfortable during these short journeys. It is also noted that the first line in Table 2 above provides further relevant information regarding the specifications and capacities of these boats.

2.3. Setting Load Cases

The boat that sails between riverbanks has a main load derived from the number of passengers, not from fuel consumption. Therefore, this paper uses several loading scenarios that align with the vessel's operating conditions, namely when fully occupied 100%, 80%, 60%, and 40% of maximum passengers. In calculating load cases in Table 3, several variables need to be considered, including boat weight, the boat′ s centre of gravity, the number of passengers, and the cargo weight. Light Weight Ton (LWT) and Dead Weight Ton (DWT) are calculated assuming the Boat is in full draft condition [18]. In this case, variations in length and width for each hull model result in different boat weights, as dictated by their respective designs. The number of passengers is determined based on the minimum standard area per boat. With this Area, the Boat′ s deck is plotted into a grid for each model and size, allowing for a systematic determination of the maximum number of passengers that can be accommodated.

Table 3. Load Cases

Loadcase	Jukung (v=5 knots)			Ketek (v=5 knots)		
	n (passegers)	LWT and DWT (tons)	KG (m)	n (passegers)	LWT and DWT (tons)	KG (m)
Full passager	16	15.06	0.787	22	7.316	0.763
80% passenger	13	11.15	0.782	17	5.174	0.748
60% passenger	10	7.53	0.773	11	3.263	0.718
40% passenger	7	4.335	0.754	6	1.664	0.639

Additionally, the analysis of the lightship weight, additional components, and the distribution of passengers and cargo, which are predetermined, is used to determine the boat' s centre of gravity [19] [20]. The centre of gravity directly influences the boat' s equilibrium and stability, which is why this calculation is important. The structural characteristics of both boat models can be easily compared using the vertical centre of gravity (KG) in Table 3. The stability and compliance of conventional vessels with operational safety norms can only be assessed using this data. Boat designers and operators must understand the KG to assess the vessel' s ability to remain upright in various conditions, ensuring passenger safety and operational efficiency. Jukung carries fewer passengers but has a greater total weight compared to Ketek. At full load, Jukung weighs 15.06 tons with a KG of 0.787 m, while Ketek weighs 7.316 tons with a KG of 0.763 m. The reduction in passengers decreases both weight and KG, with a more significant decrease observed in Ketek (to 0.639 m). Ketek exhibits greater stability due to its lower centre of gravity, whereas Jukung is heavier with a higher centre of gravity.

2.4. Stability Criteria

Upon determining the total centre of gravity of the boat with the initial number of occupants, the subsequent step is to calculate the GZ value (stability arm distance) using specific equations at a heel angle of 12°. Eq. 1 and Eq. 2 are employed to calculate the initial equilibrium moment by multiplying the GZ calculation result by the boat' s total weight [16] [14]. Subsequently, the stability moment value is verified by comparing it to the criterion moment value, which is determined by employing the formula specified in Eq. 3 and Eq. 4 [15]. The number of passengers is reduced as a new input to conduct an iteration if the calculation results indicate that the boat' s stability moment exceeds the criterion moment value. The objective of this decrease in the number of occupants is to lower the boat' s centre of gravity, thereby increasing the GZ value and achieving the criterion moment.

