Quasi-Static Numerical Modeling of an Ore Carrier Hold

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ABSTRACT: The problems associated with ore carriers' incidents, have preoccupied international organizations and many research laboratories which have been mobilised to identify the causes and seek for the solutions. The cargo liquefaction is considered to be the major cause of ore carriers' capsizing. The final aim of this research is to establish a new test procedure for evaluating the shear strength of loaded ore in view of its liquefaction prevention. First, a brief review is presented about the possible origins of cargo instability and examines the stress distribution by means of a quasi-static numerical modelling. Second, an assessment of the shear ratio variation, in terms of the hold inclination is established. According to this analysis, at a 15° hold inclination, the maximum shear ratio is less than 0.2 in all pile areas except under the residual slopes and at the surface that are assumed to be the most vulnerable parts.

KEYWORDS: Cargo, Ore carrier, Liquefaction, Numerical modeling, Shear ratio.

1. INTRODUCTION

Since the first specialized bulk carrier was built in 1852, economic forces have fuelled the development of these ships, causing them to grow in size and sophistication. Today's they have become specially designed to maximize capacity, safety, efficiency, and durability. Currently, bulk carriers make up 15% - 17% of the world's merchant fleets and range in size from single-hold mini-bulkers to mammoth ore ships able to carry 400,000 metric tons of deadweight (DWT) (Wikiwand, 2016).

The International Convention for the Safety of Life at Sea (SOLAS, 1974), defines bulk carrier as a ship which is constructed generally with single deck, topside tanks and hopper side tanks in cargo spaces, and it intended primarily to carry dry cargo in bulk, and includes such types as ore carriers and combination carriers. To simplify, a bulk carrier is a merchant ship specially designed to transport unpackaged bulk cargo, such as grains, coal, ore, and cement in its cargo holds (Figure 1).

The International Maritime Solid Bulk Cargoes Code (IMSBC, 2008) defines the solid bulk cargo as any material, other than liquid or gas, consisting of a combination of particles, granules or larger pieces of material, generally uniform in composition, which is loaded directly into the cargo spaces of a ship without any intermediate form of containment. Bulk cargo can be very dense, corrosive, or abrasive.

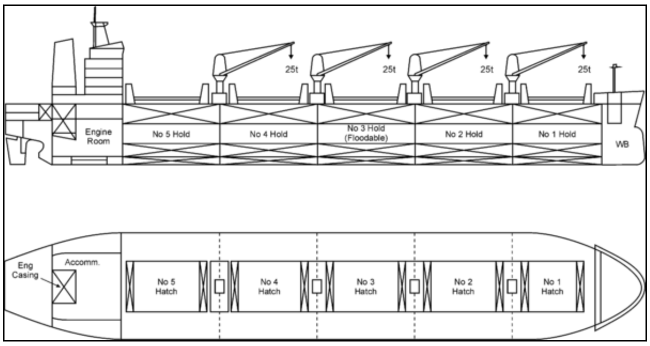

Figure 1 Bulk carrier (Wikiwand, 2016)

The safe transportation of solid bulk cargoes is a responsible task as their shipment may be associated with several hazards such as cargo liquefaction resulting in reduced ship stability, and even capsizing; Fire or explosion owing to chemical hazards; and ship structures damage due to poor loading procedures (INTERCARGO, 2013).

The most frequent and disastrous hazard is cargo liquefaction as it can cause ship structural damages, loss of lives, total loss of ships and high cost insurance matters. Liquefaction turns what appears to be a safe cargo into an easily movable one that can bear a detrimental effect on a ship's stability. It occurs when the cargo, loaded with high moisture content, is exposed to swell motions where it may lose its shear strength and turns into a fluid state (INTERCARGO, 2013).

Over the recent years, there is an increasing number of bulk carriers lost their intact stability due to cargo liquefaction. Part of them developed large angles of list whilst others unfortunately capsized. Table 1 in section 3 below illustrates the casualties happened in the last decade that involved severe ship stability failure due to cargo liquefaction. In fact, there is a wide range of ore cargoes that may liquefy, and they vary in their appearance and physical properties (Wang, et al., 2010). Therefore, international regulations have since been introduced to improve ship design and inspection, and to streamline the shipment of dangerous cargoes. For instance, in order to strengthen the safety regulation of the shipped liquefiable cargoes, the International Maritime Organization (IMO) published the IMSBC code, which became mandatory on January 1, 2011, under the SOLAS Convention. Its primary aim is to facilitate the safe stowage and shipment of solid bulk cargoes and to give detail information about the intended cargo to the ship. The IMSBC Code divides cargoes into three groups. Group A: cargoes which may liquefy (including Nickel and Iron ores). Group B: cargoes which possess a chemical hazard and could give rise to a dangerous situation on a ship. Group C: cargoes which are neither liable to liquefy nor possess chemical hazards (INTERCARGO, 2013).

