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Stability Analysis of a Bulk Carrier under Damage Scenarios during the Loading of Polymetallic Nodules in the Clarion–Clipperton Zone

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ABSTRACT: A potential consequence of loading polymetallic nodules (PMNs) in a marine environment is liquefaction. During loading operations in the Clarion–Clipperton Zone (CCZ), the ship is exposed to cyclic rolling and pitching, which increases the risk of cargo liquefaction. This phenomenon poses a particular danger when PMNs liquefy under certain conditions. Combined with cargo shifting, liquefaction can significantly compromise the vessel's transverse stability —even when it occurs in a single cargo hold. Due to the limited operational experience in transporting PMNs, this study investigates the key risk factors affecting ship stability. The research discusses the likelihood of liquefaction, the influence of wind lever arms, and critical roll amplitudes under conditions where the weather criterion is not fulfilled. These aspects are analyzed through three representative damage scenarios. The findings indicate that, for the vessel analyzed, flooding in a single compartment does not result in overall stability failure. However, strict monitoring of cargo moisture content in relation to the transportable moisture limit (TML) remains essential to mitigate risks. The study concludes with practical recommendations to assist ship operators in managing these challenges effectively.

1 INTRODUCTION

Ship stability primarily depends on the position of its center of gravity relative to the transverse metacenter. The presence of partially filled tanks or free surfaces within cargo holds can severely compromise stability, potentially leading to vessel instability or capsizing[1], [2]. Liquefaction of cargo, where wet granular bulk cargoes transform into a fluid-like state, poses significant risks during transportation [3]. PMNs, due to their nature and moisture content, are susceptible to liquefaction under certain conditions.

Between 1988 and 2015, 24 suspected liquefaction incidents were reported, resulting in 164 fatalities and the loss of 18 vessels [3] pp – 1. Apart from several other reasons which put ships in danger, as argued by the International Association of Classification Societies [4], cargo liquefaction remains one of the most significant threats to ship safety.

While bulk carriers generally exhibit favourable intact stability margins, they may become particularly vulnerable to stability issues under specific conditions, as highlighted by Krata et al. [5] due to significant corrections to the transverse metacentric height caused by free surfaces. These corrections, illustrated in Fig. 1, highlight the influence on FSC values with respect to the displacement of bulk carriers.

From this perspective, the aforementioned considerations result in modifications to a vessel's seakeeping properties, primarily characterized by the following phenomena[6]-[8]

- Decrease transverse metacentric height (GM).
- Increased angle of heel.
- Reduced righting arms (GZ).

- Decreased dynamic stability.
- Change in the roll period of the ship.

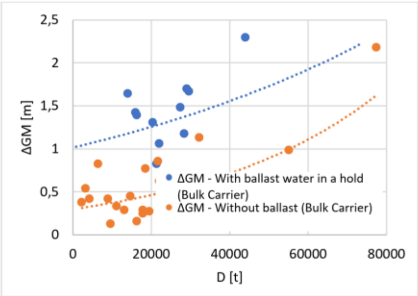

Figure 1 Stability corrections (FSC) based on analysis, developed using data from [5]

1.1 *Description of PMNs*

From a transportation perspective, the mass of PMNs and their liquefaction parameters are crucial for assessing the safety of bulk cargo transportation. Several studies [9]–[11] have evaluated their physical properties in the context of deep-seabed characteristics. The density of PMNs ranges from 1.75 to 2.40 kg/m³, while water content varies significantly between 39% and 66%. Using pycnometric techniques[11], the specific density of PMNs was determined to average 3.31 kg/m³. These findings emphasize that PMNs must be treated as heavy cargo.