$$GZ_{at\ 12^o} = KN_{at\ 12^o} - KG.\sin\theta \tag{1}$$

$$M_{GZ} = \Delta.GZ_{at\ 12^o} \tag{2}$$

$$M_{KR} = 0.25\Delta\frac{v^2}{L}(0.7H - 0.5T) + n(0.2B + 0.1) \tag{3}$$

$$M_{GZ} \geq M_{KR} \rightarrow criteria\ passed \tag{4}$$

$$GM_0 = MB + KB - KG \tag{5}$$

$$MG_0 \geq 0.15\ m \rightarrow criteria\ passed \tag{6}$$

Where M_{GZ} is the stability moment arm of the boat, in ton-meters (ton.m), Δ is the displacement of the boat in tons (t), and GZ is the stability arm at 12°, in meters (m). KN is the form stability lever, the distance from the keel to the buoyancy centre in meters (m). KG is the vertical distance from the keel to the centre of gravity in meters (m). M_{KR} is the heeling moment expressed in ton-meters (ton.m), caused by the combined effects of turning and passenger movement. L, B, H, and T are the boat' s Length, width, Height, and Draft, respectively, measured in meters (m). n is the number of passengers onboard, expressed in persons. This iterative process is carried out by gradually reducing the number of passengers until a stability moment value is achieved that meets the MGZ ≥ MKR requirement according to the safety criteria, based on the Regulations for Small Vessels up to 24 m – Part 5C.1.2.1.1 established by the Biro Klasifikasi Indonesia (BKI) [15]. The MG_0 value itself is obtained from the sum of the distance between the metacentre and the centre of buoyancy (MB) and the distance between the keel and the centre of buoyancy (KB), which is then reduced by the distance between the keel and the centre of gravity (KG). Additionally, the supplementary stability criterion requires $MG_0 \geq 0.15$ m in accordance with the intact stability code 2008 set by the International Maritime Organization (IMO) [16]. Systematic load adjustment ensures that the boat achieves stable conditions for safe operations. This method is crucial for maintaining the vessel' s balance and safety, thereby preventing all possible risks associated with instability during operation.

3. Results and Discussion

3.1. Boats Hydrostatic

In this section, a comparison of hydrostatic calculations is conducted between the Jukung boat and the Ketek across four variations of the vessel's load cases, namely full passenger, 80% passenger, 60% passenger, and 40% passenger. The hydrostatic data compared include the displacement (Δ), block coefficient (Cb), the longitudinal centre of buoyancy (LCB), the distance from the keel to buoyancy (KB), and the metacentre to buoyancy (BM). The calculation results are then presented in Table 4. The evaluation of these hydrostatic parameters is essential for assessing the vessels' performance and safety under different loading conditions. By comparing the Jukung and Ketek, the analysis reveals how each boat's hull form and design characteristics influence its stability, buoyancy, and overall seaworthiness. In particular, values such as the KB, and BM provide important insights into the ship stability of the vessels. These findings form the basis for further discussion on the suitability and operational advantages of each vessel type, as elaborated in the subsequent sections.

Table 4. Hydrostatic Data

Loadcase	Jukung					Ketek				
	Δ (tons)	Cb (-)	LCB (m)	KB (m)	BM (m)	Δ (tons)	Cb (-)	LCB (m)	KB (m)	BM (m)
Full passager	15.06	0.684	4.686	0.408	0.906	7.316	0.466	5.224	0.308	0.988
80% passenger	11.15	0.653	4.341	0.322	1.109	5.174	0.449	5.200	0.248	1.100
60% passenger	7.53	0.609	3.918	0.240	1.412	3.263	0.432	5.171	0.188	1.206
40% passenger	4.335	0.548	3.349	0.158	1.998	1.664	0.412	5.137	0.127	1.274

Based on Table 4, the displacement (Δ) of Jukung decreases from 15.06 tons at full load to 4.335 tons at 40% load, with the block coefficient (Cb) reducing from 0.684 to 0.548. The longitudinal centre of buoyancy (LCB) decreases from 4.686 m to 3.340 m, while the vertical centre of buoyancy (KB) shifts from 0.408 m to 0.158 m, and the metacentre to buoyancy (BM) increases from 0.906 m to 1.998 m. For Ketek, Δ decreases from 7.316 tons to 1.664 tons, Cb from 0.466 to 0.412, LCB from 5.224 m to 5.137 m, KB from 0.308 m to 0.127 m, and BM rises from 0.988 m to 1.274 m. Therefore, Jukung is more suitable for responsive load capacity and has better initial stability, while Ketek offers a slimmer hull. The data in Table 3 can be linked to the ship's MG stability criteria according to Eq. 5. The ship's KG value is obtained by referring to Table 3, while the stability criteria follow Eq. 6.