For Group A cargoes, the IMSBC code recommends for materials prone to liquefaction several laboratory tests namely the Flow Table, the Penetration test and the Proctor/Fagerberg test to minimize the risk of liquefaction. They allow determining the upper bound of moisture content of cargo, which is defined by the Flow Moisture Point (FMP). It is the moisture content permitting the material for passing from solid to liquid state. The IMSBC Code provisions are that cargo must be shipped at moisture content significantly less than the FMP. According to the SOLAS Convention (1974), it is required that cargoes which may liquefy shall only be accepted for loading when their actual moisture content is less than their Transportable Moisture Content. For the Flow Table Test and Penetration Test, the TML is defined as 90% of the FMP. The TML of a cargo determined using the

Proctor/Fagerberg test is taken as equal to the critical moisture content at 70% degree of saturation.

Unfortunately, there are problems with both the determination of TML and moisture content due to the non-homogeneous form of the loaded cargo. Actually, much of the material is very fine clay-like particles but there are also larger rock-like particles. It may also be difficult to find qualified laboratories that are willing to certify the FMP of materials other than concentrates. Several laboratories have obtained widely differing results on samples supposedly representing the same cargo. This could be attributed to the composition and physical behavior which can differ greatly from mine to mine, from shipment to shipment, from the same mine, and even within a single cargo (North of England P&I Association, 2015).

This issue has raised awareness of researchers and made them concerned about finding a more reliable test procedure to assess the cargo liquefaction potential. For instance, Ota et al. (2000) suggested a new test procedure for evaluating the shear strength of nickel ore and thus the suitability for carriage of the cargo. The test procedure uses a 'cone Penetrometer', as showed in Figure 2, to measure the shear strength of a graded sample of nickel ore suitably compacted in a standard container.

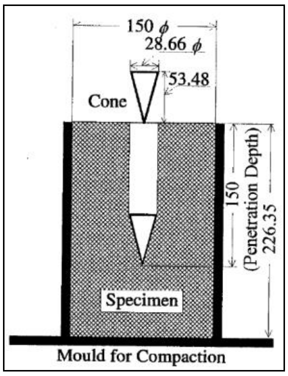

Figure 2 Cone penetrometer test (Ota et al, 2000)

Other researchers like Zou et al. (2013) have conducted a numerical simulation methodology, using the Level Set Method for the sloshing motion of fluid in a rectangular tank. The qualitative and quantitative results as free surface displacements and results as phase lags of the rolling motion with respect to the rolling axis have been presented. The simulations have shown that fluid with viscosity can have a negative effect on the stability of ships under the circumstances of beam waves and winds.

Despite the great importance of cargo liquefaction for ship's safety, a coherent, science-based, framework for the transportation of bulk cargoes has not been fully set up yet. Most of the existing codes contain instructions for the safe handling (loading, unloading) and stowage of bulk cargos which are mainly empirical. However, complexities can arise due to the complex ship-cargo responses to random external excitations, the variety of transported materials substantially differing in properties and sizes, the presence of humidity etc…

Taking into account all these features, an implementation of an adequate test to judge the liquefaction potential of cargoes before their shipment, is the final aim of this research. To do so, this work presents a preliminary study in order to understand the mechanism of cargo liquefaction and analyse the shear ratio variation during the shipment.

In the first part of this paper, an investigation on the cargo liquefaction phenomenon was elaborated. Afterwards, a quasi-static numerical model is established to analyse the hold stability and the stress variations. Later, an examination of shear ratio is conducted in order to enable an estimation of the maximum shear ratio and analyse its sensitivity according to the rolling movements that the ore carrier can undergo.

2. INVESTIGATIONS ON CARGO LIQUEFACTION

An investigation on cargo liquefaction was carried out to understand the mechanism of cargo liquefaction, highlight the potential causes and the possible consequences and finally summarize all the proposed solutions. Such a synthesis is elaborated for the first time and aims to eventually raise researchers and seafarers' awareness about this issue.