1.2 *PMNs Properties and Associated Risks*

Analyses conducted by Bureau Veritas for Blue Nodules demonstrated that PMNs could be classified as "Manganese Ore," a cargo type included in the 2020 release of the International Maritime Solid Bulk Cargoes (IMSBC) [13]. According to the IMSBC, the bulk density of manganese ore ranges from 1.450 to 3.200 kg/m³, with a typical moisture content up to 15%. However, research [14] indicates that the free moisture content of well-drained PMNs can reach 20%, exceeding IMSBC values. Additionally, studies [15], suggest that even low-moisture cargo could still lead to liquefaction, necessitating stricter moisture control. During maritime transportation and loading in open seas, a combination of cyclic loading, fine particles, and moisture content can cause liquefaction [2]. This may result in the bulk carrier listing or capsizing. External factors, such as rain and monsoon conditions, can exacerbate moisture levels in the cargo without visible signs [16] Admittedly, comprehensively understanding the behavior of granular materials remains extremely challenging, as these materials exhibit significant variation under differing environmental and experimental conditions [17].

1.3 *Influence of Grain Size on Liquefaction*

As argued by Oldendorrf company grain size of cargo directly influences the risk of liquefaction [18]. In general, the size of nodule particles before extraction varies between 3–4 cm [19] as shown in Fig.2.

The particle size of PMNs, as tested in reliability analyses of mining systems, showed that hydrodynamic lifting motors and pumps undergo repeated impeller blade impacts and fragmentation, altering particle sizes within limits ranging from 1 mm to 15 mm [20], This variability poses an increased risk of liquefaction, especially in scenarios involving long vertical hydraulic pipeline lengths that have not yet been adequately tested.

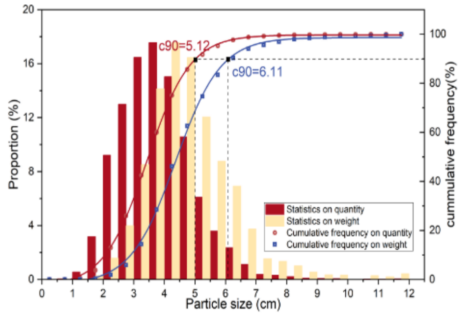

Figure 2. Cumulative proportions of the number and mass of nodules in different particle sizes [18, p. 7]

1.4 *Challenges in Ship Stability*

Current ship stability criteria are insufficient to reliably assess the risks associated with transportation of wet bulk cargoes, especially with the transport of PMNs. However, the research by Kacprzak [21] showed that, in intact conditions, the current model for assessing ship stability is sufficiently reliable, even when compared with roll motion predictions. Nevertheless, specific cargo implications highlight the need for updated stability assessments tailored to bulk carriers transporting liquefiable cargo. It is crucial that ships are made aware of the risks associated with loading PMNs as cargo. Despite existing studies on ship stability and liquefaction, no comprehensive assessment has yet addressed PMN-specific loading scenarios under offshore environmental conditions.

1.5 *Aim and Objective of the study*

The aim of this study is to assess the risk of ship stability failure during cargo liquefaction scenarios involving the flooding of a single cargo hold in a bulk carrier, with a primary focus on directly addressing whether liquefaction in one hold will result in the failure to meet regulatory criteria. The analysis focuses on the loading phase, during which the calculated righting arm (GZ) values may reach their minimum in the simulated sequence — while still remaining positive — potentially representing the most vulnerable intact stability condition. Under such circumstances, liquefaction may be initiated by the cumulative effect of repeated roll and pitch motions, which compress the cargo and force pore water out. Currently, operational experience with transporting potentially liquefiable materials (PMNs) under offshore conditions remains limited.

The specific objectives of this study are as follows:

- To analyze the stability of a bulk carrier under a flooding scenario involving one cargo hold filled with potentially liquefiable material.
- To assess vessel stability in accordance with IS Code (weather criterion).
- To identify critical roll amplitudes beyond which the vessel fails to meet the weather criterion
- To evaluate the impact of varying wind lever arms on ship stability and roll behavior.

– To propose practical recommendations for enhancing the safety of bulk carriers transporting PMNs.

