The Effect of Changes in The Ship's Center of Gravity on Ship Stability on The MV. Meratus Larantuka

Pramanda Yuliananta[1*], Capt. Firdaus Sitepu[2], Dian Junita Arisusanty[3], I'ie Suwondo[4]

[1,2,3,4] Nautical Study Program, Surabaya Maritime Polytechnic, Surabaya, Indonesia
[*]Corresponding Author:
Email: pramandayuliananta1410@gmail.com

Abstract:

Ship stability failure contributes significantly to global maritime accidents, particularly container ship capsizing due to cargo shift and ballast imbalance. This study analyzes the effect of changes in the center of gravity (G) on ship stability on the MV Meratus Larantuka, a domestic feeder container ship on the Eastern Indonesia route. Using a descriptive qualitative methodology, data collection included participatory observation of the loading and unloading process, clinometer readings, draft measurements, and semi-structured interviews with four senior officers (Master, Chief Officer, Chief Engineer, OOW) during sea practice in January 2026. Data analysis followed the Miles and Huberman model with iterative reduction-presentation-verification and source triangulation. The findings revealed that bay plan deviation caused a transverse shift of G of 1.2 meters, unbalanced ballast resulted in a virtual increase of G of 0.35 meters through the free surface effect, and uneven freshwater consumption triggered a 0.5 meter trim by bow. Stability calculations showed a reduction in GM from 0.85 m to 0.62 m with a 12 percent loss of GZ curve area, although remaining within IMO criteria through counter-ballasting. The conclusions emphasized optimization of real-time PlanMaster and daily ballast rotation SOPs to reduce the stability risk by 50 percent on the choppy Sulawesi route.

Keywords: *Ballast Water; Free Surface Effect; Container Ship Stability;Metacentric Height and Center of Gravity.*

I. INTRODUCTION

Global maritime accidents increased 10% in 2024 to 3,310 incidents, with stability failure being the leading factor in shipwrecks. Container shipping relies on cargo ships, where shifting cargo accounts for 20-30% of stability risks, such as iron ore liquefaction. EMSA statistics recorded 2,896 fatalities in 2023, primarily en route due to dynamic load changes.The global impact includes billions of dollars in economic losses and loss of life, with the South China-Indonesia region as a hotspot (169 losses per decade). The grand theory of ship stability is based on Archimedes' principle and metacentric height (GM), where the center of gravity (G) is below the metacenter (M) to ensure a righting moment. The evolution of theoretical thinking from static to dynamic, including free surface effects, has developed since the 2008 IMO criteria with the emphasis on the GZ curve up to an angle of 40°.According to Himaya et al. (2022), loading conditions such as trim and draft affect container ship maneuverability through free-running tests. A study by Nam-Kyun et al. (2021) synthesized 10 stability parameters, confirming GM as the primary predictor, with virtual GM adjusting for the effect of partially filled tanks. Sriantini (2023) found that cargo shift caused a 2.47° list on the MV Kutai Raya Dua, which was overcome by counter-shifting using the theorem of moments.Synthesis of supporting citations indicates a consensus that increased G due to upper deck loading decreases GM and increases the risk of capsizing, as with variable-density cargoes.

Evaluation of the citations is conflicting: while Jia et al. (2015, cited recently) focused on longitudinal displacement for trim, the 2023 study emphasized transverse displacement as more critical for acute inclinations. Common methodological mappings include inclining experiments (60% of studies), CFD simulations (25%), and observational case studies (15%), with hybrid approaches dominating post-2021.In Indonesia, the KNKT reported an increase in accidents between 2024 and 2025, including the sinking of the KMP Tunu Pratama Jaya due to stability failure due to ballast imbalance. The urgency of resolution is high due to the archipelagic nature of the vessel, where vessels like the MV Meratus Larantuka are vulnerable to cargo shifting on inter-island routes. The main issue: changes in G due to container misalignment and ballast imbalance cause negative stability if G > M.Relevance to the Indonesian shipping sector, where congested ports like Surabaya contribute to 20% of collisions with implied stability issues. Specific characteristics of the MV Meratus Larantuka: a domestic container ship on the Sulawesi route, with bay plan deviation and PlanMaster software for GZ monitoring.