2.1 The mechanism of cargo liquefaction

According to Koromila et al. (2013), cargoes that are at risk of liquefaction are those containing at least some fine particles and moisture and further mined or stored in exposed areas which allow the soaking up of large amounts of water. Such cargoes at the time of loading are typically in granular state and look like dry. However, whilst at sea, they are subject to agitation due to the engine vibration; ship's rolling as well as swell impact. The oscillatory ship movement leads to resettling of the cargo particles and compaction of the inter-granular spaces. This compaction raises the water pressure sharply, forcing the particles apart, potentially leading them to lose direct contact. The cargo loses its shear strength and thus conditions are created for the material to behave like a liquid, i.e. to liquefy (IMO, 2012) (Figure 3). Although in some cases there is no obvious water, the cargoes become soft and loose, even leading to moving. Thus, the ore carrier's stability is greatly reduced, causing a shipwreck.

Figure 3 Liquefied Nickel ore
(North of England P&I Association, 2015)

2.2 Causes of cargo liquefaction

Conferring to investigations carried on several case histories of cargo liquefaction, five main potential causes have been identified for leading or contributing to cargo liquefaction. First, as reported by the Swedish Club (2012), the major reason of cargo liquefaction is related to unsafe storage conditions. In fact, due to the remoteness of mines from loading/port facilities, cargoes are stockpiled, uncovered usually next to the sea, meaning that they are subject to all weather conditions. During rain and monsoon seasons, the moisture content of the cargo will increase and this could not be visibly seen. The areas with high profile problem and where many casualties related to cargo liquefaction have occurred are characterized by a humid or tropical climate such as India (for iron ore fines), Philippines, Indonesia and New Caledonia (for nickel ore) (Andrei and Pazara, 2013). Second, conforming to the International Association of Classification Societies (IACS, 1998), researches show that insufficient loading plan and improper handling of heavy and high density cargo during loading and unloading cause dangerous situations for ship structure and create excessive stress. Moreover, inadequate pre-loading plans, rudimentary and limited loading equipment and methods, improper load distribution between holds, asymmetric load distribution, overloading or partially filled holds, physical and structural damage during discharging also cause fatal structure damage to ship hull. The third reason of cargo liquefaction is attributed to poor compliance of some shippers with the testing and certification requirements about moisture test of cargo required by the IMSBC Code, pitiable ships to shore communication, ignorance and deviation from loading plans. The non-involvement of seafarers is due essentially to the complexity of the pre-loading tests and procedures. The fourth cause was deduced after Zou et al. (2013) investigation of a number of ore carriers to understand how cargo liquefaction leads to the loss of stability. They noted that all ore carriers incidents, including sunken ones, were in good working condition, but experienced force 6–8 (Beaufort scale) beam winds and 2–4 m swells while sailing. As a matter of fact, big waves pass much energy to the cargo making its internal moisture rearrange or migrate to the surface and lead eventually to form free surface or cargo movement. The final identified cause is related to the cargo nature since most casualties commonly involved unprocessed or minimally processed ore cargoes; such as nickel ore, iron ore fines and iron sand. Those cargoes are fine grained soils containing high moisture, although they do not visibly appear wet.

2.3 The consequences of cargo liquefaction

Unfortunately, in previous literatures there are a number of investigations and analyses about cargo liquefaction, but there is little information on how the loss of stability could be attributed to the cargo liquefaction. The mechanisms of capsizing still remain uncertain (Zou et al., 2013). According to the accounts of survivors, all sunken ore carriers had developed a list before capsizing; this has led to a speculation that the sinkings are possibly attributed to the loss of stability. Furthermore, with reference to Xiaonan et al. (2014) statistical investigation, in 18 accidents out of 23, the free surface or cargoes sliding has occurred in the sunken ore carriers. The behaviour of a potentially liquefiable cargo and its threat to the ore carrier's stability is closely related to the effect of a liquid free surface. Indeed, certain cargoes are susceptible to rapid moisture migration and may flow to one side of the ship with a roll one way but not completely return with a roll the other way, progressively leading to loss of stability. Since ore carriers are not designed to carry liquid or semi-liquid cargoes, and when this process happens, it can cause stability problems such as small lists, collapsing cargo and in many cases it can result in huge sudden dangerous cargo movements that may lead to ship's capsizing and sinking. The free surface effect may take place gradually, giving seafarers time to compensate for a shift in cargo or they may occur in mere minutes that there is insufficient time to send off a distress signal before the vessel and crew are lost (Andrei and Pazara, 2013).

