American Journal of Traffic and Transportation Engineering
2025, Vol. 10, No. 1, pp. 1-10
https://doi.org/10.11648/j.ajtte.20251001.11

Research Article

A Study on the Safety Risks of Maritime Transport of Nickel Ore

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Abstract

In recent years, the maritime industry has been confronted with a troubling trend: the increasing frequency of nickel ore transport accidents at sea. These incidents have cast a spotlight on the urgent need to bolster the safety protocols governing nickel ore sea transportation and to mitigate the risk of self-sinking in nickel ore carriers. This paper conducts an in - depth study of the cargo characteristics of nickel ore by reviewing relevant domestic and foreign literature on nickel ore transportation in the past decade and the relevant regulations of the latest IMSBC Code. Combining with the author's experience in nickel ore transportation during the tenure as a captain, the paper carefully explores the causes of liquefaction, and examines the adverse effects of the free surface and cargo movement on the ship's stability. It concludes that the principal culprit behind the self-sinking of nickel ore carriers is the excessive moisture content of the nickel ore cargo, which surpasses the Transportable Moisture Limit (TML). This excess moisture precipitates cargo liquefaction within the ship's holds, giving rise to a free surface on the cargo and inducing cargo movement. These factors precipitously degrade vessel stability. When vessels laden with liquefied cargo encounter adverse maritime conditions—such as high winds and heavy seas—during transit, the risk of capsizing and sinking becomes perilously elevated. Based on the inherent challenges and risks in current maritime nickel ore transportation, this paper puts forward targeted countermeasures and emergency measures. That is, ships transporting nickel ore must strictly abide by the IMSBC Code and the relevant regulations of the ship management company regarding the transportation of flowable cargoes. These measures include controlling the moisture content of nickel ore before loading, ensuring the seaworthiness of the ship, formulating good cargo handling plans, establishing a reasonable transportation route, and developing emergency response measures to mitigate the risk of ship capsizing due to instability in emergency situations. These findings are intended to serve as a valuable compass for the safe operation of nickel ore transportation at sea, guiding industry stakeholders toward enhanced safety and risk management.

Keywords

Nickel Ore Transport, Liquefaction, Effect of Free Surface, Safety Risks, Safety Assurance

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Received: 21 January 2025; **Accepted:** 24 February 2025; **Published:** 13 March 2025

1. Introduction

Nickel is a crucial non-ferrous metal raw material, indispensable in the production of stainless steel, high-nickel alloy steel, and alloy structural steel. Its strategic significance extends to the military domain, where it is integral to the manufacturing of aircraft, radar systems, missiles, tanks, naval vessels, spacecraft, and atomic reactors. In the civilian sector, nickel is commonly employed to produce structural steel, acid-resistant steel, and heat-resistant steel, finding widespread application in machinery manufacturing industries. Additionally, nickel serves as a ceramic pigment and anti-corrosion coating. Nickel-cobalt alloys, as permanent magnetic materials, are extensively utilized in fields such as electronic remote control, the nuclear energy industry, and ultrasonic technology. In recent years, the burgeoning new-energy vehicle sector has further driven the demand for nickel. However, the global distribution and consumption of nickel resources remain highly imbalanced [1].

The primary source of nickel is nickel ore. The global distribution of nickel ore is mainly concentrated in the tropical and subtropical regions of the Pacific Rim, as well as in countries like Russia and Australia. Many countries have a scarcity of nickel ore and have to rely on imports, making nickel ore transportation crucial to a country's economic lifeline and economic security. The main mode of nickel ore transportation is maritime transport. However, due to the fluidization characteristics of nickel ore, when external factors such as vibration, swell, and strong winds act upon it, the internal shear strength of the cargo can be easily lost, causing the cargo to behave like a liquid and form a free surface. This situation poses significant risks to the stability of the vessel and creates substantial hidden dangers for the safety of maritime cargo transportation [2].

In recent years, several severe shipwreck accidents have occurred due to improper loading of nickel ore. To enhance the safety of nickel ore transportation and prevent the occurrence of shipwrecks involving nickel ore carriers, it is crucial to analyze the safety risks associated with maritime transport of nickel ore and identify corresponding countermeasures. At present, a number of professionals have conducted research on Nickel Ore and its Safe Shipment and proposed some security measures.

Shen J. based on the special properties of nickel ore, analysis the root cause why nickel ore are easy to liquefaction when carried on board, point out the key point of safe transport nickel ore is keep its moisture content below TMP, also represent some useful precautions on nickel ore safe shipment [3].

