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The Effect of Nickel Ore Liquefaction on Ship Stability

Fakhri Akbar Ayub*[1], Fanny Darwani Putri[1]

[1]Naval Architecture and Marine Engineering, Universitas Pembangunan Nasional "Veteran" Jakarta, Indonesia

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Nickel ore; Liquefaction; ship stability; free surface effect; bulkhead

ABSTRACT – Nickel ore liquefaction poses a critical threat to vessel stability because the cargo may transition from a solid to a fluid state, potentially causing rapid heeling and, ultimately, sinking. Under a substantial external shock, liquefied cargo may fail to return to its original position, thereby altering the cargo distribution and adversely affecting vessel stability and motion. Accordingly, this study investigates the effects of varying proportions of solid and liquid nickel ore, with the combined composition maintained at 100%, on the stability and motion characteristics of the MV Nur Allya. Five loading conditions were considered: 100% solid, 75% solid–25% liquid, 50% solid–50% liquid, 25% solid–75% liquid, and 100% liquid. Among these conditions, Case 1 produced the most favourable stability performance, with a maximum righting arm (GZ) of 1.064 m. To further mitigate the liquefaction hazard, a longitudinal bulkhead was incorporated into the cargo hold for all five loading cases. The results show a modest improvement in stability between Case 1 and Case 5 following the installation of the bulkhead. However, although the longitudinal bulkhead reduces the stability risks associated with cargo liquefaction, its installation also decreases the cargo-carrying capacity of the vessel, highlighting a trade-off between enhanced safety and cargo utilization.

*Corresponding Author | Ayub | ✉ (fakhriakbar@upnvj.ac.id)

INTRODUCTION

Nickel is a metallic chemical element that is relatively soft in its freshly mined state but exhibits enhanced mechanical strength and corrosion resistance when alloyed with other metals, particularly iron (Fe) and chromium (Cr) [1]. These properties render nickel indispensable in a wide range of industrial and domestic applications, including the manufacture of cutlery, automotive and motorcycle exhaust systems, and durable watch components. In addition, nickel is a fundamental constituent of stainless steel and is extensively utilised in copper plating, battery technologies, and the electronics industry [2]. The processing chain of nickel ore generally comprises extraction, size classification, stockpiling, and subsequent transportation.

Indonesia has established itself as the world's largest producer of nickel ore, thereby playing a critical role in the global supply of nickel raw materials [3]. In 2023, Indonesia recorded a production volume of 2 million tonnes. By 2024, of the 3.7 million tonnes of nickel produced globally, Indonesia's output had increased to approximately 2.2 million tonnes, substantially exceeding that of the Philippines 330 thousand tonnes, Russia 210 thousand tonnes, and Canada 190 thousand tonnes [4]. It is reported that approximately 98% of Indonesia's nickel exports are directed to China, with the remainder supplied to the European Union [5]. Consequently, maritime transportation, predominantly by bulk carriers, serves as a critical link between production regions and international consumption markets.

Nickel ore is transported as a solid bulk cargo and, due to its high fine-particle content and moisture sensitivity, is particularly susceptible to liquefaction during sea voyages [6],[7]. Under the combined effects of ship motions, mechanical vibration, and cyclic loading [8], loose granular cargo containing sufficient pore water may undergo compaction, leading to a reduction in interparticle voids and a corresponding increase in excess pore water pressure [9]-[12]. This process diminishes effective intergranular contact forces, resulting in a loss of shear strength and a transition from a quasi-solid state to a viscous, fluid-like behaviour [13],[14]. Such rheological transformation enables the cargo to flow within the hold, thereby introducing dynamic mass redistribution that can severely compromise vessel stability.

From a ship stability perspective, liquefied nickel ore can induce a pronounced free surface effect within the cargo hold. When a partially liquefied cargo mass shifts in response to vessel heel or roll, the centre of gravity of the cargo migrates transversely, reducing the vessel's initial metacentric height (GM), diminishing the righting lever, and narrowing the range of positive stability [15]-[17]. This progressive degradation of transverse stability increases the likelihood of developing a permanent list and, in extreme sea states, can precipitate sudden capsizing

[18]-[20]. The coupling between cargo sloshing dynamics and ship motions therefore represents a critical mechanism linking material-level liquefaction processes with macroscopic seakeeping performance and safety [21],[22].