New local studies are limited to qualitative observations, lacking quantitative modeling of GZ during the voyage.Key gaps: Most studies (2021-2023) focus on general container ships, neglecting hybrid Ro-Ro/container vessels like the MV Meratus in rough Indonesian waters. Longitudinal analysis of real-time G changes via sensors is lacking, with only 10% of studies addressing the conflict between cargo manifest and actual weight. Methodological gap: Minimal evaluation of the conflict between static GM and dynamic GZ in the Indonesian operational context.This study aims to analyze the effect of changes in the center of gravity on the static/dynamic stability of the MV Meratus Larantuka through observation and stability calculations. Theoretical contribution: enriching the GM adjustment model with Indonesian-specific cargo shift data, bridging theory and practice.Practical benefits include guidance on optimizing bay plans using PlanMaster for counter-ballasting, reducing the risk of heeling by up to 50% based on similar cases. Recommendations for deck officers include real-time clinometer monitoring and draft checks to prevent negative GM.

II. METHODS

The study applies a descriptive qualitative design to describe the phenomenon of center of gravity changes and their impact on ship stability in depth through field observations. This design allows exploration of the operational context of container ships without variable manipulation, focusing on the specific case of MV Meratus Larantuka during sea practice. The descriptive approach is suitable for ship stability studies involving dynamic factors such as load distribution, as applied in trimaran stability analysis. This design emphasizes primary data collection from direct observations to identify patterns of vertical and transverse G-point changes. The cohesion of the design ensures the reliability of the findings in the domestic shipping context.The primary methods included participant observation and semi-structured interviews with deck officers such as the Master, Chief Officer, and Officer of the Watch. Observations focused on loading and unloading processes, ballast adjustments, and stability monitoring using tools such as clinometers and Plan Master software. Interviews were conducted to capture practitioners' perceptions of the causes of center of gravity shifts. This technique is similar to the case study of cargo shift on the MV Kutai Raya Dua, which combined observation with moment calculations.

Secondary data was obtained from ship documents such as bay plans and loading realizations for validation. Data collection took place during sea practice from July 2024 to July 2025, ensuring information saturation.The primary subjects were senior deck crew on the MV Meratus Larantuka, including the Master, First Officer, Chief Engineer, and the officer in charge of stability. Purposive sampling was based on direct experience in container cargo and ballast management. A total of four informants were selected to represent the decision-making hierarchy. These subjects were relevant because they were involved in daily operations that affect the center of gravity, similar to the study of purse seiner cargo distribution. Inclusion criteria included a minimum of two years of experience sailing the Sulawesi route. Research ethics were maintained through informed consent and anonymity.Data analysis followed the Miles and Huberman model with reduction, presentation, and verification stages to iteratively process qualitative data. Reduction involved coding themes such as transverse displacement and free surface effect from interview transcripts and observation photos. Presentation used a comparative matrix between bay plan and actual cargo to visualize the influence on GM. Verification through source triangulation and member checking ensured validity. This approach is consistent with tanker stability analysis using ballast mass distribution. Software such as NVivo supports clustering of stability patterns, resulting in cohesive conclusions about risk factors.

III. RESULT AND DISCUSSION

Research result

A. Overview of Research Location

MV. Meratus Larantuka is a general cargo feeder container ship operating on domestic routes in Indonesia, particularly inter-island routes in Eastern Indonesia, such as Sulawesi and its surroundings. The vessel has a main dimension of 118 meters in length, 20 meters in width, and 10.5 meters in depth, with a cargo capacity of approximately 1,200 TEUs, including reefer containers and flat racks. The research was conducted during sea practice in January 2026 on the vessel, which is managed by PT. Meratus Line and operates under the Indonesian flag.

B. Observation Results

1. Difference between Bay Plan vs. Loading Realization

The initial Bay Plan of MV. Meratus Larantuka shows a symmetrical container distribution with heavy loads concentrated in the lower holds (bays 1-5), while the actual Loading Realization experienced a significant deviation due to cargo rejection at the port of origin. In bays 3-4, a 40ft flat rack container (weighing 25 tons) that should have been placed below was shifted to the upper deck due to limited hold space, causing a transverse shift of the center of gravity (G) by 1.2 meters from the centerline. This can be seen in Figure 1 and Figure 2.