Lee H L. developed a response plan for a handymax bulk carrier liquefaction incident, with the objective to reduce the risk of capsizing and reclaim its stability by redistributing her homogeneous stowage loading on board into alternate loading [4].

Mohajerani A. reviewed the behaviour of Iron Ore Fines during marine transportation by analysing the factors that lead to geotechnical related failures. proposed some possible solutions that may be implemented and recommendations for further studies, in order to reduce the likelihood of cargo shift occurring [5].

Zou Y. took advantage of numerical simulations to make a thorough analysis on the physical mechanisms of capsizing and found that the collapse of the shear force which is mainly determined by the viscosity coefficient has led to a shift of the liquefied cargo when the inertial force of the liquefied cargo is greater than the shear stress, thus causing an abrupt loss of the stability [6].

Munro M C. investigated the collective causes of liquefaction of solid bulk cargoes on board bulk carriers in order to make recommendations to prevent future incidents from occurring [7].

Based on the current research on the sea transportation of nickel ore, this paper proposes more targeted and operable safety and emergency measures from the aspects of route design, cargo loading, unloading, supervision, ship operation, etc., by studying the properties of nickel ore and the stability of ships, combined with the requirements of IMSBC CODE for the transportation of nickel ore and other flowable cargoes, as well as the maritime practice experience of nickel ore transportation.

2. Nickel Ore Cargo Properties and Causes of Liquefaction

2.1. Nickel Ore Cargo Properties

Section 7 of the IMSBC Code (International Maritime Solid Bulk Cargoes Code) describes the characteristics, potential hazards, and preventative measures to minimize the risks associated with Group A cargoes (cargoes that may liquefy). Group A cargoes may appear as dry granular materials when loaded but can contain a significant amount of moisture, which can cause them to become liquefied or unstable due to compaction and vibration during navigation. When the moisture content in the cargo exceeds the Transportable Moisture Limit (TML), liquefaction can occur, causing the cargo to shift. Some cargoes are prone to moisture migration, and even if the average moisture content is below the TML, hazardous bottom wetting can still occur. Although the surface of the cargo may appear dry, unnoticed liquefaction that leads to cargo shifting can also occur. Cargoes with high moisture content are particularly prone to sliding at a significant incline. When forming a viscous fluid state, if the ship lists to one side, the cargo may flow to that side, but it may not completely flow back when the ship lists to the opposite side. This can cause the ship to gradually reach a dangerous angle of heel and suddenly capsize.

Nickel ore is classified as a cargo that may liquefy. Its particle diameter is generally less than 2 mm, with uneven particle sizes, and its moisture content typically ranges from 20% to 50%. Tropical lateritic nickel ore, in particular, is a wet-type lateritic nickel ore, with a Flow Moisture Point (FMP) of approximately 35% to 38%. The Transportable Moisture Limit (TML) is set at 90% of the FMP, which equates to a moisture content of around 31.5% to 34.2%. Due to its high moisture content, it has a tendency to liquefy. Its density is slightly lower than that of other ores, with a stowage factor of 0.55 to 0.71. The characteristics of nickel ore are shown in Table 1:

Table 1. *Characteristics of Nickel Ore Cargo.*

Physical Properties			
Size	Angle of Repose	Bulk Density (kg/m³)	Stowage Factor (m³/t)
Variety	Not Applicable	1400 to 1800	0.55 to 0.71
Hazard Classification			
Category	Subsidiary Hazard	MHB	Group
Not Applicable	Not Applicable	Not Applicable	

2.2. Causes of Nickel Ore Liquefaction

Nickel ore extraction at mining sites involves a long and complex process. Most nickel ore mining areas are newly developed ports, and the moisture content of the cargo depends on its natural moisture conditions. Shippers and shore facilities often lack adequate storage yards for drying the cargo and sufficient tarpaulin covers. Transport barges usually lack hatch covers and drainage equipment or measures. As a result, the methods, measures, and conditions for reducing moisture content are very limited, as shown in Figure 1. This is especially problematic during the rainy season, as the actual cargo loaded onto the ship may significantly differ from the cargo characteristics testing report obtained within seven days before loading. It is common for the overall moisture content in the cargo holds to exceed the TML or even the FMP. Discrepancies between the moisture content reports and cargo information declarations provided by the shipper and the actual loaded cargo are also common.