Within the regulatory framework, a bulk carrier is defined as a vessel of single-deck construction, fitted with topside and hopper side tanks, and specifically designed for the carriage of dry cargo in bulk [23]. The International Maritime Solid Bulk Cargoes (IMSBC) Code further classifies hazardous solid bulk cargoes into three categories: Groups A, B, and C [24]. Group A cargoes are characterised by a combination of fine particles and sufficient moisture content, which may cause them to liquefy during a voyage and induce a cargo shift [25]. Such cargo shift and liquefaction have posed the greatest threat to human life and the loss of ships in all ship capsize accidents [26].

Liquefaction-induced instability typically occurs when the moisture content (MC) exceeds the Transportable Moisture Limit (TML). Furthermore, certain cargoes are prone to internal moisture migration, which can result in the formation of a hazardous wet base even when the average MC remains below the TML [27]. As a result, a cargo surface may appear visually dry while concealed liquefaction develops within the bulk mass. This condition is particularly critical for shallow cargo layers and steep surface angles, where the propensity for lateral slippage and flow is significantly amplified

To mitigate moisture-related risks during loading, strict operational control of cargo moisture content is essential. The Flow Moisture Point (FMP) denotes the moisture content at which a solid bulk cargo begins to exhibit flow characteristics and undergoes a transition toward fluid-like behaviour [28]. In contrast, the Transportable Moisture Limit (TML) specifies the maximum moisture content at which the cargo can be transported safely without an unacceptable risk of liquefaction [29]-[31]. Accordingly, regulatory provisions establish the TML at 90% of the FMP, providing a defined safety margin below the moisture content associated with the onset of flow behaviour.

Numerical and experimental investigations of ship stability under cargo liquefaction have expanded considerably over the past decade. Combined shaking-table experiments with righting-lever (GZ) curve analysis to quantify the loss of stability that follows liquefaction in a bulk carrier's holds [32], and subsequent naval-architectural work extended this approach to progressively larger numbers of liquefied holds and to alternative internal subdivisions, including a longitudinal bulkhead [33]. Numerical frameworks based on discrete-element and coupled fluid-structure modelling, have been developed to capture cargo shift and its interaction with vessel motion [34]. Taken together with the acknowledged variability of laboratory TML determination itself [35], this body of work indicates that liquefaction rarely presents as a single sharply defined transition. It develops progressively and because moisture migration can generate a localised wet base even when the declared average moisture content complies with the TML [27], a vessel may in practice encounter any intermediate condition between fully solid and fully liquefied cargo. Existing stability assessments have generally represented liquefaction as a state leaving the stability consequences of graded, partial liquefaction of the cargo mass itself comparatively unexplored, particularly for the Indonesian nickel ore that now dominates global seaborne trade in this commodity.

Addressing the consequences of liquefaction once it occurs rather than relying on moisture control at loading alone, requires a complementary structural measure. A longitudinal bulkhead fitted along the hold centreline divides each cargo compartment into port and starboard sections. Because the free-surface moment of a liquid surface is proportional to the cube of its breadth [36]. Such subdivision in idealised terms, reduce the free-surface moment of a liquefied compartment to roughly one-quarter of its undivided value, thereby limiting the associated loss of metacentric height and righting lever. Prior numerical work indicates that such subdivision can keep a vessel within IMO intact-stability limits even when a substantial number of compartments contain liquefied cargo.

Alternative countermeasures have also been proposed, including water-absorbing polymer additives and pneumatic restraint devices, however, concerns over their effect on cargo composition, added handling cost, and limited field validation have restricted their adoption [37]. A longitudinal bulkhead was therefore selected for the present investigation as a passive, structurally verifiable, and industry-precedented intervention, notwithstanding its own trade-offs of reduced cargo volume and deadweight capacity and increased steel weight and construction cost.

The present study addresses the gap identified above by assessing intact stability under a graded representation of nickel-ore liquefaction, in which the cargo is modelled across five progressively liquefied conditions from fully solid (100% solid - 0% liquid) to fully liquefied (0% solid - 100% liquid), in 25% increments rather than the binary, hold-by-hold liquefaction states considered in earlier work. This resolution was chosen to trace the trend of stability degradation across intermediate, physically realistic liquefaction extents while keeping the number of simulation cases tractable; finer increments were judged unnecessary at this exploratory stage, since the objective is to characterise the overall trend rather than to resolve a precise liquefaction-onset threshold, which cannot in any case be determined with certainty given the acknowledged variability of TML testing [35]. In parallel, and for the reasons outlined above, the effect of fitting a longitudinal bulkhead is examined across the same five liquefaction conditions, to evaluate its potential to mitigate the associated loss of stability. The assessment is performed as a numerical, code-based intact-stability evaluation against the applicable IMO criteria [38], consistent with the approach used in comparable prior studies.