2 RESEARCH METHOD

2.1 *Vertical and transverse shifts of VCG due to liquefication and cargo shift*

The free surface correction (FSC) is a mathematical approach used to consider the effect of the additional heeling moments caused by liquids during roll and heeling. These effects are typically represented as a virtual rise in the vertical center of gravity (KG), resulting in a corrected KG′ value, as shown in Eq. (1) [21]. This approach reduces the ship's righting arm curve (GZ) to reflect the destabilizing influence of the free surface.

$$KG' = KG + FSC \tag{1}$$

Free surface moment (FSM) may be calculated using methods presented in [22]. However, a widely used approach simplifies the process by basing the calculation on the moment of inertia of the tank horizontal projection. This method is typically applied during the calculation of initial stability and is expressed by Eq. (2), where $I_b \rho$ represents FSM

$$FSC = \frac{I_b \rho}{D} \tag{2}$$

where: I_b – lateral moment of inertia based on dimensions of the ships hold [m^4], ρ – density of fluid [t/m^3], D – displacement of ship [t].

In general, Eq. (2) for correcting KG is applicable only for relatively small angles of heel. Despite this limitation, it is commonly used worldwide due to its simplicity [5]. FSC is particularly significant in scenarios involving partially filled tanks or cargo holds. While the method has some recognized limitations, it often represents the worst-case moment, irrespective of the tank's or cargo holds filling level. Notably, a study by Krata [5] found that the highest values of FSM occur when the tank is filled between 40 and 60% of its volume, as illustrated in Fig. 3.

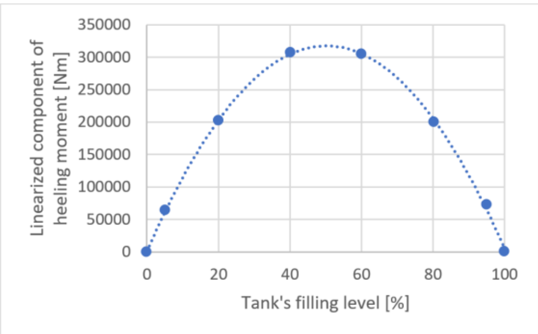

Figure 3. FSM in function of tanks filling level – developed based on data from [5]

Research conducted by S. Ferauge [23] uses an alternative approach to the calculation of Free FSM correction for fluidized cargo, emphasizing its applicability to high-density materials such as PMNs. Given the unique physical properties of PMNs, including their high density and AOR, this method offers improved accuracy in modeling stability scenarios. The formula for FSC under such conditions is expressed by Eq. (3)

$$\delta G_v = \frac{\rho_c L B^3}{12D} \tan(AOR) \tag{3}$$

δG_v – correction to KG due to fluidized cargo [m], L,B – main dimensions of ships hold [m], tan(AOR) – tangent of Angle of Repose ρ_c – density of cargo [t/m^3]

Eq. (3), unlike the classical FSC method, includes the tangent of the angle of repose (AOR), which reflects the geometry of the cargo surface in the hold. This allows for a more accurate representation of the free surface effect for materials such as PMNs. Although Eq. (3) does not explicitly depend on the filling ratio, the expected variability of FSM with tank filling — as shown in Fig. 3 — can be used to estimate its relative influence. Therefore, the formulation used in this study combines the material-specific advantage of AOR with a conservative approach to FSM magnitude.

Building on this formulation, the effect of the fluidized cargo is incorporated into the stability analysis through a correction to the ship's vertical center of gravity (KG), calculated as follows:

The KG of the ship is corrected by δG_v as calculated using Eq. (4): $KG' = KG + \delta G_v$ (4)

Finally, the corrected GZ curve, adjusted for the δG_v is expressed by Eq. (5):

$$GZ(\varphi) = lk - KG' \cdot \sin(\varphi) \tag{5}$$

where: lk – cross curves of stability [m], φ – angle of heel [°]

In this study, the corrected GZ curve will be utilized as the basis for further stability analysis, using Eqs. (4) and (5) to model scenarios involving PMNs liquefaction effectively. From an engineering safety perspective, simplifying assumptions and overestimation are preferred to ensure that worst-case scenarios are adequately captured. Major accidents often follow an unforeseen sequence of events, this constitutes a scenario gap [24], [25]. In this research, the unknown risks associated with potential liquefaction of PMNs are addressed by applying the worst-case free surface moment, regardless of the cargo hold's filling level. Therefore, in this study, FSC is calculated using Eq. (3), as it represents the worst-case scenario appropriate for modeling the potential liquefaction of PMNs.