3.2. KN Curves at A Heel Angle of 12°

Figure 4 presented in the graphic illustrates the relationship between displacement and the value of stability KN at a heel angle of 12º, with the horizontal axis (x-axis) representing the amount of displacement and the vertical axis (y-axis) indicating the value of stability KN. In the graph, there are two curves distinguishing the types of vessels: a straight-line curve representing the Jukung boat, while the striped curve represents the Ketek boat. Generally, the stability KN value for both types of vessels decreases as displacement increases, indicating a reduction in vessel stability as the load increases. However, it is specifically observed that the Ketek boat consistently has a higher stability KN value compared to the Jukung boat across the entire range of displacement observed. The KN value for the Jukung ranges from 0.291 meters at low displacement to decreasing to 0.11 meters at high displacement, while the Ketek boat has a higher KN value, ranging from 0.66 meters to 0.27 meters. Thus, it can be concluded that at a heel angle of 12º, the Ketek boat demonstrates a superior level of stability compared to the Jukung boat under all tested displacement conditions.

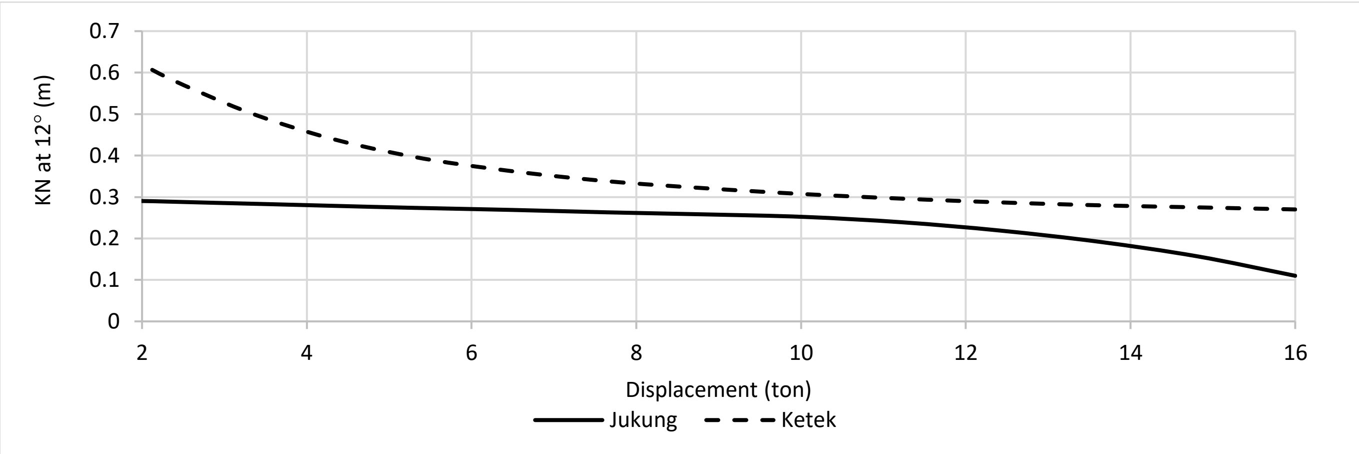

Figure 4. KN Curves at heel angle 12°

3.3. Righting Lever (GZ)

Jukung boats and Ketek boats are open-deck vessels; therefore, the GZ arm criteria apply only up to small angles. Within this angle range, the ship stability assessment is based on the value of the righting moment (M_{GZ}) at a 12° heel, which is required to be greater than the heeling moment (M_{KR}), while also considering the MG_0 value as a secondary criterion to ensure the safety and comfort of the vessel during operation. From the calculation analysis results, significant variations in GZ values were found, where these changes are strongly influenced by the distribution of passenger loads at 100%, 80%, 60%, and 40% of full capacity. In the presented stability curves, the x-axis represents the heel angle, while the y-axis shows the vessel's GZ lever value, covering angles from 0° to 12°. The curves clearly display the development of the GZ lever arm value as the heel angle increases, including the GZ value at a 12° heel, as well as the MG_0 values of the vessel under the tested load conditions. Specifically, Figures 5, 7, 9, and 11 show the stability curves for the Jukung vessel at passenger loads of 100%, 80%, 60%, and 40% full capacity, respectively, while Figures 6, 8, 10, and 12 show the stability curves for the Ketek vessel under the same load conditions. Analysing these curves is crucial for understanding the stability characteristics of both vessel types across various load variations, making it a primary reference for ensuring the safety and performance of the boats during navigation.