METHODS

Ship dimension and general arrangement

MV Nur Allya is designed with several compartments, including accommodation and navigation spaces, engine rooms, cargo holds, and tanks. The accommodation spaces are located in the superstructure, whereas the navigation control room is situated within the deckhouse.

The main dimensions of the ship used in this study are shown in table 1.

Table 1. Ship dimension [41]

Dimensions	Units
Length overall (m)	189.99
Length between perpendicular (m)	182.00
Length of waterline (m)	187.46
Breadth (m)	32.26
Depth (m)	17.00
Draught (m)	12.272
Displacement (tonne)	62.162

The engine room contains a single main engine that serves as the vessel's propulsion unit. Three auxiliary engines and electric generators are installed on the tween decks between the engine rooms. A dedicated emergency generator unit is housed in the emergency generator room. Access to the engine room is provided via a watertight door on the main deck. Five cargo holds located forward of the engine room and superstructure. Access to the holds is provided by five cargo hold doors, designated Cargo Hold No. 1 - 5. The cargo hold specifications in accordance with the MV Nur Allya's latest status can be seen in the table 2.

Table 2. Loading condition [41]

Item Name	Quantity	Unit Mass (Tonne)	Total Mass (Tonne)	Unit Volume (m^3)	Total Volume (m^3)
Lightship	1	8394.00	8394		
Cargo Hold 5	73.64 %	13579.59	10000	10445.844	7692.307
Cargo Hold 4	69.22 %	16612.56	11500	12778.893	8846.154
Cargo Hold 3	71.53 %	15378.81	11000	11829.86	8461.54
Cargo Hold 2	62.79 %	16721.58	10500	12862.759	8076.924
Cargo Hold 1	65.36 %	13005.57	8500	10004.287	6538.462

IMO intact stability regulations

The static stability of the vessel under each loading condition was evaluated against the intact stability criteria for cargo ships set out in IMO Resolution A.749(18), Code on Intact Stability for All Types of Ships Covered by IMO Instruments, subsequently consolidated into the 2008 Intact Stability (IS) Code (IMO, 2008). These criteria specify minimum admissible values for the righting-lever (GZ) curve and the initial metacentric height (GM), representing the reserve energy and initial stiffness a vessel must retain in order to resist, and recover from, heeling moments under operational and severe sea conditions. Table 3 summarises the six criteria applied in this study.

Table 3. IMO intact stability criteria

Criteria	Physical significance	IMO threshold
Area $(0° - 30°)$	Righting energy up to 30° heel; capacity to absorb heeling moments in normal operation	$\geq 0.055\ m \cdot rad$
Area $(0° - 40°)$	Righting energy up to 40° heel or the downflooding angle, whichever is lower; reserve stability under severe conditions	$\geq 0.090\ m \cdot rad$
Area $(30° - 40°)$	Righting energy between 30° and 40° heel; ability to recover from large-angle inclinations	$\geq 0.030\ m \cdot rad$
$GZ_{max\ (at\ t \geq 30°)}$	Peak value of the righting lever	$\geq 0.20\ m$
Angle of GZ_{max}	Heel angle at which the peak righting lever occurs	$\geq 30°$
Initial GM	Metacentric height at small heel angles; initial stiffness and roll behaviour	$\geq 0.15\ m$

Free surface effect

When granular cargo liquefies, moisture accumulating at the surface of the cargo mass forms a free surface capable of shifting relative to the vessel during rolling, analogous to a free liquid surface in a partially filled tank [34]. This free surface effect reduces the vessel's effective metacentric height and must be corrected for in both the GZ curve and the initial GM whenever liquid, or liquid-like, cargo is present, consistent with the free-surface correction requirements of the 2008 IS Code [38]. The classical free surface moment of a cargo hold is defined as

$$FSM = i \times \rho \tag{1}$$
$$\delta GM = FSM/\Delta \tag{2}$$

where i is the transverse second moment of area of the free surface about the ship's centreline, ρ is the density of the liquefied material, Δ is the vessel's displacement, and δGM is the resulting virtual loss of metacentric height. Corrections to the initial metacentric height and righting lever curve must be handled separately as follows:

$$M_{fs} = v\ x\ b\ x\ r\ x\ k\ x\ \sqrt{\delta} \tag{3}$$

where:

