Prevention of liquefaction of transported ores in bulk carriers

Prévention de la liquéfaction des minerais transportés dans les vraquiers

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ABSTRACT: When some solid bulk cargoes such as concentrates, unprocessed nickel ores and iron ore fines are shipped with high moisture or under excessive dynamic loading induced by rough seas, ore liquefaction may occur. This has been known to result in major cargo displacement/shift, causing the vessel to capsize. Since 1988, 24 suspected liquefaction incidents were reported, resulting in 164 casualties and 18 vessels' loss. The aim of this study is to investigate causes and consequences of cargo liquefaction on board bulk carriers with a view of providing future researchers with useful recommendations and efficient tests. This was achieved first, by carrying out a summary of the wide range of factors that influence cargo liquefaction and an overview of the soil mechanics principles that can be used to explain cargo shift and its consequences. Afterwards, an assessment of the regulatory existing controls and experimental tests used to prevent cargo liquefaction is elaborated and recommendations based on the key findings are then provided to detect cargo liquefaction.

1 INTRODUCTION

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 ship's rolling under the swell impact. 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.

An investigation on cargo liquefaction was carried out to understand the mechanism, highlight the collective potential causes, assess the existing test methods and finally provide recommendations to prevent the occurrence of future incidents.

This paper presents an improved representation of the cargo shift problem, with a view of providing future researchers with a basis to further assess the suitability of the available testing procedures to detect cargoes which may liquefy.

2 FACTORS INFLUENCING CARGO LIQUEFACTION

In order to make recommendations to prevent future liquefaction incidents from occurring, previous incidents have been analyzed to determine major factors causing cargo liquefaction.

These causes can be classified as follows onto factors related to cargo nature and behavior and factors related to voyage conditions.

2 .1 *Cargo nature and behavior*

The cargo susceptibility to shift depends on its initial state in the hold, how it has been processed, handled and loaded.

The cargo initial state is defined by the bulk density, initial void ratio, effective normal stress and shear stress (stress history).

The way the ore has been processed tells about its mineralogy, grain size, particles' shape, void ratio and permeability.

The storage and transport conditions define if the cargo moisture content has been subject to any changes due to uncovered handling in areas open to the ingress of rainwater.

The loading procedure affects the initial geometry of the ore pile in the hold and its state of compaction that can be described in terms of loose or dense, over-consolidated or normally-consolidated and stiff or soft state.

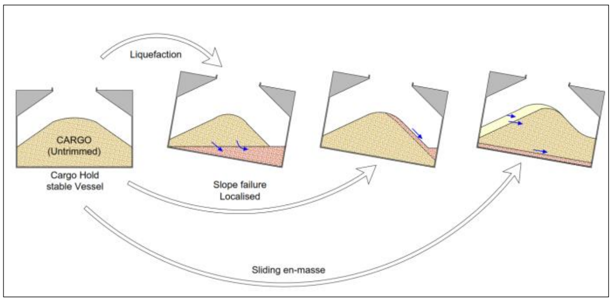
2 .2 *Sea condition*

A bulk carrier's motions at sea also depend on the sea-state and the ship's behavior (speed, heading relative to the waves).

In fact, the sea condition can be described in terms of the effective stress path and, include drained or undrained, cyclic or static, frequency, period and amplitude of loading. After Zou et al. (2013), 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.

3 MECHANICS OF CARGO SHIFT

The mechanisms that cause a particular cargo to shift are complex and largely unknown. Based on a literature review,



three failure modes, presented in figure 1, are envisaged.

Figure 1.Mechanics of cargo shift.

3 .1 *Cargo liquefaction*

Under the cyclic stresses caused by ocean waves, a particle rearrangement and a compaction of the mass will occur. This latter result in a lowering of the void and the pore water pressure will progressively increase with shear load in some parts of the cargo.

Eventually, this may lead to a loss of effective stress and hence a significant reduction of shear strength. This cargo sections will become susceptible to displacement. If the shear resistance becomes less than the applied shear stress (i.e. ship roll), the ore pile may undergo significant deformation. The material is then said to have liquefied (Seed and Idriss, 1982). Thus, cargo displacement in significant volume can cause the ship to take on a list.