Figure 1. *Storage and Barge Transport of Nickel Ore.*

Nickel ore itself is classified as a cargo that may liquefy, and a portion of water is present within the cargo. During transportation, factors such as the ship's rolling or impact can lead to liquefaction. A significant amount of water accumulates on the cargo's surface, forming a free surface-like condition that reduces the ship's stability. Combined with the effects of wind and waves, the ship continuously rolls and pitches. This slurry not only reduces the ship's stability lever but also accelerates the liquefaction of the nickel ore. On the other hand, the dry side of the cargo hold sinks and does not easily move back and forth with the ship's rolling, increasing the angle of heel and, in severe cases, leading to the ship's capsizing and sinking.

3. Causes of Self-Sinking in Nickel Ore Transport Ships

The dangers associated with the transport of nickel ore mainly stem from three aspects: first, the high moisture content of the cargo at the bottom of the hold, causing bottom cargo wetting and the risk of overall or partial cargo sliding; second, the high moisture content of the surface cargo, leading to surface seepage and liquefaction, resulting in the risk of flow (as shown in Figure 2); third, the high overall moisture content, causing the cargo pile in the hold to soften like a semi-fluid, leading to deformation of the entire cargo pile and shifting of the center of gravity.

Figure 2. *Liquefaction of Nickel Ore in the Cargo Hold.*

In summary, the primary cause of self-sinking during the maritime transport of nickel ore is due to the formation of a free surface from liquefaction and the subsequent movement of the cargo. Solid cargo becomes fluid and mobile when wet, and once the liquefied cargo shifts to one side of the hold, it generates a heeling force. The farther the cargo moves from the center, the more significantly the righting level is reduced. This results in a weakened ability of the vessel to return to its original stable state, thereby reducing the initial stability height. When the righting moment of the vessel becomes less than the heeling moment imposed by external wind and waves, the vessel is at risk of capsizing and sinking.

3.1. Effect of Free Surface

Most cases of instability in ships are the result of free surface effects. This occurs when tanks within the ship are only partially full, or slack. When a ship heels, liquid within a partially filled tank will move to the low side. It will be seen that this adversely affects the transverse statical stability of a ship. It is essential that the crew fully understand the effect of free surface on transverse statical stability and the necessity to maintain to a minimum the effect of free surface any one time as appropriate.

Consider the ship shown with a partially filled tank. Imagine the liquid in the tank is frozen and the ship is heeled to a small angle. In the heeled condition GZ is the righting lever. Because the liquid is frozen it acts as a static weight and does not move (As shown in Figure 3).

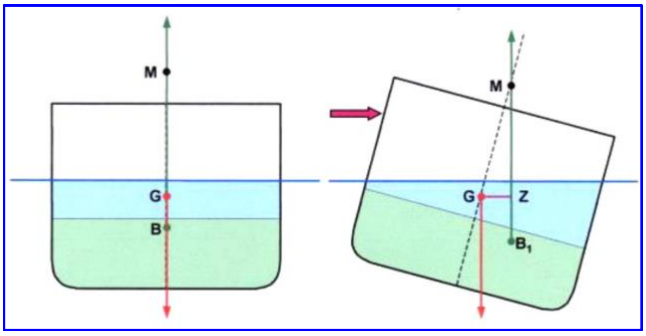

Figure 3. *Ship Heeling without Considering Free Surface Effects.*

when the liquid in the tank thaws out and is then free to move as the ship heels, as would normally be the case. In the initial upright condition everything appears as normal. But when the ship is again heeled by an external force to the same small angle of inclination. A wedge of the liquid is transferred to the low side of the ship (gg_1). Since weight has shifted G moves parallel and in the same direction as the shift of the weight (GG_1). This causes the righting lever to be reduced from GZ to G_1Z_1(As shown in Figure 4).

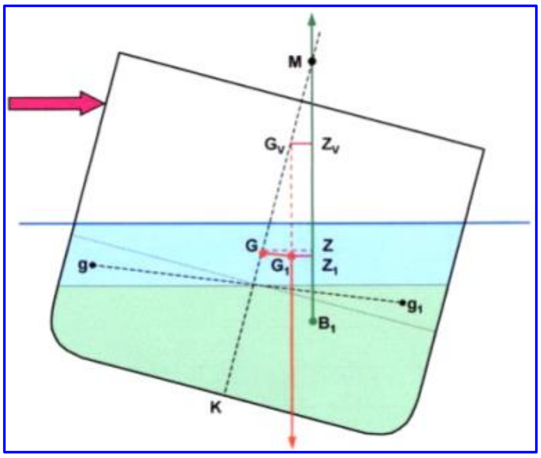

Figure 4. *Ship Heeling Considering Free Surface Effects.*

The righting lever G_1Z_1, is the same as the GZ that would have existed had G been raised to G_V. GG_V represents the virtual rise of G that results from the free surface effect of the slack tank. (G does not actually rise, but the movement of the liquid in the tank has the same effect on GZ values as if G had actually been caused to rise - hence the term 'virtual rise of G'!)