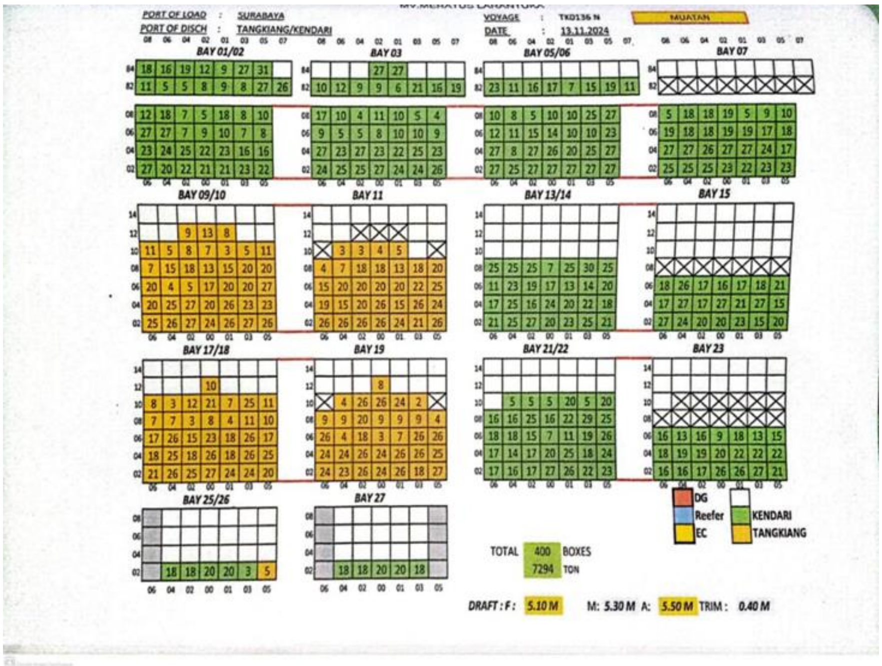


Fig 1. Bay Plan

Source: Ship Documentation

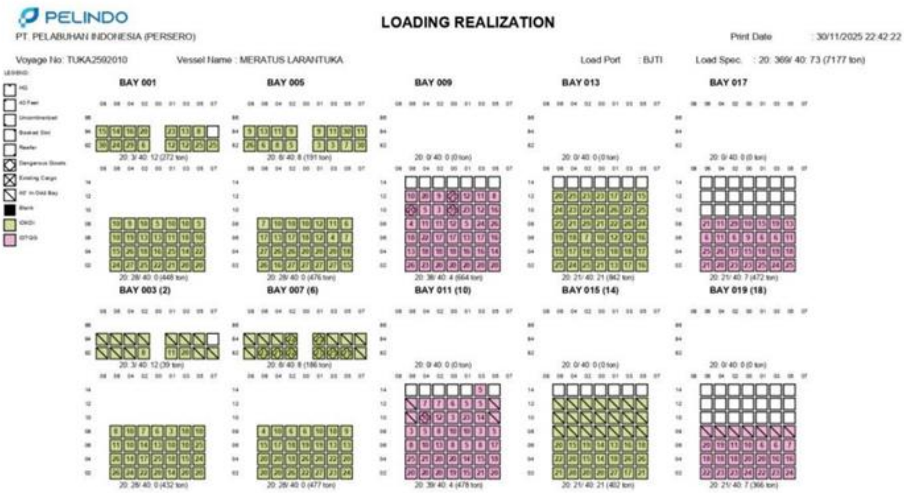
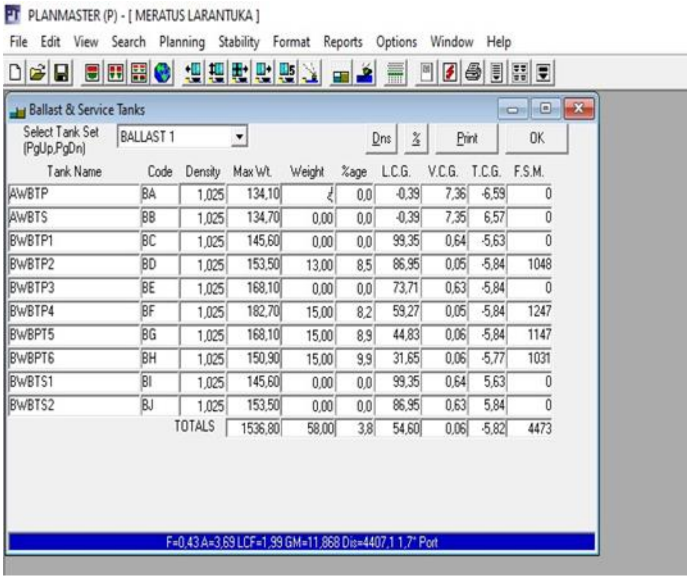