M_{fs} = Free Surface Effect slope (m. ton)
v = tank volume (m^3)
b = maximum tank width (m)
ρ = density of liquid in tank ($\mathrm{ton/m}^3$)
δ = v/b
h = maximum tank height (m)
l = maximum tank length (m)
k = b/h

It is important to note that liquefied nickel ore does not behave as an ideal Newtonian liquid. Experimental and numerical studies of nickel-ore-slurry sloshing [32],[39] and of cargo liquefaction more broadly [40] show that liquefied fine-grained ores exhibit non-Newtonian, viscoplastic behaviour with a yield stress and apparent viscosity that depend on moisture content and particle size distribution. Modelling the liquefied fraction as an equivalent Newtonian free surface, as adopted here, is therefore a simplifying and conservative idealisation, consistent with the approach used in previous stability assessments of liquefied bulk cargoes [32]. A Newtonian free surface transmits the destabilising moment more completely and more rapidly than a yield-stress slurry of equivalent volume, so the resulting reduction in GM and GZ represents an upper-bound estimate of the stability degradation caused by liquefaction.

RESULTS AND DISCUSSION

Room definition

Based on data from KNKT, there are general arrangement drawings, capacity plans, stowage plans, and stability booklet data that have been obtained. Therefore, in this study, hull modelling was carried out with a scale of 1:1. Table 4 shows the room definition of MV. Nur Allya

Measurements were taken from point AP to both tank lengths, then the afterpeak and forepeak measurements were obtained. Next, measurements were taken where the top view of the tank position yielded the F. Portside and F. Starboard data. Then, the F. Top and F. Bottom measurements were obtained from the ship's baseline to the height of the tank on the ship. After that, the load case was input with the total mass according to the stowage plan.

Table 4. Room definition for case 1

Name	Intact Perm	Damaged perm	specific gravity	Aft (m)	Fore (m)	F. port (m)	F. Stbd (m)	F. Top (m)	F. bot (m)
Cargo hold 5	95	85	1	25,15	54,05	-15	15	19	1,691
Cargo hold 4	95	85	1	54,05	85,3	-15	15	19	1,691
Cargo hold 3	95	85	1	85,3	114,2	-15	15	19	1,691
Cargo hold 2	95	85	1	114,2	145,45	-15	15	19	1,691
Cargo hold 1	95	85	1	145,45	174,35	-15	15	19	1,691
WBT 5	95	85	1,025	28,423	54,05	-20	20	1,691	0

WBT 4	95	85	1,025	54,05	85,3	-20	20	1,691	0
WBT 3	95	85	1,025	85,3	114,2	-20	20	1,691	0
WBT 2	95	85	1,025	114,2	145,45	-20	20	1,691	0
WBT 1	95	85	1,025	145,45	174,35	-20	20	1,691	0

Stability analysis without longitudinal bulkhead

The stability assessment was performed on Nur Allya's, with principal particulars summarised in Table 1. Five loading conditions were analysed in this study to determine the effect of nickel ore liquefaction on ship stability. The liquefaction conditions are shown in Table 5.

Table 5. Liquefaction condition

Case	Solid	Liquid
1.	100%	0%
2.	75%	25%
3.	50%	50%
4.	25%	75%
5.	0%	100%

Ship modelling is carried out in accordance with the main dimensions and general arrangement. The ship's stability and free surface effect are then simulated/studied under assumed loading conditions to determine the liquefaction conditions under which the ship experiences poor stability. The results of these stability calculations are then analysed in accordance with IMO Regulation A.749 (18) Code on Intact Stability to determine whether each loading condition complies with IMO regulations.

Hydrostatic and large-angle stability calculations were performed, with the vessel in the latest condition. For each of the five cases in Table 5, the specified solid/liquid mass fraction was implemented as follows: the solid fraction retained its as-loaded vertical centre of gravity (VCG) and did not contribute to the free-surface correction; the liquid fraction was modelled as an equivalent free liquid occupying the corresponding proportion of the hold cross-section, with its free surface moment computed from Equations (1) - (3) and applied as a virtual rise in VCG in accordance with the procedure. This treatment was applied to all cargo holds simultaneously, reflecting a uniform-liquefaction assumption, and the GZ curve was recomputed at each heel angle to capture the combined effect of the shifted VCG and reduced effective GM.

