NATIONAL TECHNICAL UNIVERSITY OF ATHENS
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DIPLOMA THESIS

‘INVESTIGATION OF NICKEL ORE LIQUEFACTION IN BULK CARRIERS’

By

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Κι αν φτωχική την βρεις, η Ιθάκη δεν σε γέλασε.

Έτσι σοφός που έγινες, με τόση πείρα,

Ήδη θα το κατάλαβες οι Ιθάκες τι σημαίνουν

Κ. Π. Καβάφης

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ABSTRACT

The present study is a detailed investigation of the phenomenon of nickel ore liquefaction, based on a series of experiments. In order to understand the behavior of nickel ore during its transportation and the reasons that lead to the phenomenon of liquefaction, a theoretical description of the phenomenon is given, explaining the way that liquefaction occurs. On closer examination of the materials that are sensitive to this phenomenon, an explanation of the basic characteristics of the granular materials is given. The effects of liquefaction in the bulk carriers are also being elaborated, in addition to references of the most important accidents due to liquefaction. Following, in the experimental part, tests are executed with two different samples of nickel ore and their behavior is observed.

One of the basic observations of the experiments is that the phenomenon of liquefaction occurs differently in each of the test samples, even though the material is the same. In particular, the one sample liquefies when its moisture content is 18.3% whereas the other one liquefies when its moisture content is 29.7% proving that the density and the chemical composition of the material affect its behavior.

Later, the stability of a vessel is tested so as to examine how it can be affected by the cargo's liquefaction. A key finding is that homogeneous loading of cargo leads to great loss of stability after the liquefaction of the cargo, while the alternate loading is proved to be safer when liquefaction occurs in some of the holds. Finally, a comparison is carried out with the stability of a bulk carrier that has a longitudinal bulkhead in order to evaluate its use. It is proven that the use of a longitudinal bulkhead can increase the stability of the vessel and make it safe even when its cargo is liquefied.

ΠΕΡΙΛΗΨΗ

Η παρούσα διπλωματική εργασία αποτελεί μια λεπτομερή έρευνα του φαινομένου της ρευστοποίησης του μεταλλεύματος νικελίου, με βάση μια σειρά πειραμάτων. Προκειμένου να γίνει κατανοητή η συμπεριφορά του μεταλλεύματος νικελίου κατά τη διάρκεια της θαλάσσιας μεταφοράς του, αλλά και οι λόγοι που οδηγούν στο φαινόμενο της υγροποίησης, μια θεωρητική περιγραφή του φαινομένου γίνεται στο πρώτο μέρος αυτής της εργασίας. Η σημασία αυτού του φαινομένου τονίζεται μέσα από τη λίστα των ναυτικών ατυχημάτων που έχουν προκληθεί λόγω της ρευστοποίησης του φορτίου τους. Τα βασικά χαρακτηριστικά των κοκκωδών υλικών αναφέρονται στη συνέχεια, σε μία προσπάθεια εξέτασης των υλικών που είναι ευαίσθητα σε αυτό το φαινόμενο. Οι επιπτώσεις της ρευστοποίησης του νικελίου στα πλοία μεταφοράς χύδην φορτίου επίσης μελετώνται. Τέλος, προτεινόμενες λύσεις στο πρόβλημα της ρευστοποίησης επισημαίνονται.

Το δεύτερο μέρος της εργασίας περιλαμβάνει την πειραματική διαδικασία που πραγματοποιήθηκε με μία τράπεζα ταλαντώσεων έξι βαθμών ελευθερίας. Τα υλικά που εξετάστηκαν είναι δύο διαφορετικά δείγματα μεταλλεύματός νικελίου (λατερίτη) που παρείχε η Ελληνική Γενική Μεταλλευτική και Μεταλλουργική Εταιρεία ΛΑΡΚΟ. Τα πειράματα διεξήχθησαν για ένα συγκεκριμένο εύρος συχνοτήτων και πλάτους αρμονικής διέγερσης.

Μια από τις βασικές παρατηρήσεις των πειραμάτων ήταν ότι το φαινόμενο της υγροποίησης εμφανίζεται με διαφορετικό τρόπο σε κάθε δείγμα, παρόλο που το υλικό είναι το ίδιο. Συγκεκριμένα, το ένα δείγμα ρευστοποιείται όταν η περιεκτικότητά του σε υγρασία είναι 18,3% ενώ το άλλο ρευστοποιείται όταν η περιεκτικότητά του σε υγρασία είναι 29,7%, αποδεικνύοντας ότι η πυκνότητα και η χημική σύνθεση του υλικού επηρεάζουν τη συμπεριφορά του.