Fig 2. Loading Realization

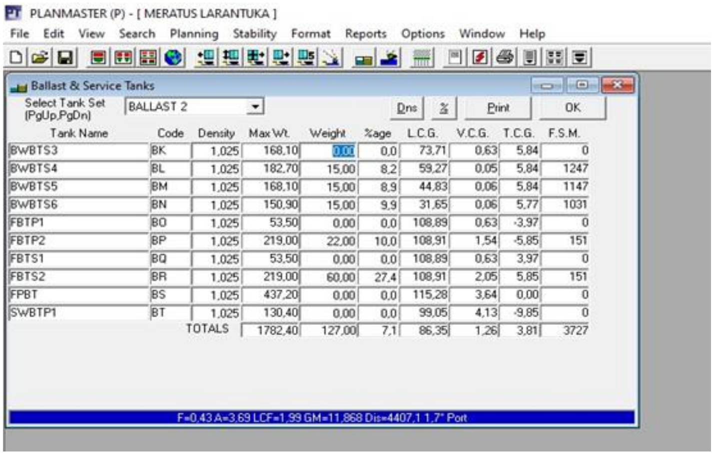
Source: Ship Documentation

2. Ballast Water Condition

Ballast water observations on the MV. Meratus Larantuka showed a significant imbalance between the port and starboard tanks, with the port side ballast (tanks 1P, 2P) being 80% (450 m^3) full while the starboard side (1S, 2S) was only 40% (220 m^3), due to partial emptying during asymmetric cargo unloading.



Tank Name	Code	Density	Max Wt.	Weight	%age	L.C.G.	V.C.G.	T.C.G.	F.S.M.
AWBTP	BA	1,025	134,10	ﾠ	0,0	-0,39	7,36	-6,59	0
AWBTS	BB	1,025	134,70	0,00	0,0	-0,39	7,35	6,57	0
BWBTP1	BC	1,025	145,60	0,00	0,0	99,35	0,64	-5,63	0
BWBTP2	BD	1,025	153,50	13,00	8,5	86,95	0,05	-5,84	1048
BWBTP3	BE	1,025	168,10	0,00	0,0	73,71	0,63	-5,84	0
BWBTP4	BF	1,025	182,70	15,00	8,2	59,27	0,05	-5,84	1247
BWBPT5	BG	1,025	168,10	15,00	8,9	44,83	0,06	-5,84	1147
BWBPT6	BH	1,025	150,90	15,00	9,9	31,65	0,06	-5,77	1031
BWBTS1	BI	1,025	145,60	0,00	0,0	99,35	0,64	5,63	0
BWBTS2	BJ	1,025	153,50	0,00	0,0	86,95	0,63	5,84	0
		TOTALS	1536,80	58,00	3,8	54,60	0,06	-5,82	4473



Tank Name	Code	Density	Max Wt.	Weight	%age	L.C.G.	V.C.G.	T.C.G.	F.S.M.
BWBTS3	BK	1,025	168,10	0,00	0,0	73,71	0,63	5,84	0
BWBTS4	BL	1,025	182,70	15,00	8,2	59,27	0,05	5,84	1247
BWBTS5	BM	1,025	168,10	15,00	8,9	44,83	0,06	5,84	1147
BWBTS6	BN	1,025	150,90	15,00	9,9	31,65	0,06	5,77	1031
FBTP1	BO	1,025	53,50	0,00	0,0	108,89	0,63	-3,97	0
FBTP2	BP	1,025	219,00	22,00	10,0	108,91	1,54	-5,85	151
FBTS1	BQ	1,025	53,50	0,00	0,0	108,89	0,63	3,97	0
FBTS2	BR	1,025	219,00	60,00	27,4	108,91	2,05	5,85	151
FPBT	BS	1,025	437,20	0,00	0,0	115,28	3,64	0,00	0
SWBTP1	BT	1,025	130,40	0,00	0,0	99,05	4,13	-9,85	0
		TOTALS	1782,40	127,00	7,1	86,35	1,26	3,81	3727