The issue of cargo shift onboard a ship in waves has been extensively studied by [26] – [28] Then the transverse center of gravity (YG) deviates from zero (i.e., YG $\neq$ 0), the vessel develops a static list. In such scenarios, the GZ curve must be corrected to account for the shift using the following Eq. (6) [29].

$$G_1 Z_1(\varphi) = GZ(\varphi) - \Delta YG \cdot \cos(\varphi) \tag{6}$$

where: ΔYG – transverse shift of centre of Gravity [m].

These corrections are crucial for proper assessment in flooding scenarios. The above equations are formulated based on methodologies presented in the literature [21], [29]–[33]. The corrected G1Z1 curve thus serves as the basis for conducting a detailed stability analysis in accordance with the weather criterion outlined in the IS Code. However, the impact of free surface on the ship stability is discussed in detail in [8].

2.2 *Stability assessment by IS Code*

The formulation of the Weather Criterion is based on empirical relationships developed many years ago for vessels that do not necessarily represent modern ship designs with large superstructures [34]. In [35]–[38] various approaches to stability assessment are discussed, including alternative calculation methods permitted under the assumptions of the Second-Generation Intact Stability Criteria (SGISC).Many authors argue that current stability assessments, which rely on the standard assumptions of the IS Code, may be insufficient. Therefore, more detailed analyses — as proposed under SGISC — are recommended. The International Maritime Organization (IMO) has introduced SGISC, which incorporates five different failure modes, in response to recurring incidents linked to inadequate stability. In this study, we focus on damage stability based on Dead Ship Condition mode.

However, it should be emphasized that this research does not attempt to modify the existing Weather Criterion. All calculations — particularly those involving the Weather Criterion — are performed strictly in accordance with the standard IS Code, but the criterion is further extended in this study to determine the specific roll amplitudes at which the vessel fails to meet statutory stability requirements.

3 RESULTS

3.1 *Ship used in simulation*

To calculate ship stability under a specific flooding scenario involving a single hold, a B517 series vessel [39] was utilized. The detailed characteristics of the ship are presented in Tab. 1

Table 1. Principal Dimensions and Specifications of Bulk Carrier BCS-1

	Bulk carrier B517
Length between perpendiculars LBP [m]	185.00
Moulded breadth B [m]	24.40
Design draught T [m]	11.011
Deadweight DWT [t]	33390

In this study, the ship's stability is analyzed using the loading sequence method B, as developed in the author's work[40]. The analyzed bulk carrier has favorable stability characteristics due to its design, which incorporates both long and short holds. The short holds are specifically used for carrying heavy cargo. In the case of liquefaction, the transverse moment of inertia in short holds is approximately 38% lower compared to long holds of this ship. Moreover, shorter holds have a lower volume capacity, which increases the height of the cargo, raising the vertical center of gravity (VCG) in each hold. This, in turn, reduces the transverse GM which results in a decrease of roll accelerations. On the other hand, an increase in cargo volume correlates with the expected FSM, as discussed before and shown on Fig. 2.

3.2 *GZ curves during loading simulation in intact condition*

Large stability margin during loading simulation is observed, which decreases during last loading stages

Fig. 3 presents the GZ curves during the loading simulation. Based on Fig. 3, it can be observed that from the beginning of the loading process (stage 0), there is a significant increase in GZ values. After loading stage 1, the GZ values start to decrease, reaching their lowest point at the final loading stage.