When calculating the GM of a ship it is important that the effects of free surfaces in slack tanks are considered. The loss of GZ will be greater as the number of slack tanks increases, the cumulative effect of all slack tanks must be accounted for.

It is always the fluid GM that must be determined to take account of the reduction in GZ values that arises from liquid movement within the ship as it is heeled.

3.2. Effect of A Transverse Shift of Weight (List)

When a ship is initially upright with G on the centre line, heeled by an external force to some angle q (large or small) with a weight 'w' on one side (Figure 5). The righting lever is GZ.

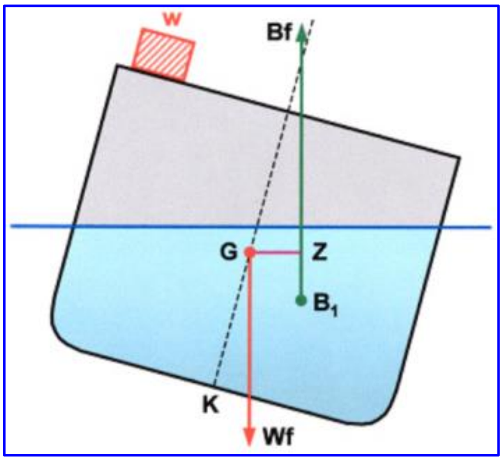

Figure 5. *Ship Heeling Before Weight Shift.*

The weight is then moved across the deck to the other side causing G to move parallel to and in the same direction as the shift of weight to G_H. The ship heeled to the same angle of heel as before (Figure 6).

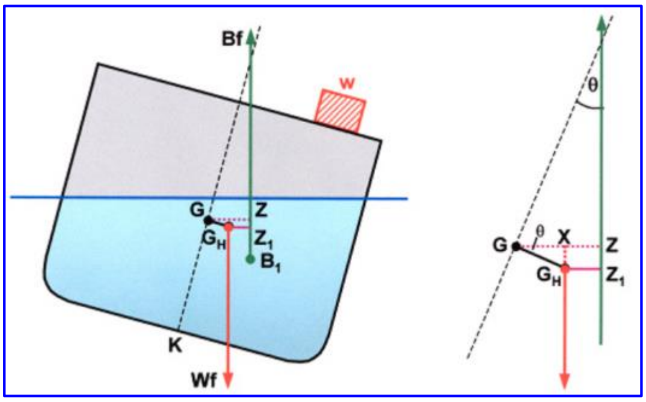

Figure 6. *Ship Heeling After Weight Shift.*

The righting lever has been reduced from GZ to G_HZ_1 as a result of the transverse shift of weight. The decrease in GZ at a particular angle of heel can be easily determined by:

$$\text{LOSS OF GZ}=GG_H\times\cos\theta$$

After nickel ore liquefies, water forms a free surface on the top layer, and the cargo also moves with the ship's rolling, generating a heeling moment that reduces stability. The second edition of the "Guidelines for the Safe Carriage of Nickel Ore" published by the ClassNK (Nippon Kaiji Kyokai) concludes that there is no significant difference between the movement of nickel ore and grain in terms of their impact on stability [8]. The International Grain Code (IMO) showed that the Master should ensure the ship is upright prior to sailing to minimize the adverse effects of grain shift. It should always be borne in mind that in extreme circumstances there may be a potential for cargo shift, which may further significantly reduce the stability of an already listed ship.