2.4 Solutions for cargo liquefaction

This issue has awakened the awareness of different involved institutions such as industries, researchers and ship masters. For instance, some scientists proposed the use of absorbing materials as an alternative to decrease the moisture content of cargoes prone to liquefaction. Popek (2011) investigated the possibility of using biodegradable thermoplastic materials to decrease the risk of cargo passing into the liquid state. After experimenting different mixtures of various starch material percentages, he concluded that the ability to absorb water is related primarily to the composition and percentage of starch material. On the other hand, many international maritime regulations recommended appropriate ways of cargo loading for avoiding capsize. Indeed, cargo trimming is a mandatory requirement in all holds for some materials, especially where there is a risk of cargo shifting or where liquefaction could take place. Industrials are also concerned about cargo liquefaction issue and proposed a new design of an anti free surface effect ore carrier (Laffoucrière, 2011). The major advantage of this ship is its holds design as it responds to the danger of free surface, makes this risk disappear and also allows for cargo loading without testing its humidity. As illustrated in Figure 4, it only allows a small movement of load and thus preserves the cargo balance with a capacity of 27000 tones. The downside of this solution is that there aren't a sufficient number of such available ore carriers.

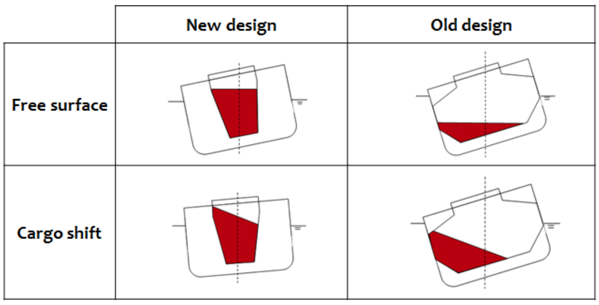

Figure 4 New ore carrier design

3. MATERIALS AND METHODS

3.1 Materials

The incidents cited in Table 1 were mostly linked to bulk carriers that foundered when carrying Nickel ore which is an inhomogeneous low-grade material consisting of very fine clay-like particles and larger rock-like particles. The Nickel ores' mineral structure and the weathering processes affecting them are such that they naturally display high water content with moisture varying from 20 to 28 % for rocky ore and 28 to 35 % for earthy ore and as much as 40 % in some earthy, clayey ores.

Table 1 Ore carrier casualty report (INTERCARGO, 2013)

Year	Lost ships	Lost lives
2011	13	38
2010	7	44
2002-2009	48	158

Preliminary consolidated undrained tests with measure of pore water pressure (CU+u) were elaborated on saturated nickel ore samples. The response to the applied consolidation stresses of 65 kPa, 130 kPa and 260 kPa, showed that the nickel ore sample is a slightly delating material with an apparent cohesion C' of 5 kPa and an internal friction angle φ' of 33°. The results of the geotechnical characterization of this sample indicated it is a highly plastic silt and looks like a fine lateritic soil, with the presence of many small friable aggregates that can be smashed by hand. The average permeability obtained by preliminary oedometer tests was about 5×10^{-7} m/s.

3.2 Methods

This study considers a quasi-static simulation of the rolling motion of a bulk carrier with rectangular holds. For simplicity, the parameters of liquefied cargo are assumed to be the same in all parallel cross sections of the holds and can be represented in a 2D cross section in plane strain. The numerical model of the hold is carried out by using commercial design software PLAXIS based on the Finite Element Method.

Since the rolling of the ore carrier appears to be the most risky motion, this study was limited to analyze its effect on the cargo. Under quasi-static modeling, this movement has been reduced to a progressive inclination of the hold from a horizontal state to a 15° inclined stated as illustrated in Figure 5. The choice of the rolling angle embraced in this simulation was deduced from investigations carried on previous incidents, where most of the ore carriers have developed a list between 15 and 18 degree when carrying liquefied nickel ore on journeys from New Caledonia to Australia.