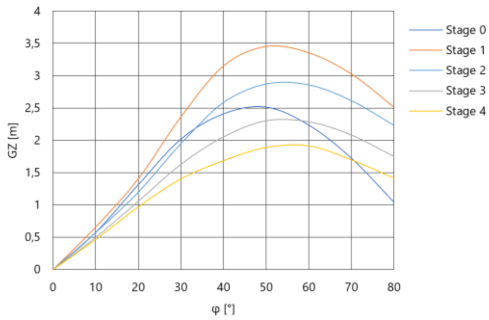

Figure 3. GZ curves for each loading stage

In general, this ship, under intact conditions, maintains positive stability throughout the loading process. However, since this analysis considers the worst-case scenario with respect to weather criteria, the last loading stages should be regarded as unfavorable, due to the largest mass of loaded nodules PMNs and maximum number of cyclic pitch and roll motion and lowest values of GZ arms.

3.3 *Stability Failure Scenarios and the impact on GZ Curves*

The transverse shift of cargo toward the starboard side is examined under three distinct damage scenarios. The transverse cargo profiles within the hold are illustrated in Figs. 4, 5, and 6. The cross-sectional areas of the cargo profiles are identical, indicating that the total amount of cargo remains constant across all scenarios.

In this study, cargo hold No. 1 of Bulk Carrier B517 is analysed. The damaged condition corresponds to internal flooding due to liquefaction of cargo within this hold. The permeability factor is included to indicate the proportion of the cargo hold volume available for internal flooding due to liquefaction. It is used here only for descriptive purposes and does not refer to flooding caused by hull breach. Relevant parameters are listed in Table 2.

Table 2. Parameters of the flooded hold resulting from liquefaction

Parameter	Hold no. 1 of Bulk Carrier B517
Hold length [m]	21.00
Hold Breadth [m]	24.40
Hold Height [m]	15.70
Flooded volume [m³], % of hold	2316.7, 48 %
Permeability factor [-]	0.529

The resulting ship static list is based on a hypothetical shift of cargo, with the corresponding values as follows:

- Damage scenario 1: $\varphi c = 10[°]$, $VCGc = 6.38$ [m], $\Delta YG = 0.283$ [m](see Fig. 4),

– Damage scenario 2: φc = 16.5[°], VCGc = 6.56 [m], ΔYG = 0.461 [m] (see Fig. 5),
– Damage scenario 3: φc = 22[°], VCGc = 6.79 [m], ΔYG = 0.569 [m] (see Fig. 6)

where: φc – angle of list of cargo [°], TCGc – Transverse centre of gravity of cargo [m], ΔYG – Difference of transverse ships center of gravity [m]

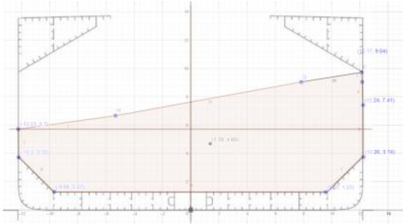

Figure 4 Cargo Profile within Hold under Damage scenario 1

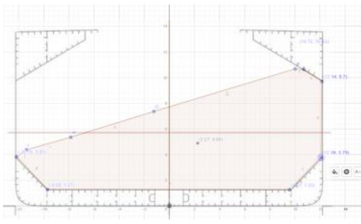

Figure 5. Cargo Profile within Hold under Damage scenario 2

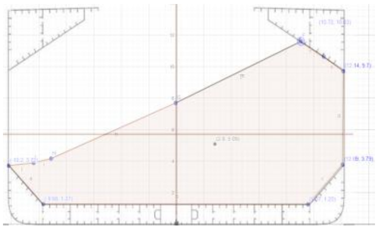

Figure 6. Cargo Profile within Hold under Damage scenario 3

The combined effects of liquefaction (FSC correction) and cargo shift (ΔYG correction) on the GZ curves in intact condition are illustrated in Fig. 7, which presents the final G_1Z_1 curves impacted by all aforementioned factors.