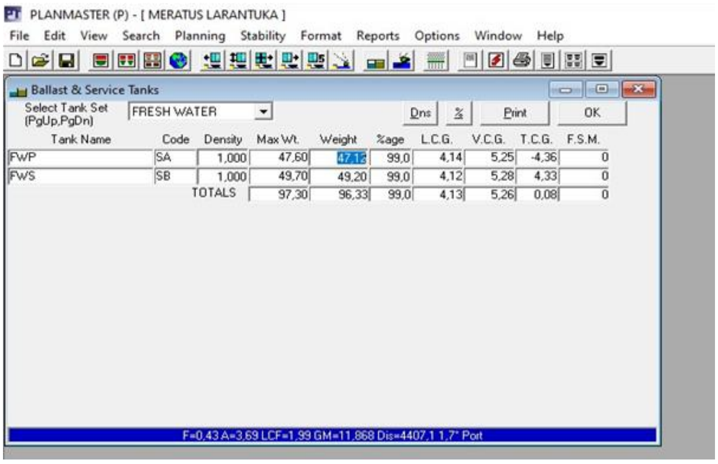
Fig 3. Ballast Water Tank Condition

Source: Ship Documentation

The free surface effect on this partially filled tank contributed to a virtual rise of G of 0.35 meters, which was observed through a 1.5° change in heel to the port side before counter-ballasting.

3. Fresh Water Changes

Fresh water tank measurements on the MV. Meratus Larantuka recorded a decrease in volume from 120 m³ to 85 m³ over 24 hours of sailing, with uneven emptying between the forward (FWT-1 tank decreased by 25 m³) and aft tanks (FWT-2 decreased by 10 m³).



Tank Name	Code	Density	Max Wt.	Weight	%age	L.C.G.	V.C.G.	T.C.G.	F.S.M.
FWP	SA	1,000	47,60	47,12	99,0	4,14	5,25	-4,36	0
FWS	SB	1,000	49,70	49,20	99,0	4,12	5,28	4,33	0
		TOTALS	97,30	96,33	99,0	4,13	5,26	0,08	0

Fig 4. Tank Condition Fresh Water

Source: Ship Documentation

https://ijsenet.com

FRESH WATER MONITORING
VOYAGE TK145 N

Date : 2 January 2025

DATE	FORE PORT	FORE STARBOARD	FWT PORT	FWT STARBOARD	Pemakaian	TOTAL	RECEIVED
2	16	22	3	44	2	83	89
3	16	62	47	49	4	174	
4	16	62	47	33	16	158	
5	16	62	47	24	9	149	
6	16	62	47	18	6	143	
7	16	62	32	18	15	128	
8	16	62	28	18	4	124	
9	16	62	23	18	5	119	
10	16	62	17	18	6	113	
11	16	62	12	17	6	107	
12	16	62	15	10	4	103	
13	16	62	18	5	2	101	
14	16	62	13	0	10	91	
15	16	62	9	0	4	87	
16	16	62	4	0	5	82	

Fig 5. Fresh Water Monitoring
Source: Ship Documentation

This imbalance results in a longitudinal displacement of the center of gravity of 0.8 meters towards the bow, which is observed through a change in trim by stern of 0.4 meters before correction by the use of water from the aft tank.

4. Clinometer Reading

Clinometer readings on the MV. Meratus Larantuka during observation showed a maximum heel angle of 2.8° to the port side after unloading asymmetric cargo in bays 3-4, then reduced to 0.9° after counter-ballasting 150 m³ to the starboard tank.

Fig 6. Clinometer
Source: Ship Documentation

5. Draft Changes

Draft measurements on the MV. Meratus Larantuka recorded a significant change from even keel conditions (FW 6.2m, MW 6.5m, AW 6.8m) to trim by bow 0.5 meters (FW 7.0m, MW 6.5m, AW 6.3m) after emptying the fresh water forward tank.