Based on numerous investigation reports of self-sinking nickel ore transport ships, the primary cause of most self-sinking incidents is due to the excessive moisture content of the loaded nickel ore, exceeding the Transportable Moisture Limit (TML). This leads to the liquefaction of the cargo within the hold, forming a free surface on the cargo and causing cargo movement. The ship's stability then declines sharply. When the ship encounters adverse weather conditions such as high winds and waves, the combined effects of wind, waves, and ship motions cause the cargo on the other side of the hold to dry out and settle, preventing it from restoring its original position with the ship's rolling. This further increases the angle of heel [9]. According to the formula for the reduction of the righting lever of a ship at a certain angle of heel, LOSS OF GZ=$GG_H \times \cos\theta$. As the angle of heel increases, the center of gravity G of the ship further shifts to the inclined side, and the righting lever G_HZ_1 further decreases (as shown in Figure 6). The reduction of the righting lever leads to a decrease in the righting moment. When the righting moment of the ship is less than the heeling moment caused by external forces, it ultimately results in ship's capsizing and sinking. It is important to note that if the moisture content of the cargo at the bottom of the hold exceeds the TML, even if the moisture content of the cargo at the top of the hold does not exceed the TML and the overall moisture content of the hold is below the TML, the entire cargo hold can still liquefy after the ship encounters severe weather conditions for two days [10].

4. Problems and Risks in Maritime Transport of Nickel Ore

4.1. Inaccuracy of the "Cargo Declaration" Provided by the Shipper

The "Cargo Declaration" is an important basis for determining whether the cargo meets maritime transport standards, especially for cargoes prone to liquefaction. It includes critical factors such as the Flow Moisture Point (FMP), Transportable Moisture Limit (TML), and the moisture content of the cargo.

Requirements of "IMSBC Code": The shipper shall be responsible for ensuring that sampling and testing for moisture content is conducted as near as practicable to the date of commencement of loading. The interval between sampling/testing and the date of commencement of loading shall never be more than seven days. If the cargo has been exposed to significant rain or snow between the time of testing and the date of completion of loading, the shipper shall be responsible for ensuring that the moisture content of the cargo is still less than its TML, and evidence of this is provided to the master as soon as practicable.

However, due to the limited number of independent, qualified laboratories and institutions capable of conducting cargo inspections in some nickel ore exporting countries, most inspections are performed in on-site laboratories at the mining sites. It is challenging to ensure these facilities have the standard inspection equipment and proper testing environments. Additionally, the chemical and physical properties of nickel ore vary by location, making it difficult to accurately determine the Transportable Moisture Limit (TML) and the moisture content of the cargo [11]. Moreover, to reduce inspection costs or due to constraints from the cargo transport contract's loading period, shippers may create false cargo declarations even when the moisture content of the cargo has not met the transportable standards.

4.2. Precipitation During Barging and Loading

As previously mentioned, the global distribution of nickel ore is mainly concentrated in the tropical and subtropical regions of the Pacific Rim, which are characterized by a tropical rainforest climate. This climate features high temperatures, heavy rainfall, and minimal temperature variation throughout the year. Despite the moisture content of the cargo being tested and meeting the transportable standards within seven days before loading, the mode of nickel ore transport often involves barging. Most transport barges lack hatch covers and other protective facilities, as well as drainage equipment and measures. During the barging or loading period, if there is significant rainfall, the moisture content of the nickel ore can increase substantially, often exceeding the Transportable Moisture Limit (TML).

4.3. Non-compliance by Crew with Relevant Provisions of the IMSBC Code

The IMSBC Code clearly outlines the determination procedures and the guidelines for loading, carrying, ventilation, and weather considerations for Group A cargoes, including nickel ore. However, self-sinking incidents involving nickel ore transport ships often result from crew negligence or a partial understanding of the rules. For instance, crew members may fail to properly develop loading plans in strict accordance with the IMSBC Code, inadequately test the moisture content of the cargo, fail to close the hatches promptly during rainfall, improperly trim the cargo or use unreasonable trimming methods, have malfunctioning bilge systems, ensure the cargo hatch covers are not watertight, neglect to regularly inspect the surface condition of the cargo during navigation, underestimate the risks of liquefied nickel ore, and fail to take appropriate and effective measures to prevent cargo movement after liquefaction has occurred.

4.4. Improper Route Design and Ship Handling Methods

Sometimes, in order to save transportation costs, charterers request the captain to plan the route based on the shortest distance principle. However, the shortest route may encounter severe weather conditions such as strong winds and high waves due to seasonal climate changes during transit, and there may be no suitable sheltered anchorages or ports along the way for emergency stops. Under the influence of strong winds and waves, the ship's rolling and pitching intensify, further exacerbating the liquefaction of the nickel ore in the cargo hold. If the ship is improperly handled at this time and navigates in a way that encounters beam seas, severe rolling can easily lead to the ship capsizing.