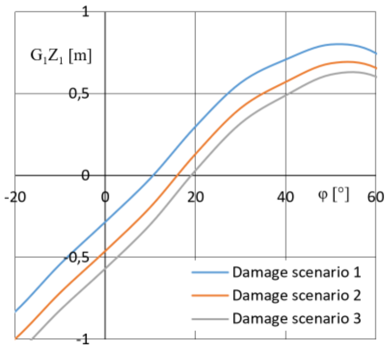

Figure 7. Influence of liquefaction and cargo shift on Final GZ Curves in three damage scenarios

In damage scenario 1, G_1Z_1 is reduced by 58%, while in damage scenario 3, the reduction reaches up to 67% in comparison to the intact condition. Under damage conditions, the angle of the maximum righting arm is reduced by an estimated 10°. This indicates that cargo shift associated with liquefaction significantly decreases the stability margin. The static list of the ship, resulting from the combined effect of liquefaction and cargo shift, is shown in Fig. 8. The cargo list φc is correlated with the ship's static list $φ_0$. An increase in the cargo list in the hold does not cause a proportional increase in the ship's static list. This indicates that the greater the cargo heel, the smaller its impact on the ship's heel, suggesting a nonlinear effect, as shown in Fig. 8

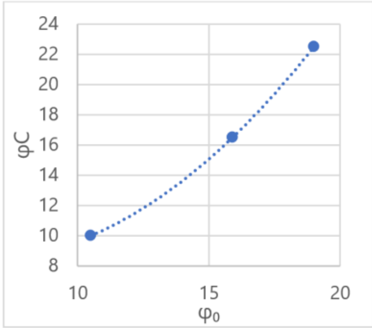

Figure 8. Relation between cargo list in hold to ship list considering all corrections to GZ

3.4 *Stability analysis based on weather criterion*

According to the assumptions of the IS Code, with a static wind pressure of P = 504 Pa, a range of roll motion amplitudes leading to noncompliance with the statutory weather criterion was determined using the authors' proprietary software.

The G_1Z_1 curves were described by polynomial functions, which facilitate a precise analysis. The areas under the G_1Z_1 curve were calculated using Simpson's rule, a standard method widely accepted in naval engineering. This method of integration is commonly used in naval architecture [41] and is recommended in ship loading manuals as a technique for determining the b/a ratio. The b/a ratio is an important factor in assessing the ship's stability under rolling motion, where a value of b/a < 1 indicates the threshold at which the vessel may become unstable [22]. By analyzing the b/a ratio in relation to roll amplitudes, critical roll amplitudes that lead to the failure of the weather criterion (b/a = 0.999) were identified. The values of roll motion leading to non-fulfillment of the weather criteria are as follows:

– Damage scenario 1 $φ_1$ (b/a = 0.999) = 34.7[°]
– Damage scenario 2 $φ_1$ (b/a = 0.999) = 27.8[°]
– Damage scenario 3 $φ_1$ (b/a = 0.999) = 23.6[°]

The relationship between the b/a ratio and roll amplitudes under the three damage scenarios is illustrated in Fig. 9.

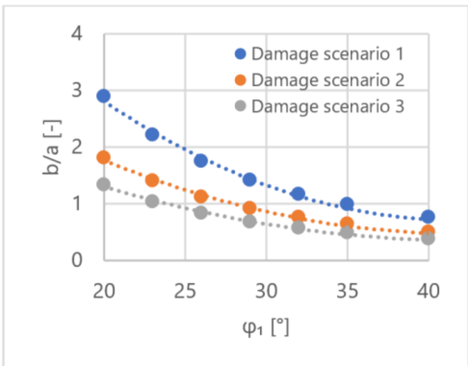

Figure 9. b/a ratio as a function of roll amplitudes for the investigated damage scenarios (standard wind lever arms).

3.5 *Critical roll amplitudes influenced by wind levers*

An increased wind levers alters the static heel induced by steady wind action; thus, the enhanced wind effect reduces the amplitude of roll motions, leading to a failure to meet the weather criterion.

Fig.10, 11, and 12 present the influence of varying roll motion amplitudes on the b/a ratio for several configurations of wind lever arms under Damage scenarios 1,2 and 3.