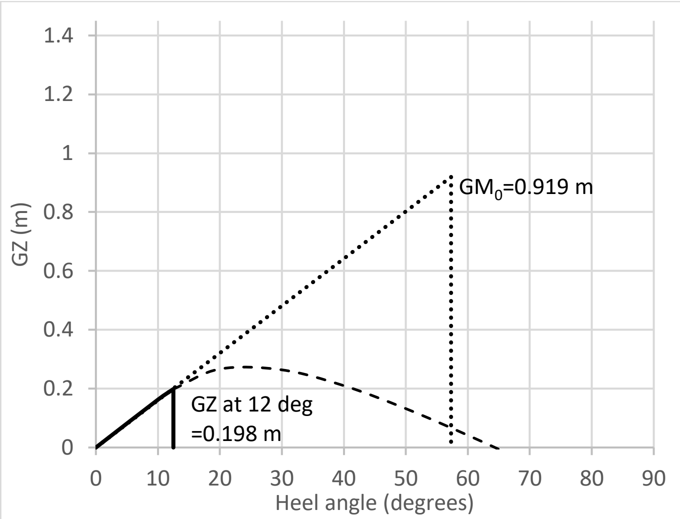

Figure 5. The Jukung at full passenger load

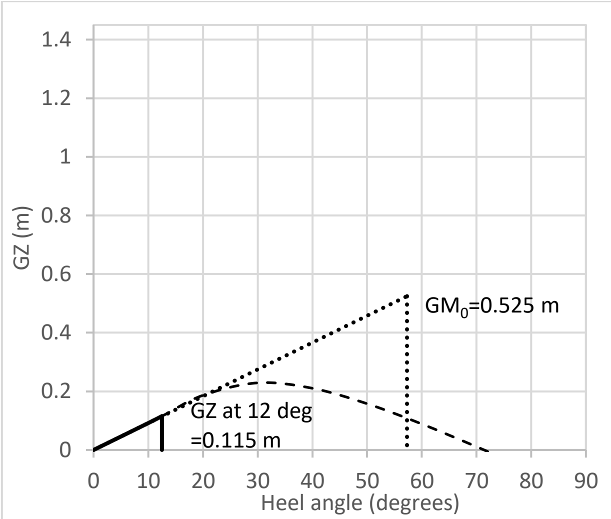

Figure 6. The Ketek at full passenger load

Figures 5 and 6 present the stability curves of the Jukung and Ketek boats, respectively, up to a heel angle of 12°. At this angle, the righting arm (GZ) value for the Jukung boat is 0.198 meters, whereas the Ketek boat has a GZ value of 0.115 meters. This means that the righting arm of the Jukung is approximately 65.7% higher than that of the Ketek, demonstrating significantly better stability under the same conditions. Furthermore, the Jukung vessel has an MG_0 value of 0.919 meters, while the Ketek vessel has an MG_0 value of 0.525 meters. This shows that the MG_0 of the Jukung is approximately 75% higher than that of the Ketek. Both vessels were analysed under full passenger load to represent their maximum operational capacity. This approach ensures that the stability assessment reflects the most critical loading scenario, where the weight and distribution of passengers could substantially impact the boat's balance and safety. By considering the full passenger load, the results provide a realistic evaluation of each vessel's performance under typical, real-world conditions. Based on these findings, it is clear that the Jukung boat demonstrates markedly better stability at an inclination angle of 12°, which is a crucial factor for ensuring passenger safety and vessel operability during normal use.