The righting-lever curve was evaluated over a heel range of 0° to 150°, at 10° increments, at even keel and zero trim. Dynamic wind heeling (the weather criterion of IMO A.749(18)) was not separately evaluated in this study. Each of the six criteria in Table 3 was then checked automatically for every case, producing the results reported in Figure 1 and Table 5.

Figure 1 shows the results of the Nickel Ore load stability analysis. Cases 1-4 meet the criteria but, for case 5 does not meet these criteria due to its low GM value. The ship's criteria do not comply with IMO regulation, resulting in the ship failing because its cargo has changed to 100% liquid and the cargo hold is not fully loaded. This could cause the ship to capsize.

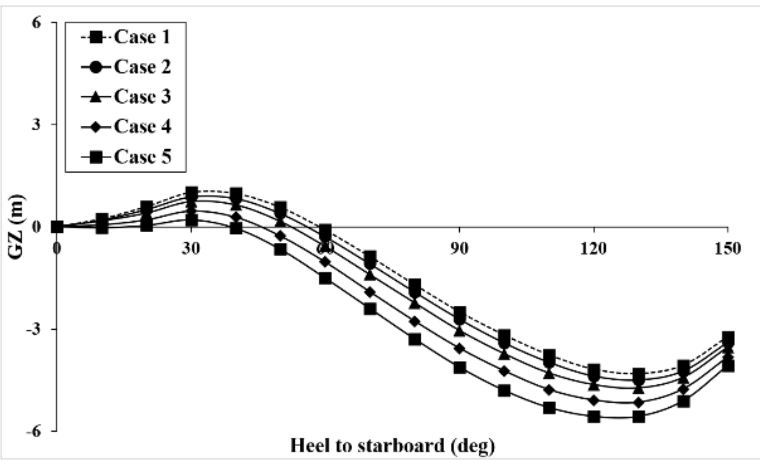

Figure 1. GZ curve for all case without longitudinal bulkhead

Under 100% solid cargo conditions, the IMO regulation applicable to all ships has been met. The results of the criteria analysis under 100% solid cargo conditions can be seen in Table 6.

Table 6. Results of intact stability analysis without longitudinal bulkhead for each case

Criteria	Case 1	Case 2	Case 3	Case 4	Case 5
$Area_{0-30\text{deg}}$	Pass	Pass	Pass	Pass	Fail
$Area_{0-40\text{deg}}$	Pass	Pass	Pass	Pass	Fail
$Area_{30-40\text{deg}}$	Pass	Pass	Pass	Pass	Fail
$maxGZ_{30\text{deg}}$	Pass	Pass	Pass	Pass	Fail
$Angle_{maxGZ}$	Pass	Pass	Pass	Pass	Pass
$initial_{GM}$	Pass	Pass	Pass	Pass	Fail

Stability analysis with longitudinal bulkhead

To reduce the Free Surface Effect, the author provides a solution by modelling the cargo space with the addition of a Longitudinal Bulkhead. Ships with longitudinal bulkheads in the cargo space are more effective against the dangers of liquefaction [31]. Based on the ClassNK Guidelines for the Safe Carriage of Nickel Ore Appendix D, Therefore, the longitudinal bulkhead thickness to be used is 0.1 m.

The addition of longitudinal bulkhead variations was carried out based on Table 4. This was done to reduce the free surface effect on the ship. The results of the analysis of the addition of longitudinal bulkhead variations can be seen in the following graph.