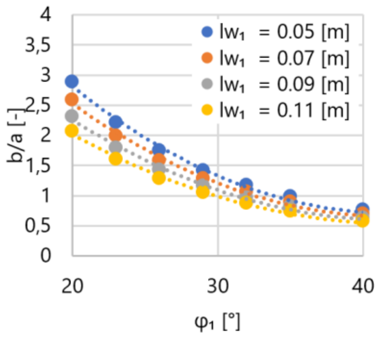

Figure 10. b/a ratio in damage scenario 1 for different set of wind levers

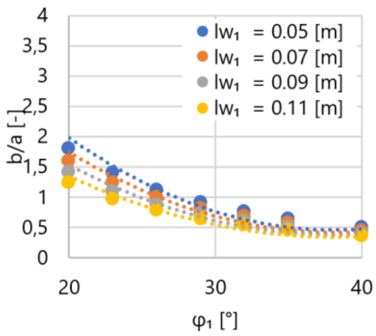

Figure 11. b/a ratio in damage scenario 2 for different set of wind levers

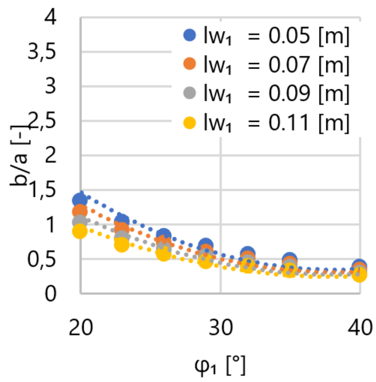

Figure 12. b/a ratio in damage scenario 3 for different set of wind levers

As shown in Fig. 13, increasing the wind lever arm (lw1) causes a noticeable decrease in the roll amplitudes at which the weather criterion is no longer satisfied (i.e., when b/a < 1).

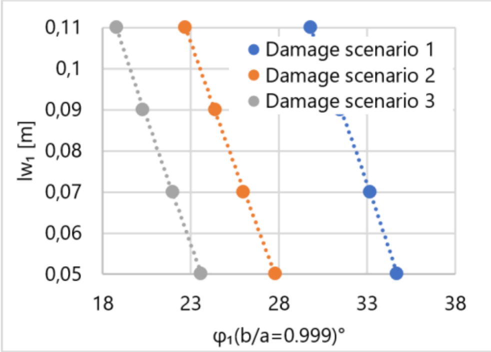

Figure 13. Limiting roll amplitudes as a function of wind lever arms causing non-fulfillment of the weather criteria.

The above analysis showed that the critical roll amplitude is reduced by:

– 14.1% for damage scenario 1,
– 18.3% for damage scenario 2,
– 20.4% for damage scenario 3.

This progressive reduction indicates a strong sensitivity of the system to external wind lever arms. The trend confirms that even moderate increases in wind lever arms can significantly diminish the vessel's safety margins under roll-inducing conditions.

4 DISCUSSION

The analysis conducted highlights the dynamic interplay between cargo configuration and damage scenarios that affect ships stability. The simulation results for the B517-series bulk carrier indicate that, under intact conditions, the vessel maintains a satisfactory stability margin throughout the loading process. However, this margin notably decreases during the final loading stages, when the accumulation of cargo mass and increased pitch and roll amplitudes pose a greater risk of liquefaction.

The impact of liquefaction and transverse shift of cargo in the analyzed damage scenarios indicates a gradual deterioration of the ship's transverse stability. Although the ship's heel does not increase proportionally with the heel of the liquefied cargo, the observed nonlinearity suggests that at higher cargo heel angles, its influence on the overall ship heel decreases. For increasing severity of the damage scenarios, the critical roll amplitude required to reach the failure threshold (b/a = 0.999[-]) decreases significantly— from 34.7° in damage scenario 1 to just 23.6° in damage scenario no 3. These results reinforce the need to assess liquefaction-prone cargoes not only through static stability margins but also in the context of dynamic responses during realistic sea states.

Additionally, the study demonstrates that increased wind lever arms reduce the allowable roll amplitudes before violating the weather criterion. Increasing the static wind lever arms resulted in a reduction of the roll amplitudes at which the vessel fails to meet the weather criterion—by 14.1%, 18.3%, and 20.4% for damage scenarios 1, 2, and 3, respectively. This trend indicates that the effect of changing wind lever arms on critical roll amplitudes is approximately linear.