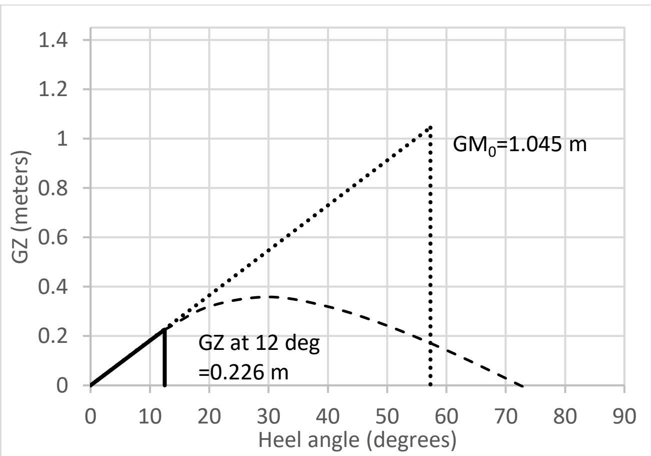

Figure 7. The Jukung at 80% passenger load

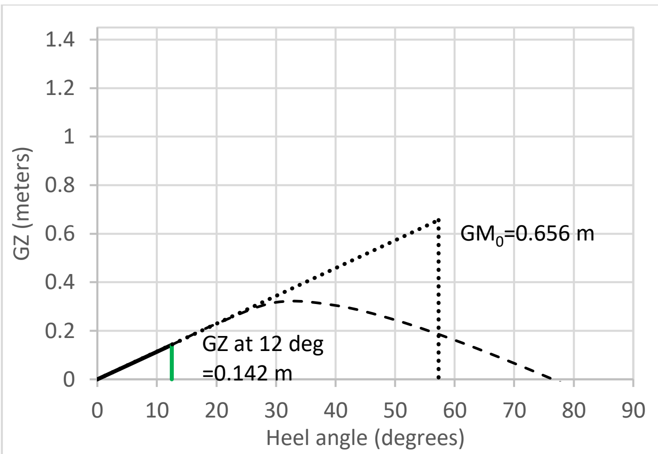

Figure 8. The Ketek at 80% passenger load

Figure 7 shows the righting arm (GZ) height of the Jukung boat at 0.226 meters under an 80% passenger load. In comparison, Figure 8 shows the GZ height of the Ketek boat at 0.142 meters under the same load, indicating that the Jukung boat's GZ arm is approximately 52.11% larger than that of the Ketek boat. This significant difference highlights the superior stability characteristics of the Jukung boat, even when operating below full passenger capacity. Moreover, the Jukung vessel has an MG_0 value of 1.045 meters, which is higher than the MG_0 value of the Ketek vessel, at 0.656 meters. Expressed as a percentage, the MG_0 of the Jukung vessel is significantly higher than that of the Ketek vessel, further reinforcing the observed differences in stability between the two boats.