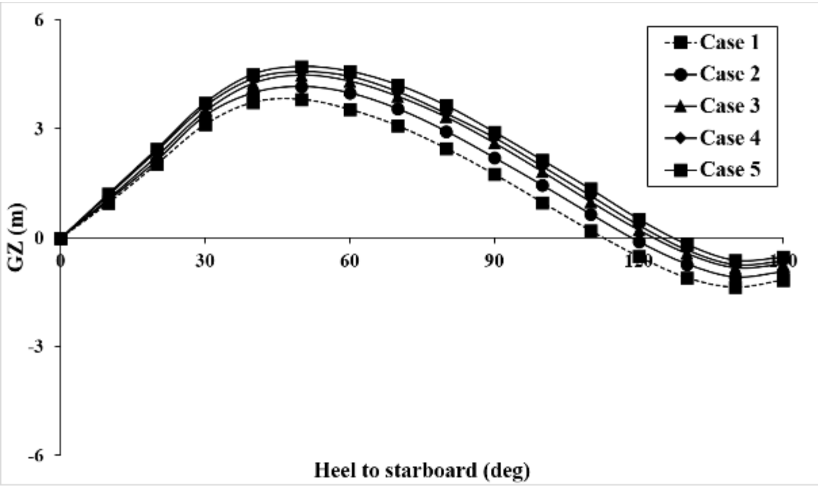

Figure 2. GZ curve for all case with longitudinal bulkhead

Figure 2 shows the results of the Nickel Ore load stability analysis with longitudinal bulkhead. There is a clear increase in the GZ curve due to longitudinal bulkheads subdivide the cargo space in the transverse direction, limiting the width over which liquefied cargo can shift, thereby substantially reducing the free surface moment and the associated loss of stability. By restricting transverse cargo flow, longitudinal bulkheads help maintain righting levers during rolling and heavy weather, reduce the risk of sudden large angles of heel, and improve survivability in dynamic loading conditions. This subdivision is particularly critical for nickel ore, where liquefaction can occur without warning despite apparent surface dryness. This is consistent with the results of the intact stability analysis shown in Table 7.

Table 7. Results of intact stability analysis with longitudinal bulkhead for each case

Criteria	Case 1	Case 2	Case 3	Case 4	Case 5
$Area_{0-30\text{deg}}$	Pass	Pass	Pass	Pass	Pass
$Area_{0-40\text{deg}}$	Pass	Pass	Pass	Pass	Pass
$Area_{30-40\text{deg}}$	Pass	Pass	Pass	Pass	Pass
$maxGZ_{30\text{deg}}$	Pass	Pass	Pass	Pass	Pass
$Angle_{maxGZ}$	Pass	Pass	Pass	Pass	Pass
$initial_{GM}$	Pass	Pass	Pass	Pass	Pass

CONCLUSION

Ship stability was assessed under five loading conditions characterised by different solid - liquid cargo ratios. The findings demonstrate a clear decline in stability as the proportion of liquid cargo increases. Maximum stability was achieved under the fully solid cargo condition, with a metacentric height (GM) of 1.287 m, while progressive reductions in stability were observed with increasing liquid content. In the fully liquid cargo condition, the GM became negative (-0.339 m) and the righting arm was minimal, indicating an unstable state. This loading scenario fails to satisfy the requirements of the IMO Intact Stability Code, as the inadequate restoring moment substantially elevates the risk of capsizing or sinking. To improve vessel stability and mitigate the risk of capsizing, longitudinal bulkheads were installed within the cargo hold and analysed under the same five loading conditions, ranging from fully solid to fully liquid cargo. The results reveal a marked enhancement in stability performance, with GM values increasing from 5.507 m in the fully solid condition to 6.703 m in the fully liquid condition, while the maximum righting arm (GZ) rose from 3.828 m to 4.733 m across the cases. These findings indicate that longitudinal bulkheads effectively limit the adverse effects of cargo liquefaction and significantly enhance the vessel's righting capability, although a slight reduction in cargo capacity may result.

REFERENCES

[1] Kar, S., Meena, L.K., Srivastava, V.C. and Mandal, G.K., 2024. Microstructural, Mechanical, And Corrosion Behaviour of Ni–Fe-Cr-Al and Ni–Fe-Cr-Al-Co Alloys. Transactions of the Indian Institute of Metals, 77(5), pp.1299-1311. https://doi.org/10.1007/s12666-023-03054-5

[2] Dilshara, P., Abeysinghe, B., Premasiri, R., Dushyantha, N., Ratnayake, N., Senarath, S., Ratnayake, A.S. and Batapola, N., 2024. The role of nickel (Ni) as a critical metal in clean energy transition: applications, global distribution and occurrences, production-demand and phytomining. Journal of Asian Earth Sciences, 259, p.105912. https://doi.org/10.1016/j.jseaes.2023.105912

[3] Lo, M.G., Morgans, C.L., Santika, T., Mumbunan, S., Winarni, N., Supriatna, J., Voigt, M., Davies, Z.G. and Struebig, M.J., 2024. Nickel mining reduced forest cover in Indonesia but had mixed outcomes for well-being. One Earth, 7(11), pp.2019-2033. https://doi.org/10.1016/j.oneear.2024.10.010

[4] U.S. Geological Survey, 2025. Mineral commodity summaries 2025: U.S. Geol. Surv., https://doi.org/10.3133/mcs2025, (ISBN: 78-1-4113-4595-9, Pp124).