5. Safety Measures for Nickel Ore Transport

Based on the causes of nickel ore liquefaction, its impact on ship stability, and the issues and risks associated with maritime transport, ensuring the safety of nickel ore sea transportation primarily involves controlling the moisture content in the ore. Additionally, it requires attention to the condition of the maritime vessels themselves, as well as routine preparation, emergency preparedness, and emergency response measures [12].

5.1. Controlling the Moisture Content of Loaded Nickel Ore

Due to the excessive moisture content in nickel ore, a free surface can form on the surface of the cargo hold. In severe cases, this can cause the entire cargo in the hold to shift. Both the free surface and the shifting of the cargo can gradually shift the ship's center of gravity towards the side of the tilt, reducing the righting level and the righting moment. When the ship's righting moment becomes less than the heeling moment imposed by external wind and waves, there is a risk of the ship capsizing and sinking. Therefore, controlling the moisture content of the cargo during the loading of nickel ore is crucial. In maritime practice, the moisture content of loaded nickel ore can typically be controlled from the following aspects:

1) Before loading, the captain should request the shipper to provide a complete and valid cargo declaration as early as possible. The cargo declaration materials should include, at a minimum, information on the stowage factor, trimming methods, likelihood of shifting, moisture content, TML, and Flow Moisture Point (FMP). The captain should carefully study the information in the cargo declaration, particularly the moisture content and the TML. If the moisture content of the cargo is very close to the TML, it is important to consider the reliability of the cargo declaration provided by the shipper and the potential increase in moisture content due to possible precipitation. Therefore, close attention should be paid to the condition of the cargo during the loading process.

2) Before loading each barge of cargo onto the ship, crew members need to conduct on-site sampling of the cargo from different parts of the barge to test its moisture content. If there is a discrepancy between the suitability of the cargo for loading and the cargo declaration, loading should be immediately halted, and evidence should be collected. The incident should be promptly reported to the company, P&I Club, cargo owner, charterer, agent, and other relevant parties, with detailed records carefully maintained. There are two common methods used by the crew to test the moisture content of nickel ore:

a) Cylinder Test Method Introduced by the IMSBC Code [13]

Half fill a cylindrical can or similar container (0.5 to 1 L, capacity) with a sample of the material. Take the can in one hand and bring it down sharply to strike a hard surface such as a solid table from a height of about 0.2 m, Repeat the procedure 25 times at one or two second intervals. Examine the surface for free moisture or fluid conditions. If free moisture or a fluid condition appears, arrangements should be made to have additional laboratory tests conducted on the material before it is accepted for loading.

Figure 7. Cylinder Test Program.

b) Oven-Drying Method

Sampling 5-10 KG, place it in an oven and bake for 1-2 hours. Then, put it on a stove and dry it until no steam comes out from the cargo surface and the cargo is completely dry. After drying, weigh the sample to determine the weight of the evaporated water and calculate the moisture content of the cargo. Ensure the cargo moisture content is below the TML before allowing it to be loaded onto the ship.

c) Hand Squeeze Test

Grab a handful of the cargo and squeeze it tightly with your fingers slightly apart. If the cargo seeps through the gaps between your fingers, it indicates that the moisture content is excessive, and the cargo should not be loaded onto the ship.

3) According to Regulation 34-1 of Chapter V of SOLAS, the captain is granted absolute authority to make or execute any decisions necessary for the safety of life at sea and the protection of the marine environment based

on their professional judgment [14]. If the cargo shows issues after testing with methods such as the CAN TEST, if there is evident standing water on the barge or cargo pile, if there is splashing cargo inside the hold during loading, if there is a free surface on the top of the cargo in the hold, or if there is evidence that the certificates are not reliable, the captain can decide to refuse loading.

4) During the loading process, if rain occurs, the cargo hold hatches should be closed promptly. To prevent the inability to close all cargo hold hatches in case of sudden rain, hatches of cargo holds not engaged in loading operations should remain closed throughout the loading process. During unloading, unless all cargo is being discharged at the same port, the same requirements as during loading should be followed.

5) Before loading, all cargo hold hatches should undergo chalk and hose testing to ensure they are weather-tight and in good condition. If any issues are found during testing, the captain should immediately report to the management company. When departing fully loaded, all cargo hold hatch covers should have their securing bolts tightened.

6) All cargo hold bilge alarm systems, bilge piping systems, sounding pipes, and other related systems must be in good working condition. During navigation, the bilge wells, ballast water tanks, and water tanks should be checked at least twice daily, in the morning and evening, to ensure they are functioning normally. If any abnormalities are found, the cause should be promptly investigated. Any seepage water from the cargo should be promptly discharged, and detailed records should be maintained in the ship's logbook.