3 .2 *Slope failure*

Slope failure may occur when the shearing stresses applied from the ship's motions overcome the frictional and cohesive forces that provide the pile with static strength. Unlike liquefaction, this may occur in wet or dry cargoes and it is usually discussed in terms of two primary types: translational and rotational. For a translational failure, the failure surface occurs approximately parallel to the ground surface and is typically shallow. For a rotational slide, the sliding surface is approximately circular and is often much deeper within the slope and may gradually flatten out the cargo pile through the voyage. Typically, the displaced mass is small and has negligible impact on ship stability due to the symmetry of roll motion which distributes material to both sides of the hold. However, in some particular cases, a cargo displacement may occur to only one side of the hold when localized pore pressures and decreases in effective stress exist within the cargo, creating the conditions necessary for a deep failure plane that is required to promote significant mass movement.

3 .3*Sliding en masse*

Whereas a slope failure may occur from the loss of shearing resistance between particles within the granular cargo, a sliding en masse may occur if there is insufficient resistance to shear between the granular cargo particles and the cargo hold interface. A cargo slide en masse may result in a significant and rapid change in the center of gravity of a ship and therefore cause dangerous consequences. The friction between a cargo and a hold interface depends on the surface characteristics of the steel and on the cargo nature.

4 ASSESSMENT OF EXISTING REGULATIONS AND TESTS

One of the most used regulations is the International Maritime Solid Bulk Cargoes Code (IMSBC, 2013) which classifies cargoes susceptible to liquefaction in Group A. The IMSBC code incorporates a mandatory requirement for this cargo group to be strictly loaded with moisture content less than the Transportable Moisture Limit. This latter is the maximum moisture content that is safe for loading and is determined from laboratory-based testing using one of the following three test methodologies set out in Appendix 2 of the IMSBC Code: Flow Table Test (FTT), Proctor/Fagerberg Test (PFT) and Penetration Test (PTT).

The concept of a maximum moisture limit is a necessary mitigation measure to minimize the risk of cargo shift from liquefaction, and therefore reduce the probability of loss of life. However, the most effective testing and regulatory standards are not currently in place and some improvements should be done.

In fact, there have been concerns about whether the determination of TML is being effectively achieved both in respect to on one hand, the suitability of the test methods and on the other hand the reliability of these methods, for the wide ranges of cargo and carriage conditions.

The three proposed tests within the IMSBC code have non-specific methodologies which usually lead to a notable variability in results. Therefore, incidents involving cargo liquefaction continue to occur even after following the IMSBC Code recommendations.

Moreover, most tested ores are non-homogenous materials and their particle sizes may vary considerably due to the way they have been processed or to their provenance. This creates problems for laboratories to determine the flow moisture point from which the transport moisture limit is calculated. Indeed, since the cargo loaded in different holds may be inconsistent from one hold to the next, the flow moisture point may differ in each hold.

5 RECOMMENDATIONS

In order to define suitable criteria for the safe carriage of liquefiable cargo, it must accurately represent the moisture content at which a cargo is likely to liquefy and shift during carriage. However, as previously discussed, there are many factors that influence the liquefaction potential of cargoes and the moisture content can change significantly during extraction, storage, and transportation.

Determining if a cargo is safe to transport is relatively simple if the correct sampling and testing techniques are implemented. The sampling is one of the most imperative aspects of any laboratory testing because a non-representative sample of the transported cargo will be misleading. It is recommended to follow literally the sampling techniques defined in the IMSBC Code.

While transporting and stockpiling ores, protective equipment should be easily accessible and readily available for use in rainy weather. If rainfall has occurred during this time or the air humidity has been high, it is strongly recommended that, a few hours prior to loading, additional moisture content tests be performed for confirmation. During loading, it is highly recommended that when rain is forecast all cargo holds be closed.

During shipment, it is also recommended that the cargo appearance be regularly checked to make sure that state of the material does not change. If free water above the cargo or fluid state of the cargo is observed during a voyage, theMaster shall take appropriate actions to prevent cargo shifting and potential capsize of the ship.

6 CONCLUSION

This study placed significant emphasis on the importance of preventing ingress of water into the cargo during transportation, loading, and storage. From these findings, a number of recommendations and several modifications have been proposed that will improve the tests' reliability.
Sampling and testing techniques that may not be mandatory are necessary in order to reduce liquefaction incidents from occurring. The responsibly falls back onto the individual mine operators, the port authority, and the Master of the vessel to make sure that the test results are valid and representative of the cargo as well as that all necessary precautions are taken to reduce the potential for the cargo to liquefy.

7 ACKNOWLEDGEMENTS

I would like to express my deep gratitude for my supervisors for their precious advice and endless support.

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