To study the stress distribution in the loaded cargo during its journey, stability, plastic and consolidation analysis were conducted for both the horizontal and the inclined hold. Afterwards, a shear ratio study was lead to analyze its variation in terms of the hold inclination since it is the most important parameter to characterize cyclic excitation.

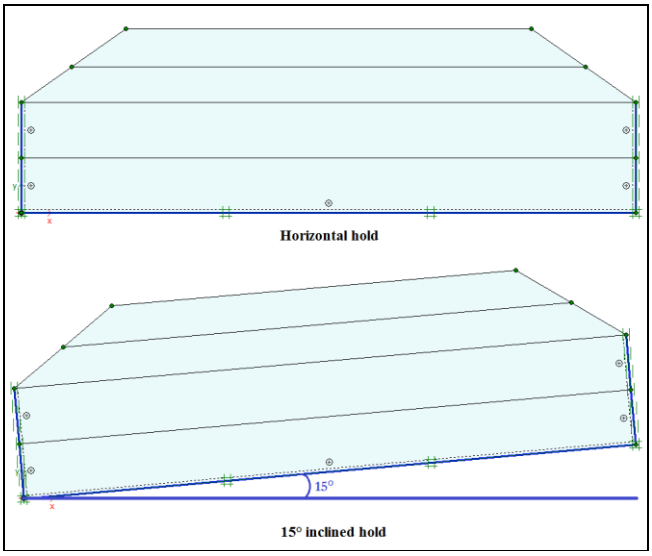

Figure 5 Hold positions

3.2.1 Stability analysis

A stability analysis was carried out in order to determine the potential sliding surfaces of the ore pile under drained and undrained conditions.

On one hand, the application of the c/φ reduction procedure in the PLAXIS code was performed under drained conditions. This method is based on the reduction of the shear strength (S_u) and the tangent of the friction angle (tan φ) of the soil in steps until the soil mass fails. Plaxis uses a factor to relate the reduction (Fs) in the parameters during the calculation with the input parameters.

On the other hand, under undrained conditions, the potential sliding surfaces were determined by mean of the calculation method of vertical slices at limit equilibrium (calculation code TALREN). This method consists in cutting the slope into fine slices so that their base can be comparable with a straight line then to write the equilibrium equations.

3.2.2 Plastic and consolidation analysis

The plastic analysis allows plotting the mean (p′) and deviator stress (q) distributions in the case of a horizontal hold and inclined hold by use of PLAXIS code modelling. The soil model used is the Mohr-Coulomb which is a linear elastic perfectly-plastic model used as a first approximation of the soil behaviour.

Consolidation was also modelled using PLAXIS, in order to analyse the generation of excess pore water pressure (PWP) in the hold.

3.2.3 Shear ratio calculation

The calculation method of the shear ratio in the case of cargo in an ore carrier hold exposed to swell motions and a specimen under cyclic triaxial test are different. As a matter of fact, in the latter case, the deviatoric stress q variation is compared to a reference value fixed at a null deviator, which corresponds to an isotropic consolidation of the specimen under a stress equal to σ_c. Thus the cyclic shear ratio R is calculated using the following formula (1):

$$R = \frac{q}{2\sigma_c} \tag{1}$$

However, for the hold case, the consolidation is not isotropic in particular under the residual slopes. Hence, the variation of the deviatoric stress Δq is compared to a reference value which corresponds to deviator q_0. The deviator stress qi for an inclination i of the hold starting from the horizontal is $\Delta q = q_i - q_0$. Furthermore, as the main stresses are not equal ($\sigma_2 \neq \sigma_3$), the consolidation stress σ_c becomes equal to the mean stress p . The shear ratio is determined according to formula (2):

$$R = \frac{\Delta q}{2p} \tag{2}$$

4. RESULTS AND DISCUSSIONS

4.1 Sliding surfaces

The application of the c/φ reduction procedure in the horizontal hold case and under drained conditions, the mass of potential instability is concentrated under the residual slopes with circular iso-values curves and it extends from the slope foot up to 80 cm upstream of the slope crest (Figure 6). For the inclined hold case, the c/φ reduction method indicates that the sliding surfaces are concentrated under the left slope and the resulted safety factor is near 1.2 (Figure 7). Thus, it is deduced that under drained conditions, the 35° residual slope with over 3m height can withstand a quasi-static 15° inclination.