This finding underscores the amplifying role of aerodynamic forces in stability failure and suggests that wind effects must be integrally considered in operational risk assessments.

Although cargo liquefaction in a single hold does not directly cause capsizing, it can significantly contribute to the risk under certain conditions. Based on the analysis, roll amplitudes exceeding 30° result in non-fulfillment of the weather criterion, which may lead to capsizing. This risk is heightened by the fact that the angle of repose (AOR) of polymetallic nodules is 33°, meaning that any roll motion exceeding this value may cause cargo shifting within each hold, even if the cargo is in a dry state. If shifting occurs in additional holds beyond the initially liquefied one, the cumulative effect may lead to a complete loss of stability and eventual capsizing According to weather statistics for the Clarion–Clipperton Zone (CCZ) the most common wave characteristic periods range between 6 and 10 seconds. As shown in the short-term prediction model of B517 bulk carrier in investigated loading simulation by Kacprzak [40] the highest roll amplitudes fall within this wave period range. These findings are valid under the assumption of constant wave parameters over a short duration. Additionally, it should be noted that, due to its ship geometric characteristics, the investigated vessel is expected to operate within an unfavorable wave period range, which corresponds to conditions that induce the highest expected roll motions.

However, a more realistic assessment should incorporate long-term prediction models. Given that the proposed ship is expected to operate year-round, a long-term model of exploitation is more appropriate, and it is likely to predict higher maximum roll amplitudes over the vessel's service life.

These findings continue previous research and suggest that, even under seemingly moderate sea conditions, dynamic effects related to liquefaction may lead to critical degradation of ship stability, and this kind of assessment should be delivered also for the master on board, with clear statement that flooding in one hold will not cause capsizing of the ship but will lead to a condition state of significantly reduced safety margin.

Based on the simulation results and stability assessment presented in this study, the following practical recommendations are proposed for vessels involved in the loading and transport of PMNs:

- Continuously monitor cargo moisture content, especially during loading, to prevent conditions leading to liquefaction.
- Perform loading operations only in calm sea states, as even moderate rolling can accelerate liquefaction. Once water is observed within one hold, this situation will not lead to vessel capsizing.
- Use onboard systems such as MRUs to monitor roll amplitudes and accelerations in real time, allowing early detection of critical dynamic conditions.
- Properly trim and evenly distribute the cargo. Since the angle of repose of PMNs is about 33°, roll motions beyond this threshold may cause cargo shift and transverse instability.
- Implement onboard emergency protocols for single-hold liquefaction, including rapid assessment of stability and clear guidance on when safety margins or weather criteria are exceeded

5 CONCLUSIONS

Polymetallic nodules (PMNs) are a cargo type not yet fully verified in terms of maritime transport safety. Their liquefaction behavior remains insufficiently understood, particularly given that mining and transshipment are expected to occur simultaneously under offshore conditions. Laboratory testing does not fully replicate the dynamic environment of real operations. This study assumes an idealized, fluid-like behavior of PMNs during liquefaction; however, in reality, the transition between granular and fluid states may be non-uniform and spatially variable. This warrants further experimental investigation.

This research evaluated whether liquefaction during the loading process poses a significant threat to vessel stability. The findings indicate that liquefaction in a single cargo hold does not cause global stability failure under low sea state conditions. Even when combined with transverse cargo shift, the effect remains limited—provided that liquefaction is confined to only one hold.

The analysis was carried out within the framework of the International Stability Code (IS Code), supplemented by second-generation intact stability criteria (SGISC), allowing for a broader and more realistic treatment of the vessel's dynamic behavior. Based on this framework, the study also developed practical recommendations for the safe handling and transport of PMNs.

Future research should focus on the development of systems capable of accurately monitoring vessel conditions during offshore operations to mitigate potential hazards. The proposed stability assessment model represents a preliminary step toward a more comprehensive evaluation framework. These results emphasize the importance of real-time onboard monitoring—particularly during marginal sea states—and may contribute to the development of future guidelines for PMN classification under the IMSBC Code.

ACKNOLEDGEMENT

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