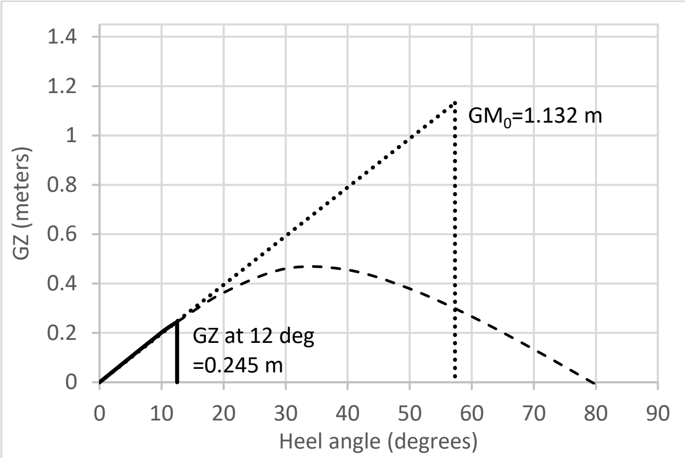

Figure 9. The Jukung at 60% passenger load

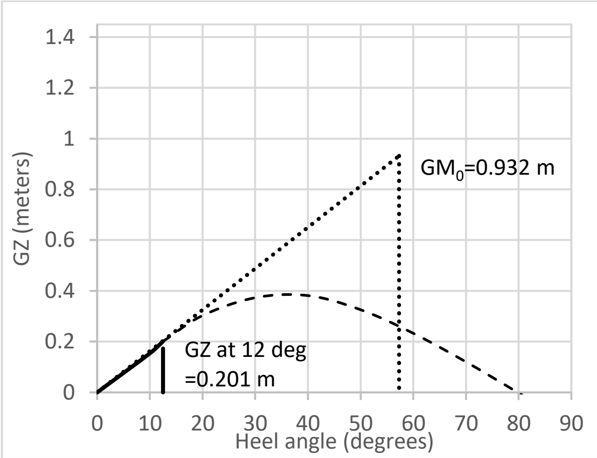

Figure 10. The Ketek at 60% passenger load

Figure 9 shows the righting arm (GZ) height of the Jukung boat at 0.245 meters with a passenger load of 60%, while Figure 10 shows the righting arm (GZ) height of the Ketek boat at 0.201 meters under the same passenger load. This indicates that the Jukung boat's righting arm is approximately 21.9% greater than that of the Ketek boat. Compared to the previous graphs at full load and at 80% passenger load, there is an increase in the GZ curve height at the 60% passenger load condition. The Jukung vessel has an MG value of 1.132 m, which is higher than the MG_0 value of the Ketek vessel at 0.932 m. Expressed as a percentage, the MG_0 value of the Jukung vessel is approximately 21.5% higher than that of the Ketek vessel. This condition indicates an improvement in the stability of both types of boats as passenger load increases.

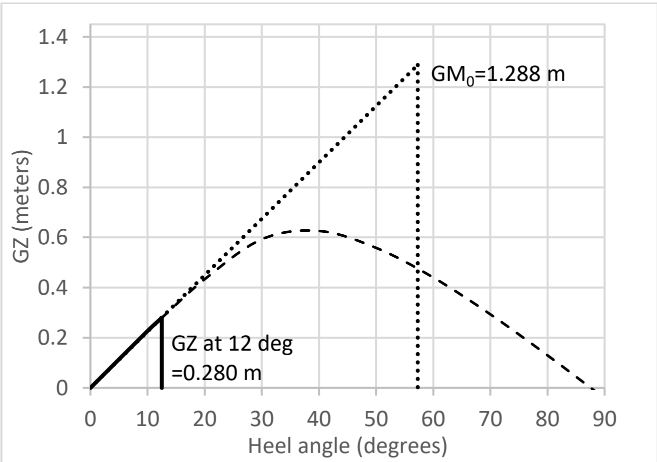

Figure 11. The Jukung at 40% passenger load

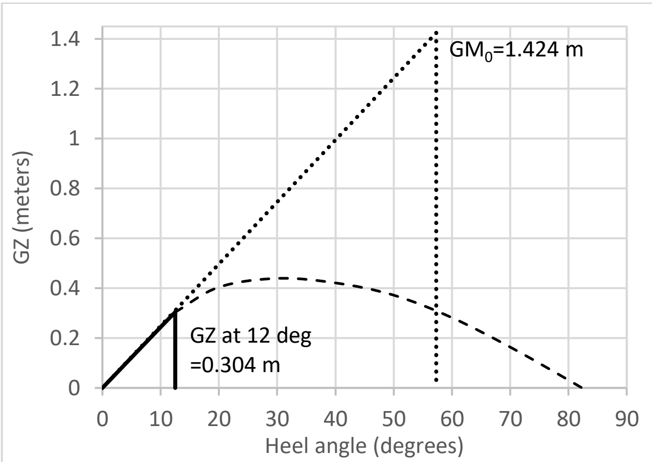

Figure 12. The Ketek at 40% passenger load

Figure 10 shows the righting arm (GZ) height of the Jukung boat at 0.280 meters with a passenger load of 40%, while Figure 11 shows the righting arm (GZ) height of the Ketek boat at 0.304 meters under the same passenger load. This indicates that the Ketek boat's righting arm is approximately 8.6% greater than that of the Jukung boat. The Jukung vessel has an MG_0 value of 1.288 m, which is higher than the MG0 value of the Ketek vessel, which is 1.424 m. Expressed as a percentage, the MG_0 of the Jukung vessel is lower compared to the Ketek vessel.