7) During navigation, especially when there are waves on deck or in humid weather, ventilation of the cargo spaces is not permitted. If there is ample sunlight and calm seas, the cargo hold hatches can be opened to air-dry the cargo, allowing the evaporated moisture to be released. Additionally, the condition of the cargo in the hold should be monitored for any changes in its form.

5.2. Routine Preparation

During the loading and transportation of nickel ore, in addition to controlling the moisture content of the cargo itself, it is also necessary to ensure that the ship's drainage system is functioning properly to promptly remove any accumulated water in the cargo holds. During the stowage process, efforts should be made to minimize the impact of free surface effects on the ship's stability. Additionally, the ship's seaworthiness should be ensured to enhance its ability to withstand external factors. It is also advisable to select a reasonable planned route to reduce the influence of external factors.

1) Ensuring the seaworthiness of the vessel, verifying the structural condition of the ship, the watertight integrity of the cargo holds, and the functionality of all cargo hold bilge alarm systems, bilge piping systems, sounding pipes, portable drainage equipment, main engine, electrical systems, steering gear, windlass, and other mechanical equipment, as well as navigation and communication devices, to ensure all equipment is safe and operational.

2) Upon receiving the voyage instructions, the chief officer must prepare the stowage and loading plan based on the cargo quantity and the specific conditions of the vessel. This includes calculating stability, strength, and trim to ensure compliance with requirements, minimizing the impact of free surfaces caused by oil and water, and ensuring that ballast water operations are carried out strictly according to management procedures. The vessel must be in a safe upright condition, and every step of the loading process as well as the final loaded condition must meet the requirements for safe navigation at sea.

3) Before the end of loading in each cargo hold, according to the relevant provisions of the IMSBC Code, the cargo should be leveled to ensure it is evenly spread across the hold bottom, allowing for uniform weight distribution and preventing excessive stress on the hold bottom due to conical stacking. When using grabs for trimming, the surface should be compacted with the grabs after leveling. The hold should be shaped into a concave form, with the center lower than the sides, to facilitate the concentration of seepage water. Additionally, a few clean, half-empty barrels with perforated walls can be buried at appropriate positions within the nickel ore to collect seepage water, which can then be pumped out using a submersible pump.

4) Based on the safety assessment of the loaded cargo, a reasonable planned route should be established. In principle, the route should ensure relatively favorable weather conditions and include ports and anchorages along the way that can be used for shelter, emergency berthing, and unloading. The largest scale nautical charts or electronic charts for the waters along the planned route and nearby emergency shelter areas must be available on the ship and updated to the latest version. Careful preparation and study of weather information should be conducted, and meteorological navigation services should be requested if necessary.

5.3. Emergency Measures

Based on multiple investigations into nickel ore transport ship sinking incidents, it has been found that the first 8-16 hours after departure is a critical period when cargo piles are prone to changes, and the first 3-5 days are a high-risk period for liquefaction. Monitoring cargo pile changes and liquefaction during the voyage is an effective way to prevent accidents [15]. Once liquefaction or movement of cargo occurs in the hold during the voyage, the ship needs to take emergency measures, including adjusting the ship's buoyancy, reducing rolling amplitude, and minimizing the effects of free liquid surfaces, to mitigate the risk of capsizing due to loss of stability.

1) If abnormal rolling occurs during the voyage, the captain should quickly identify the cause of the rolling and immediately report it to the management company, seeking shore-based support. Adjust the ship's speed appropriately to reduce wind pressure and hydrodynamic rolling moments. Adjust the course and speed to navigate with the wind and waves to reduce rolling and avoid resonance [16]. When changing the ship's course, do so when the wind and waves are minimal, avoid using large rudder angles, and prevent worsening rolling due to the combined effects of the ship's inclination during the turning process and adverse wind and wave conditions. Although counteracting with ballasting is an effective measure to reduce rolling, this method may lower the ship's reserve buoyancy and, since the cargo in the hold has already liquefied, moving cargo to the ballasted side could immediately lead to capsizing. Therefore, this method should not be used blindly.
2) Timely discharge cargo hold bilge water, including water seepage from the cargo. If weather conditions permit, open the cargo hold to pump out water from the cargo surface using a submersible pump. If it is difficult to remove surface water, try spreading large amounts of sawdust to absorb moisture to prevent an increase in free liquid surface or recurrence, thereby reducing the impact of free liquid surfaces on ship stability.
3) If adverse weather conditions prevent the ship from reducing rolling or discharging cargo seepage water, the ship should proceed to the nearest sheltered port or anchorage on the planned route. After stopping the vessel, adjust buoyancy and stability or unload the cargo at the refuge port. If, after a thorough assessment of all factors, the danger cannot be avoided, beaching the ship may be considered to prevent capsizing.