[5] Wijaya, T. and Jones, L., 2025. Indonesia, nickel, and the political economy of polyalignment in the Second Cold War. Third World Quarterly, pp.1-20. https://doi.org/10.1080/01436597.2025.2465514

[6] Lee, H.L., 2017. Nickel ore bulk liquefaction a handymax incident and response. Ocean Engineering, 139, pp.65-73. https://doi.org/10.1016/j.oceaneng.2017.04.036

[7] Shimizu, Y., Sugihara, M., 2023. A numerical approach on liquefaction of iron ore fines under roll motion of bulk carriers using microscopic fluid coupling scheme in discrete element method. Ocean. Eng. 283, 114695. https://doi.org/10.1016/j.oceaneng.2023.114695.

[8] Zou, Y., Xi, X., Su, Y., 2018. A numerical study of a highly-viscous liquefied cargo in a rectangular ship tank. Ocean. Eng. 170, 298–305. https://doi.org/10.1016/j.oceaneng.2018.10.054

[9] Kwa, K., Gourvenec, S., Evans, T., Koseki, J. and Kishimoto, K., 2024. Rolling table centrifuge modelling of partially saturated granular material to inform on instability during solid bulk cargo transport. Acta Geotechnica, 19(11), pp.7677-7697. https://doi.org/10.1007/s11440-024-02361-5

[10] Ju, L., Vassalos, D., Wang, Q., Wang, Y. and Liu, Y., 2018. Numerical investigation of solid bulk cargo liquefaction. Ocean Engineering, 159, pp.333-347. https://doi.org/10.1016/j.oceaneng.2018.04.030

[11] Baki, M.A., Rahman, M.M. and Lo, S.R., 2012. Cyclic instability behaviour of coal ash. In GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering (pp. 849-858). https://doi.org/10.1061/9780784412121.088

[12] Rahman, M.M., Baki, M.A.L. and Lo, S.R., 2014. Prediction of undrained monotonic and cyclic liquefaction behavior of sand with fines based on the equivalent granular state parameter. International Journal of Geomechanics, 14(2), pp.254-266. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000316

[13] Kowalcyzk, P. and Gourvenec, S., 2025. Solid bulk cargo liquefaction: numerical investigation and proposal of safety envelopes. Applied Ocean Research, 159, p.104607. https://doi.org/10.1016/j.apor.2025.104607

[14] Do, T.M., Laue, J., Mattsson, H. and Jia, Q., 2023. Excess pore water pressure generation in fine granular materials under undrained cyclic triaxial loading. International Journal of Geo-Engineering, 14(1), p.8. https://doi.org/10.1186/s40703-023-00185-y

[15] Munro, M.C. and Mohajerani, A., 2017. Bulk cargo liquefaction incidents during marine transportation and possible causes. Ocean Engineering, 141, pp.125-142. https://doi.org/10.1016/j.oceaneng.2017.06.010

[16] Wirawan, M., Oloan, A. F. N., Subakti, A. G., & Batosai, J. R. (2024). CFD-Preliminary Design and Stability Analysis of a High-Speed Firefighting Boat for Remote Island Waterways. *Indonesian Journal of Maritime Technology*, *2*(2). https://doi.org/10.35718/ismatech.v2i2.1228

[17] Dani, F. L., Raharja, A. M., Sihombing, H. M., & Abadi, G. W. (2026). The Effect of Hard Chine Planing Variations on Resistance and Stability of a Patrol Boat Hull . Indonesian Journal of Maritime Technology, 3(2). https://doi.org/10.35718/ismatech.v3i2.8481802

[18] Airey, D.W., Ghorbani, J., 2021. Analysis of unsaturated soil columns with application to bulk cargo liquefaction in ships. Comput. Geotech. 140, 104402. https://doi.org/ 10.1016/j.compgeo.2021.104402.

[19] Roberts, S.E., Pettit, S.J., Marlow, P.B., 2013. Casualties and loss of life in bulk carriers from 1980 to 2010. Mar. Pol. 42, 223–235. https://doi.org/10.1016/j. marpol.2013.02.011.