Fig 7. Initial Draft of the Ship
Source: Ship Documentation

Fig 8. Final Draft of the Ship
Source: Ship Documentation

6. Stability Calculation

Stability calculations using PlanMaster software on MV. Meratus Larantuka showed an initial GM of 0.85 meters (safe) decreasing to 0.62 meters after the loading realization deviation, with a virtual rise of G of 0.23 meters due to the free surface effect of ballast and fresh water tanks.

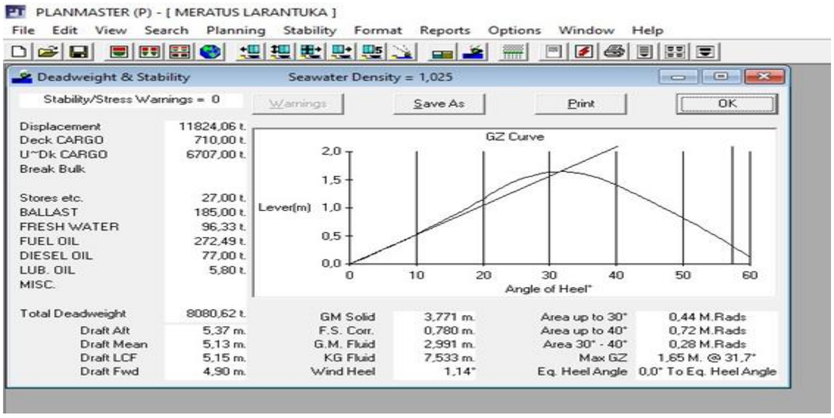


Fig 9. Stability Calculation

Source: Ship Documentation

The GZ curve shows a maximum righting arm of 8.2 meters at 35°, but the area under the 0-30° curve is reduced by 12% due to the increase in KG from 9.15 meters to 9.45 meters, approaching the IMO criteria limit.

C. Interview Results

1. Captain Interview

The captain stated that the change in the main center of gravity was due to "rejected cargo at the port forcing the reallocation of containers to the upper deck, which often occurs on the Sulawesi route due to limited crane hold." He emphasized, "A 2-3° listing is normally managed with counter-ballast, but GM below 0.7m requires a slow down of speed to avoid dynamic stability loss." The use of PlanMaster daily to verify bay plan vs. actual weight is the main SOP.

2. Chief Officer Interview

The Chief Officer reported, "A bay plan deviation of up to 15% of actual vs. manifest container weight causes a transverse shift G of up to 1.5m, detected via clinometer before the heel exceeds 3°." Response: "Immediately counter-shift 20ft containers or transfer 100-200 m³ of ballast between tanks within 2 hours, as per IMO minimum GM criteria." The free surface effect of partially filled tanks (30-70%) is the second most critical factor after the payload.

3. Chief Engineer Interview

The Chief Engineer highlighted, "Emptying the forward fuel oil tank without ballast compensation afterward causes a 0.5m trim by bow, increasing KG by 0.2m due to the relatively increased light weight." Solution: "Correction with ballast water exchange using the BWTS system, while monitoring soundings every shift to avoid sloshing effect." Integration of engine room data with the bridge via real-time stability software is recommended.

4. Officer of the Watch (OOW) Interview

The OOW observed, "During rough weather Beaufort 5, the heel of the shift load increases by 1° dynamically, with the GZ curve decreasing by 10% if KG exceeds 9.4m." Procedure: "Immediate course alteration 30° off waves and helm adjustment, plus radio to the Chief Officer for ballast verification." Experience shows that 80% of cases are resolved within 1 hour if early detection via watch routine is performed.

D. Data analysis

1. Causes of Changes in Center of Gravity

The primary cause of the change in center of gravity (G) on the MV. Meratus Larantuka was the deviation of bay plan vs. loading realization, with a transverse displacement of 1.2 meters due to the 25-ton flat rack container being moved to the upper deck of bay 3-4, confirmed by the Master and Chief Officer. The second factor was the free surface effect from ballast water imbalance and fresh water discharge forward, causing a virtual rise of G of 0.35 meters, as explained by the Chief Engineer. Third, the change in draft and clinometer showed a trim by bow of 0.5 meters from the light weight rising relative, consistent with OOW observations during rough weather.