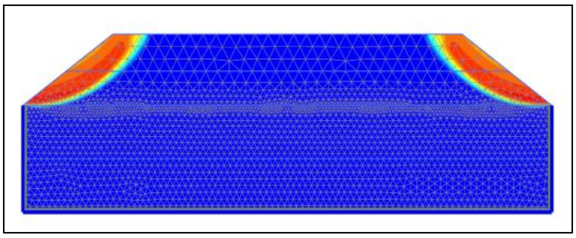

Figure 6 Areas of large deformations in a horizontal hold case under drained condition ((c′=5 kPa, φ′=33°) ; Fs=1.97

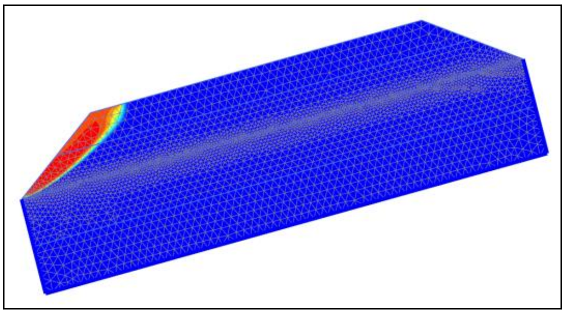

Figure 7 Areas of large deformations in case of a 15° inclined hold under drained conditions (c′=5kPa, φ′=33°) ; Fs=1.19

Under undrained conditions and by means of calculation code TALREN, it is demonstrated that the required undrained strength Su to ensure the stability with a safety factor of 1, is close to 6 kPa in a horizontal hold and to 12 kPa in a case of 15° inclined hold. This situation corresponds to a very fast loading of a very wet cargo (close to full saturation). Hence, it is assumed that for ores with high humidity, a rapid inclination of the hold at 15° can cause a remarkable deformation of the pile; this deformation includes both the residual slopes and the summit platform (Figure 8).

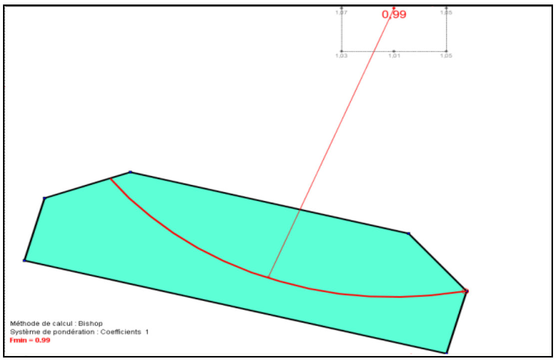

Figure 8 Areas of large deformations in the case of a 15° inclined hold under undrained conditions (C=12 kPa, φ=5°)

In a perfectly saturated, undrained sample, total volume variation is nil. As pore water is far less compressible than the skeleton, the tendency towards volume variation is entirely offset by increased water pressure. In a partially saturated sample, volume variation can occur by entrapped air compression. As a result, pore pressure increases less steeply and, therefore, when the sample is undrained, cyclic shear stress is higher.

Thus, it is deduced that for ores with high humidity, a rapid inclination of the hold at 15° can cause a remarkable deformation of the pile; this deformation includes both the residual slopes and the summit platform.

4.2 Variation of mean and deviatoric stress

Conforming to Figure 9, in a horizontal hold, it is noticed that the values of the mean and deviatoric stresses are proportional to the thickness of the cargo layer. The largest stress values are located at the base of the pile and when approaching the summit surface and the residual slopes, the stress decreases (in absolute values) gradually until becoming null.

When the hold is inclined at 15°, the distribution of mean stresses (p') is no more symmetric. The inclination causes an increase (of 35% compared to the horizontal hold case) down dip, with compressive stresses near 120 kPa and a stress decrease up dip which normally produces a de-confinement under the residual upstream slope (Figure 10). By evaluating the distribution of the deviator stress (q), Figure 11 proves that a 15° inclination of the hold causes an increase in the deviator stress under the residual down dip slope and reduces the stress in the upstream dip. At the base of the pile, the deviator increases up dip with values near 85 kPa.