For the Jukung vessel, graphs 5, 7, 9, and 11 show an increase in the GZ value at a heel angle of 12 degrees, measuring 0.198 m, 0.226 m, 0.245 m, and 0.280 m respectively. This increase is also accompanied by the MG_0 values of the Jukung vessel, with corresponding values of 0.919 m, 1.045 m, 1.132 m, and 1.288 m. Meanwhile, for the Ketek vessel, graphs 6, 8, 10, and 12 also show an increase in GZ at a heel angle of 12 degrees with values of 0.115 m, 0.142 m, 0.201 m, and 0.304 m respectively. The same increase occurs in the MG_0 values for the Ketek vessel, which are 0.525 m, 0.656 m, 1.932 m, and 1.424 m. The increase in GZ and MG_0 values in each of these graphs indicates changes in stability for both the Jukung and Ketek vessels, observable through these two main parameters: the righting arm (GZ) and metacentric height (MG_0).

3.4. Comparison of Survival Boat Stability

This section presents the values of the stability moment M_{KR} for the Jukung and Ketek boats under various load case conditions, along with the margin difference in percentage, as shown in Table 5. According to stability principles, the stable moment should be greater than the moment of stability criteria for stable and safe operation on board. A positive margin percentage indicates good stability conditions. A negative margin indicates that the stability moment does not satisfy the stability criteria. In ship stability analysis, the M_{GZ} can be calculated according to Eq. 1, and the turning moment plus passenger moment can be calculated according to Eq. 3. After calculating both moments, M_{GZ} and M_{KR}, their comparative values are done. If M_{GZ} is greater than M_{KR}, the stability criteria of the ship are satisfied; hence, the vessel can be considered stable. Therefore, this comparison becomes important for determining the safety and performance characteristics of the ship while operating in watery regions. Additionally, Table 5 also shows the difference in MG_0 values between the Jukung and Ketek boats, which represents the initial value of the transverse stability moment when the heel angle is still very small. This MG_0 value is important to indicate the initial ability of the boat to return to an equilibrium position after experiencing minor external disturbances, where this MG_0 criterion is calculated using Eq. 6.

Table 5. Comparison of stability moments

Loadcase	Jukung (v=5 knots)				Ketek (v=5 knots)			
	M_{GZ} (ton.m)	M_{KR} (ton.m)	Difference (%)	Status	M_{GZ} (ton.m)	M_{KR} (ton.m)	Difference (%)	Status
Full passager	21.991	10.346	95	Pass	14.047	13.649	3	Pass
80% passenger	19.013	8.444	142	Pass	11.072	10.548	5	Pass
60% passenger	16.308	6.497	199	Pass	7.798	6.839	14	Pass
40% passenger	13.764	4.522	238	Pass	4.509	3.731	21	Pass
Loadcase	**GM_0 (m)**	**Criteria (m)**	**Difference (%)**	**Status**	**GM_0 (m)**	**Criteria (m)**	**Difference (%)**	**Status**
Full passager	0.191	0.15	27	Pass	0.115	0.15	-23	Fail
80% passenger	0.217	0.15	45	Pass	0.142	0.15	-5	Fail
60% passenger	0.235	0.15	57	Pass	0.201	0.15	34	Pass
40% passenger	0.267	0.15	78	Pass	0.304	0.15	102	Pass

Table 5 presents a comparison between the stability moment (M_{GZ}) and the heeling moment caused by turning motion and passenger load (M_{KR}) for two types of boats, namely the Jukung boat and the Ketek boat, under various passenger load conditions. M_{KR} refers to the moment when the boat heels due to turning movements and the effect on passengers. For the Jukung boat at full passenger load, the maximum gross torque (M_{GZ}) is 21.991 ton.m, which is 95% greater than the minimum gross torque (M_{KR}) of 10.346 ton.m, indicating that the Boat is stable. When the load decreases to 80% passenger capacity, the M_{GZ} drops to 19.013 ton.m but remains 142% higher than the M_{KR} of 8.444 ton.m. At 60% passenger load, the M_{GZ} of 16.308 ton.m is still 199% greater than the M_{KR} of 6.497 ton.m. At the lowest load condition of 40% passengers, the MGZ of 13.764 ton.m remains 238% higher than the M_{KR} of 4.522 ton.m, demonstrating an increasing stability margin as the load decreases. Similarly, the Ketek boat also exhibits adequate stability under all load conditions. At full load, the M_{GZ} of 14.047 ton.m is only 3% greater than the M_{KR} of 13.649 ton.m. At 80% passenger load, the M_{GZ} of 11.072 ton.m exceeds the M_{KR} of 10.548 ton.m by 5%. At 60% load, the M_{GZ} of 7.799 ton.m remains 14% higher than the Mkr of 6.839 ton.m. At 40% passenger load, the M_{GZ} of 4.509 ton.m is 21% higher than the M_{KR} of 3.731 ton.m. This data shows that both boats consistently have a stability moment (M_{GZ}) greater than the heeling moment (M_{KR}), indicating overall stability.