[20] Sakar, C., Koseoglu, B., Toz, A.C., Buber, M., 2020. Analysing the effects of liquefaction on capsizing through integrating interpretive structural modelling (ISM) and fuzzy Bayesian networks (FBN). Ocean. Eng. 215, 107917. https://doi.org/10.1016/j.oceaneng.2020.107917

[21] Chen, Z., Gao, Y., Liao, X., Zhao, W. and Guo, D., 2024. Numerical analysis of coupling effect between sloshing and motion responses of a KCS in uni-and bi-directional waves. Ocean Engineering, 313, p.119592. https://doi.org/10.1016/j.oceaneng.2024.119592

[22] Kim, Y., Nam, B.W., Kim, D.W. and Kim, Y.S., 2007. Study on coupling effects of ship motion and sloshing. Ocean Engineering, 34(16), pp.2176-2187. https://doi.org/10.1016/j.oceaneng.2007.03.008

[23] Pintilie, A., Manea, M.G., Mărăşescu, D., Cristea, O., Burlacu, P., Clinci, C.P. and Popa, N.S., 2025. Optimization of bulk carrier hull design through CAD modelling and FEM structural analysis–a case study. Results in Engineering, 26, p.104846. https://doi.org/10.1016/j.rineng.2025.104846

[24] International Maritime Organisation (2013) International maritime solid bulk cargoes code (IMSBC Code) and supplement. 2013 Edn. ISBN 978-92-801-1587-1

[25] Spandonidis, C.C. and Spyrou, K.J., 2013. Micro-scale modeling of excited granular ship cargos: A numerical approach. Ocean Engineering, 74, pp.22-36. https://doi.org/10.1016/j.oceaneng.2013.09.015

[26] Wu, J., Meng, X., Zhang, P. and Hou, Z., 2023. Seaworthiness management of bulk carriers during the transportation process from the perspective of bauxite performance. Journal of Marine Science and Engineering, 11(2), p.303. https://doi.org/10.3390/jmse11020303

[27] Munro, M.C. and Mohajerani, A., 2018. Laboratory scale reproduction and analysis of the behaviour of iron ore fines under cyclic loading to investigate liquefaction during marine transportation. Marine Structures, 59, pp.482-509. https://doi.org/10.1016/j.marstruc.2018.02.013

[28] Wu, W., Li, Y., Zhao, Z., Zheng, Q., Zhang, C., Ji, H., Yu, X. and Yu, S., 2022. Quantitative analysis of liquefaction risk of liquefiable solid bulk cargoes during sea transport. Ocean Engineering, 258, p.111751. https://doi.org/10.1016/j.oceaneng.2022.111751

[29] Munro, M.C. and Mohajerani, A., 2015. Determination of the transportable moisture limit of iron ore fines for the prevention of liquefaction in bulk carriers. Marine Structures, 40, pp.193-224. https://doi.org/10.1016/j.marstruc.2014.11.004

[30] Munro, M.C. and Mohajerani, A., 2016. Moisture content limits of iron ore fines to prevent liquefaction during transport: review and experimental study. International Journal of Mineral Processing, 148, pp.137-146. https://doi.org/10.1016/j.minpro.2016.01.019

[31] ClassNK. (2012). Guidelines for the Safe Carriage of Nickel Ore Second Edition. In second section.

[32] Koromila, I. A., Spandonidis, C. C., & Spyrou, K. J. (2013, September). Experimental investigation of cargo liquefaction and impact on the stability of a bulk-carrier. In Proceedings of the 13th International Ship Stability Workshop (pp. 1-7).

[33] Pittara, A. (2018). Investigation of nickel ore liquefaction in bulk carriers.

[34] Ju, L. (2017). Assessment of ship cargo liquefaction.

[35] Rose, T. (2014). *Solid bulk shipping: cargo shift, liquefaction and the transportable moisture limit* (Doctoral dissertation, Oxford University, UK).

[36] Biran, A., & López-Pulido, R. (2013). *Ship hydrostatics and stability*. Butterworth-Heinemann.

[37] Popek, M. (2013). The influence of organic polymer on properties of mineral concentrates. Part II. *Polish Maritime Research*. https://doi.org/10.2478/pomr-2013-0021

[38] International Maritime Organization. (2008). International Maritime Solid Bulk Cargoes (IMSBC) Code. Section 7.3.1.1.

[39] Zhang, J., Wu, W., & Hu, J. (2017). Study on the sloshing of nickel ore slurries with three different moisture contents. *Journal of Offshore Mechanics and Arctic Engineering*, *139*(3), 032001. https://doi.org/10.1115/1.4035476

[40] Ju, L., Vassalos, D., & Boulougouris, E. (2016). Numerical assessment of cargo liquefaction potential. *Ocean Engineering*, *120*, 383-388. https://doi.org/10.1016/j.oceaneng.2016.01.024

[41] Komite Nasional Keselamatan Transportasi. (2021). Tenggelamnya Nur Allya Imo 9245237 Di Perairan Halmahera, Maluku Utara, Republik Indonesia.