6. Conclusion

Nickel ore sea transport poses significant risks. The IMSBC Code has established clear regulations for the carriage of nickel ore and other flowable cargoes. Vessels transporting nickel ore must strictly comply with the IMSBC Code and the ship management company's relevant regulations for flowable cargoes. This paper analyzes the cargo characteristics of nickel ore and the causes of self-sinking in nickel ore carriers. It combines the regulations of the IMSBC Code with common issues and risks present in current nickel ore transportation practices. Proposes safety measures, including controlling the moisture content of the cargo during transportation, ensuring the seaworthiness of the vessel, proper handling of cargo, and establishing reasonable route planning to avoid adverse weather and other external conditions. Additionally, it suggests emergency measures that can be taken if liquefaction or cargo shift occurs in the cargo hold during the voyage, such as adjusting the ship's buoyancy, reducing the amplitude of rolling, and minimizing the impact of free surfaces. These safety and emergency measures can minimize the safety risks of nickel ore maritime transportation, ensuring the safety of life, the vessel, and the cargo. They also provide valuable guidance for the safe operation of other liquefiable cargoes.

Abbreviations

IMSBC	International Maritime Solid Bulk Cargoes Code
TML	Transportable Moisture Limit
FMP	Flow Moisture Point
G	Center of Gravity
IMO	International Maritime Organization
SOLAS	International Convention for Safety of Life at Sea

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Dong X, An F, Dong Z, et al. Optimization of the international nickel ore trade network [J]. Resources Policy, 2021, https://doi.org/10.1016/j.resourpol.2020.101978

[2] He, C. Research on Risk Management of Transporting Flowable Cargoes by Ship [D]. Dalian Maritime University, 2020. https://doi.org/10.26989/d.cnki.gdlhu.2020.001966

[3] Shen J. Nickel Ore and its safe shipment [J]. Advanced Materials Research, 2012. https://doi.org/10.4028/www.scientific.net/amr.396-398.2183

[4] Lee H L. Nickel ore bulk liquefaction a handymax incident and response [J]. Ocean Engineering, 2017. https://doi.org/10.1016/j.oceaneng.2017.04.036

[5] Mohajerani A, Dean J, Munro M C. An overview of the behaviour of iron ore fines cargoes, and some recommended solutions for the reduction of shifting incidents during marine transportation [J]. Ocean Engineering, 2019. https://doi.org/10.1016/j.oceaneng.2019.04.073

[6] Zou Y, Xi X, Su Y. A numerical study of a highly-viscous liquefied cargo in a rectangular ship tank [J]. Ocean Engineering, 2018. https://doi.org/10.1016/j.oceaneng.2018.10.054

[7] Munro M C, Mohajerani A. Liquefaction incidents of mineral cargoes on board bulk carriers [J]. Advances in Materials Science and Engineering, 2016. https://doi.org/10.1155/2016/5219474

[8] Zhang, J. Study on the Stability of Nickel Ore Transported by Handy Bulk Carriers [D]. Dalian Maritime University, 2016.

[9] Gao, D. Safety Analysis of Oceanic Nickel Ore Transport [J]. Port Technology, 2017, (12): 44-48.

[10] Yang, Z. Experience in Safe Transport of Laterite Nickel Ore [J]. Pearl River Shipping, 2017. https://doi.org/10.14125/j.cnki.zjsy.2017.13.041

[11] Wu, Z., & Xie, J. Safe Transport of Nickel Ore [J]. Navigation Technology, 2017.

[12] Cao, S. Several Issues Regarding the Safe Transport of Laterite Nickel Ore [J]. Navigation Technology, 2012.

[13] The International Maritime Solid Bulk Cargoes (IMSBC) Code, 2022.

[14] International Convention for Safety of Life at Sea (SOLAS), 2024.

[15] Dai, T. Management of Bulk Carrier Cargo Transport and Port Risk Control [J]. Tianjin Navigation, 2021.

[16] Wang, C. Transport of Flowable Cargoes on Bulk Carriers [J]. Tianjin Navigation, 2021.