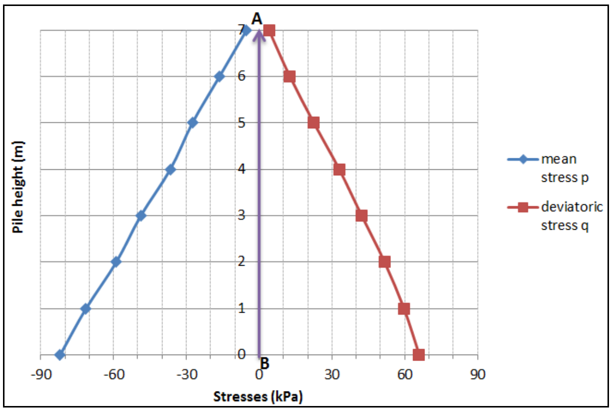

Figure 9 Evolution of mean and deviatoric stresses in terms of pile height in a horizontal hold case

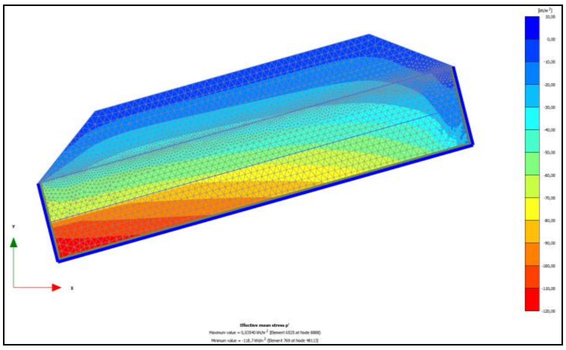

Figure 10 Iso-values of the mean stress (p′) in the case of 15° inclined hold

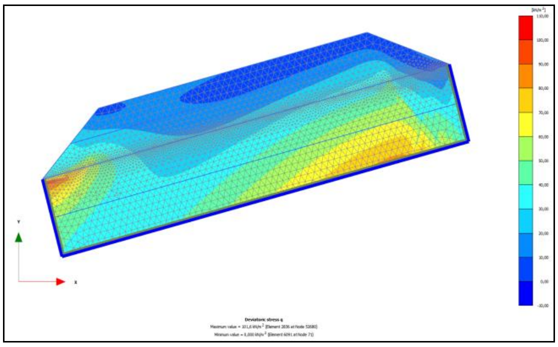

Figure 11 Iso-values of the deviator stress q in the case of 15° inclined hold

4.3 Variation of excess pore water pressure

The variation of the excess PWP was studied in terms of the ore pile height at different time steps. It was noticed that the excess PWP at the bottom of the cargo were larger than those at the top. Clearly these high values of PWP reflect the weight of cargo placed above, and they might lead to the set-up of hydraulic gradients triggering consolidation in this area. Along the journey, these PWP might flow towards the drainage boundary which is the pile surface. This might induce the reduction of the strength of the pile's upper part which has the lower confining stress causing its susceptibility to cyclic mobility. It is also noted that the consolidation rate is variable during the journey and that the cargo could not be considered fully saturated until 15 days which corresponds generally to the end of the journey. When comparing the evolution of excess PWP at different pile heights and at a fixed time interval, it is mentioned that the rate of dissipation decreases as the height of the pile increases (Figure 12).

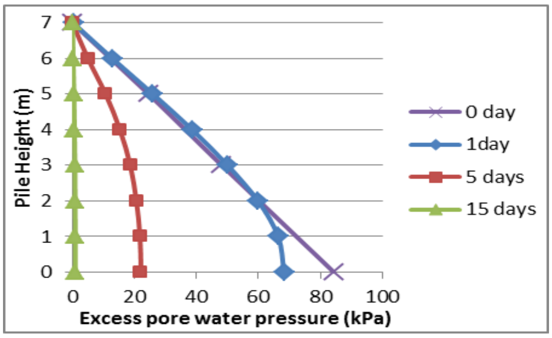

Figure 12 Excess PWP at different time steps in terms of pile height

4.4 Study of the shear ratio

In order to analyse the shear ratio variation in terms of hold inclination, iso-values of horizontal and 15° inclined hold were elaborated based on the calculation method defined by equation (2).

It is noticed according to Figure 13 that the initial ratio (horizontal hold) is close to 0.5 in terms of absolute values in the whole ore mass except near the surface of the residual slopes where it is above 0.7. The high shear ratio under the slope normally increases with an increasing angle and height of the residual slope which is of 35° to a height of 3 m.