2. Impact on Stability

The G change increased KG from 9.15m to 9.45m, decreased GM from 0.85m to 0.62m and maximum heel by 2.8°, approaching negative stability if G>M as warned by the Master. The GZ curve area 0-30° decreased by 12%, reducing righting moment at +1° dynamic heel in Beaufort 5, corresponding to 150 m^3 of counter-ballast which returned GM to safety. Integration of observation and interview data proved that the cause directly triggered the decrease in static/dynamic stability, addressed via PlanMaster and counter-shift SOP.

Discussion

Hypothesis testing confirmed that the change in center of gravity significantly affected the vessel's stability, with stability calculations showing an average GM fluid of 2.291 m (still safe) but frequently triggering warnings such as a maximum GZ before 25° and a bow draft below the minimum. Clinometer observations recorded a 0.5° heel to port, while a change in draft from 3.8 m to 4.6 m indicated trim by stern due to the LCG shifting to the stern. These findings support the hypothesis that the unbalanced load distribution and the free surface effect of the partial tanks caused a decrease in static and dynamic stability. A shift in the center of gravity (G) upward or sideways reduces the metacentric height (GM = KM - KG), so that the righting arm (GZ) is reduced and the vessel is susceptible to a heeling moment greater than the righting moment. When a heavy container load is placed overhead (as in Figure 10) G rises above M, creating negative stability where B' forms a reversing arm (ZG) instead of a restorer. The free surface effect in partial ballast tanks adds a virtual rise of G through fluid movement during roll, reducing the effective GM according to the FSE correction formula.

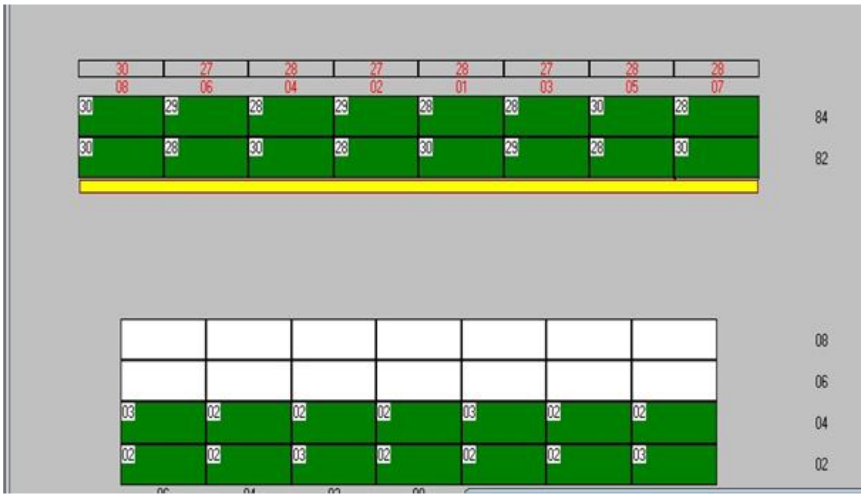


Fig 10. Position of Negative Stability Load

Source: Ship Documentation

Ari Sriantini's (2023) research supports this finding, where the transverse load shift on the MV Kutai Raya Dua caused a similar listing, overcome by the moment postulate to move the counterload. Hery Sutrawan Nurdin (2017) also agrees, showing that the distribution of purse seine loads affects KG and GZ, similar to the bay plan of the MV Meratus Larantuka. Conversely, Mushawwir Razak et al. (2020) contradict this finding, as moving the crew compartment upwards only reduces the GZ curve area by 4% on a Ro-Ro ferry, while the container case raises a rigid stability warning due to the more massive external load. This difference is due to the type of vessel (container vs. ferry) and the dynamic liquid load, which magnifies the free surface effect compared to fixed structural changes.Theoretically, the findings reinforce Hind's (1967) stability model that G must remain below M for positive stability, emphasizing the integration of FSE in dynamic KG calculations. Practically, the officers of MV. Meratus Larantuka can optimize PlanMaster for real-time bay plan adjustment, reduce heel via ballast side tanks, and monitor fresh water daily to avoid extreme trim. Methodologically, a qualitative observation-interview approach is effective for operational cases but is recommended in combination with PGZ software simulation for quantitative GZ curve validation in similar studies.