Based on calculations, the Jukung boat meets all stability requirements under all loading conditions because its GM_0 value is always higher than the minimum standard of 0.15 meters. When the boat is fully loaded with passengers, the value is 0.191 m (27% higher than the standard), and when only 40% of the passengers remain, it increases to 0.267 m (78% higher than the standard). In contrast, the Ketek boat fails to meet the requirements when fully loaded with passengers (GM_0 value is only 0.115 ton.m, 23% below the standard) and at 80% passenger capacity (0.142 ton.m, 5% below the standard). The Ketek boat only passes the stability test when the passenger load decreases to 60% (GM_0 value: 0.201 ton.m, 34% above the standard) or even 40% (0.304 ton.m, 102% above the standard). In conclusion, the Jukung is safer to use under all conditions, while the Ketek is only safe when carrying a maximum of 60% of its passenger capacity. However, the Jukung boat has a larger stability margin compared to the Ketek boat at all load levels. This difference is related to the hull shape of the two boats. The Jukung boat's U hull is relatively flat from top to bottom, whereas the Ketek boat has a V-shaped hull that widens toward the top. The flatter hull shape of the Jukung boat results in a larger righting arm (M_{GZ}) compared to the V-shaped hull of the Ketek boat. Therefore, the Jukung boat's hull design contributes to a higher stability level and a wider stability margin than the Ketek boat.

4. Conclusion

This study provides valuable insights into the stability of riverboats on the Musi River by closely examining the shapes of the Jukung and Ketek boats. Although both boats have nearly the same size, the Jukung has a larger displacement due to its relatively flat hull shape, which extends from top to bottom. Reductions in passenger load from full load to 80%, 60%, and 40% lower the vessel's centre of gravity and increase the height of the stability arm for both boats. Both the Jukung and Ketek meet the stability arm criteria under all these loading conditions; however, the Jukung consistently exhibits a higher stability moment (MGZ), which increases as the load decreases.

At full passenger load, the difference in the stability margin (MGZ ≥ MKR) is 95% for the Jukung versus only 3% for the Ketek. This difference grows substantially as the load decreases: at 80% load, 142% versus 5%; at 60%, 199% versus 14%; and at 40%, 238% versus 21%, respectively. These results confirm that both boats maintain overall stability with MGZ values greater than MKR, indicating resistance against capsizing. Regarding the initial metacentric height (GM_0), the Jukung consistently meets stability standards, with a GM_0 of 0.191 m at full load (27% above the standard) and 0.267 m at 40% load (78% above the standard). In contrast, the Ketek fails to meet the stability requirement at full load (0.115 m, 23% below the standard) and at 80% load (0.142 m, 5% below the standard), only achieving safe stability at 60% load (0.201 m, 34% above the standard) or less.

In conclusion, the Jukung is more stable and safer compared to the Ketek across all passengers loading conditions due to its hull design and favourable GM_0 values. The Ketek's lower stability, especially under full load conditions, suggests it should not be operated at maximum passenger capacity to ensure safety. This difference in stability performance is related to the hull shapes: the flat U hull of the Jukung results in larger MGZ and GM_0 than the V-shaped hull of the Ketek. Therefore, the hull design of the Jukung contributes to a higher level of stability and a wider stability margin compared to the Ketek. Further research can be developed for similar traditional boats with various size variations to facilitate the examination of the ship's stability.

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