The iso-values of shear ratio variation in the inclined hold case (Figure 14) show that it is possible to distinguish 3 parts in the mass of ore loaded into the hold: The central and lower parts, which represents nearly 80% of the ore mass, where the average variation of the ratio is limited to 0.1 (in absolute value) and the maximum point value calculated in these areas is 0.2; The summit surface of the ore pile, where the average ratio variation is limited to 0.1 (in absolute value) with a maximum value that may exceed 0.3 to less than 50 cm above the free surface; The residual slopes, where the average ratio variation can reach 0.7.

The high value of the ratio variation is due to the steep residual slopes. Thereby, the residual slopes are considered to be the most vulnerable areas to the hold inclination whether under static or dynamic loading (cyclic). This ascertainment is confirmed by previous investigations which indicate that only the upper part of the nickel ore is involved in liquefaction. The depth of liquefied layer is determined by the length of journey, structure of the ship, types of engine and propulsion, course and speed set, physical and chemical properties of the loaded nickel ore and the sea condition, etc.

For instance, Zou et al. (2013) deduced from their numerical simulations on the capsizing of Bulk carriers with Nickel ore that only the upper part of the cargo is involved in liquefaction. The carried simulations have shown that under the influence of cross winds and waves or swells, the viscous fluid can create considerable negative effects on the ship's stability, and may result in capsizing if the course, speed and winds are in favour of developing a list.

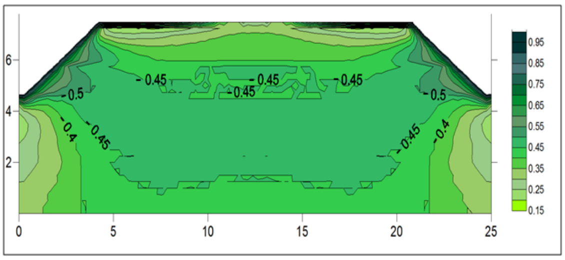

Figure 13 Iso-values of initial shear ratio for a horizontal hold

Figure 14 Iso-values of shear ratio variation for a 15° inclined hold

5. CONCLUSIONS

This study allows concluding the following statements:

- The investigation on cargo liquefaction phenomenon allows deducing the potential causes such as unsafe cargo storage, improper loading, lack of seafarers' implication, wind and swelling effects and cargo nature. To reduce the cargo liquefaction risk, different measures should be taken before shipment such as paying close attention to weather changes, identifying the accident-prone regions, seasons and cargoes, making emergency plan and mostly ensuring that the moisture content of the loaded cargo is lower than its TML as well as avoiding its increase during shipment and sailing. These are the basic premise to ensure the safety of navigation.
- When analysing the stability of the ore carrier hold using the quasi static numerical modelling, it is presumed that under drained conditions, the 35° residual slope with over 3 m height can withstand a quasi-static 15° inclination. However, under undrained conditions, this inclination can cause a notable deformation of the ore pile and therefore a slope reduction.
- The examination of the mean and deviatoric stress iso-values indicated that a 15° inclination of the hold causes an increase (in absolute value) in both stresses under the residual down dip slope and a reduction in the upstream dip.
- The analysis of shear ratio variation from horizontal to 15° inclined hold, showed that the residual slopes are the most vulnerable areas to cargo inclination under static loading. Thus, it is believed that in case of high waves, the slopes will deform under the effect of static rupture (undrained shear) and hence the cargo heap may slump in response to outward pore water flow.
- Assuming an inclination of 15 °, the maximum shear ratio is less than 0.2 in all areas of the hold, except under the residual slopes and at the surface.

It is worth mentioning that this work has been further developed by means of a dynamic numerical modeling in order to reproduce the exact solicitations that a cargo can undergo under the swell motions. This simulation is carried out in order to investigate the onset of liquefaction during the cargo journey by means of the UBCSAND constitutive model. This latter is a nonlinear stress-dependent effective stress model that captures the build-up of excess pore water pressure during cyclic loading. It was employed in this study since it is implemented in the widely used finite difference and finite element programs and potentially offers important insights on the liquefaction phenomenon.

The UBCSAND model parameters are obtained after a calibration of experimental results of cyclic triaxial shear tests carried on Nickel ores. The obtained results confirmed the ability of the UBCSAND model to capture the behavior of this soil and its aptitude to reproduce similar results to those observed in laboratory experiments.

The obtained dynamic simulations present very promising results in accordance with case histories.

6. ACKNOWLEDGMENTS

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