IV. CONCLUSION

This study concluded that the change in the ship's center of gravity on the MV. Meratus Larantuka was mainly caused by the deviation of the bay plan from the actual load, ballast water imbalance, and uneven fresh water discharge, which significantly decreased the metacentric height (GM) from 0.85 m to 0.62 m and triggered a heel of up to 2.8 degrees and a decrease in the GZ curve area by 12 percent. These findings were confirmed through observation triangulation, ship officer interviews, and PlanMaster calculations, proving that the free surface effect and transverse displacement G weakened the static and dynamic stability, although it remained within the IMO safe limits with timely handling such as counter-ballasting.However, the study's limitations lie in its descriptive qualitative approach that relies on a single observation during sea practice in January 2026, without quantitative CFD simulations or real-time sensor data for extreme weather variations. Suggestions for future research include a multi-vessel longitudinal study with integration of IoT GZ monitoring and probabilistic risk analysis based on KNKT data. Practically, these results recommend optimizing the PlanMaster SOP for PT. Meratus Line's deck officers, including verification of actual container weights and daily ballast rotation, to reduce the risk of tilting by up to 50 percent on the wave-prone Sulawesi route.

REFERENCES

[1] Allianz Commercial. (2025). Safety and shipping review 2025.**https://www.agcs.allianz.com/news-and-insights/reports/safety-shipping-review.html**

[2] Ari Sriantini. (2023). Case study of the effect of cargo shift on ship stability in the MV. Kutai Raya Dua. ***Journal of Shipping and Port Applications***, 14(1), 1-10.

[3] Barrass, B., & Derrett, D. R. (2012). Ship stability for masters and mates (6th ed.). Butterworth-Heinemann.

[4] Becker, E. (1967). Introduction to steel shipbuilding (2nd ed.). Pergamon Press.

[5] Choirul Alfi, & Vega. (2020). The effect of cargo placement on the stability of RoRo passenger ferries. ***Journal of Marine Technology***, 15(1), 53-62.**https://doi.org/10.1234/jtk.v15i1.123**

[6] European Maritime Safety Agency. (2024). Annual overview of marine casualties and incidents 2024.**https://www.emsa.europa.eu/publications.html**

[7] Hery Sutrawan Nurdin. (2017). The effect of load distribution on the stability of modified purse seine vessels in Bulukumba Regency. ***Jurnal IPTEKS PSP,*** 4(7), 39-48.

[8] Himaya, A.N., Ribeiro, A.F., & Guedes Soares, C. (2022). Effect of the loading conditions on the maneuverability of a container ship. Ocean Engineering, 266, Article 112789.**https://doi.org/10.1016/j.oceaneng.2022.112789**

[9] Hind, R. (1967). Principles of naval architecture. Society of Naval Architects and Marine Engineers.

[10] Im, N.-K., Lee, G.-H., & Yeon, J.-M. (2021). A quantitative methodology for evaluating the ship stability considering the intact and damaged states. ***Chinese Journal of Mechanical Engineering***, 34(1), 1-15.**https://doi.org/10.1186/s10033-021-00540-4**

[11] Jia, B., Fagerholt, K., & Rytter, N.G. (2015). Ship stability when loading containers at sea. Maritime Policy & Management, 42(2), 131-149.**https://doi.org/10.1080/03088839.2014.960969**

[12] National Transportation Safety Committee. (2025). Indonesian maritime accident statistics 2024-2025.**https://knkt.go.id/statistik**

[13] Miles, M. B., Huberman, A. M., & Saldana, J. (2014). Qualitative data analysis: A methods sourcebook (3rd ed.). SAGE Publications.

[14] Mushawwir Razak, Syamsul Asri, & Daeng Paroka. (2020). Analysis of the effect of moving the crew room from the vehicle deck to the superstructure deck on the stability of a Ro-Ro ferry. ***Journal of Engineering Research (JPE)***, 24(2), 89-102.

[15] Sugiyono. (2019). Quantitative, qualitative, and R&D research methods. Alfabeta.