Ολοκληρώνοντας την παρούσα διπλωματική εργασία και με σκοπό να ικανοποιήσουμε τον αρχικό στόχο για την πλήρη κατανόηση του φαινομένου και των συνεπειών αυτού, το πρόγραμμα AVEVA Marine χρησιμοποιείται, για να μελετηθεί πώς η ευστάθεια ενός πλοίου μεταφοράς χύδην φορτίου μπορεί να επιδεινωθεί μετά την ρευστοποίηση αυτού. Ένα βασικό εύρημα είναι ότι η ομοιογενής φόρτωση του φορτίου οδηγεί σε μεγάλη απώλεια ευστάθειας μετά την ρευστοποίηση του, ενώ η εναλλασσόμενη φόρτωση αποδεικνύεται ασφαλέστερη όταν εμφανίζεται το φαινόμενο σε ορισμένες δεξαμενές του πλοίου. Τέλος, πραγματοποιείται σύγκριση της ευστάθεια ενός πλοίου μεταφοράς χύδην φορτίου που διαθέτει μια διαμήκη φρακτή, προκειμένου να αξιολογηθεί η χρησιμότητα της λύσης αυτής, εν γνώσει μας βεβαίως των λειτουργικών προβλημάτων που μπορεί να προκαλεί κατά τη φορτοεκφόρτωση. Με βάση τα αποτελέσματα της έρευνας, δημιουργούνται επιπλέον ερωτήματα που χρήζουν περαιτέρω διερεύνηση.

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CHAPTER 1: INTRODUCTION

1.1 General framework and aim of research

For the maritime community, one of the biggest concerns for a vessel's operational life is its safety. Especially in the case of bulk carriers, from 2007 to 2016, 59 bulk carriers over 10,000 Deadweight (DWT) have been identified as total losses and 209 crewmembers have lost their lives (Intercargo, 2017). As it is pointed out in the same report, the highest loss of life has been attributed to cargo failure and specifically to cargo liquefaction resulting in 11 accidents and 101 lives lost or 48.3% of the total lost lives. Moreover, in 7 out of these 11 tragic accidents, the vessels were transporting nickel ore. All these lives lost at sea, prove that liquefaction needs to be addressed with the seriousness it deserves and that special attention is needed during the loading and the shipping of cargoes that may liquefy.

The objective of this diploma thesis is to examine the dynamic behavior of nickel ore within a series of experiments so as to understand better the nature of the phenomenon. Particular aim of the thesis is to calculate critical values of various parameters (amplitude, frequency and duration of stimulation, humidity levels etc.) that can lead to the liquefaction of the load, the analysis of the phenomenon, as well as the investigation of its effects on the stability of the vessel. Another aim is to assess the effect of liquefaction on vessel stability and to investigate possible ways for mitigating its effect on safety.

1.2 Focal points of interest

The main queries that have motivated the current research are:

1. Which are the critical parameters that will lead to the liquefaction of nickel ore inside a vessel’s holds?
2. How does the behavior of the nickel ore change when it liquefies?
3. In which moisture content does the nickel ore liquefy?
4. Does the density of the sample affect its liquefaction?
5. How does the cargo’s shift influence the vessel’s stability?
6. Which loading condition is safer for the transportation of nickel ore?

As the research progressed, an additional query emerged:

7. How can the use of a longitudinal bulkhead in a bulk carrier reduce the risk of liquefaction?

1.3 Thesis outline

With the aim to the fullest possible theoretical approach of the subject and the more effective presentation of the experimental results, this diploma thesis is divided into two parts, theoretical and experimental. Below is a brief description of the chapters contained in each part.

In the first, introductory, chapter are presented the general framework, the aims of the research and the focal points of interest. It is followed by a critical literature review. Next, a theoretical approach of the phenomenon of liquefaction is given. Specifically, Chapter 3 includes the definition of the phenomenon and specifies when, how and under what circumstances it occurs. Following, the most recent marine accidents due to liquefaction are analyzed in Chapter 4, in an effort to understand the reasons that led to them. Moreover, the nature and properties of the materials that can liquefy, are described in Chapter 5. Finally, the basic regulations for the loading and transporting of cargoes that may liquefy, as well as, proposed solutions for reducing the risk of liquefaction are examined in Chapters 6 and 7.

The second part of the thesis presents the experimental analysis of the liquefaction of nickel ore (laterite). More specifically, the 8th Chapter presents an introduction to the experimental layout and the materials used, as well as the procedure followed for the experiments. Following, the results of the experiments for each of the samples examined, are presented. Subsequently, Chapter 9, which refers to the analysis of the stability of a ship, carrying a cargo which may be liquefied, is given and a series of comparative diagrams for all the loading cases under consideration is produced. Chapter 10 presents the general conclusions reached by the research, and proposes subjects for future research.

CHAPTER 2: CRITICAL LITERATURE REVIEW

In this chapter, a critical literature review of the most important scientific efforts related with aspects of this thesis is provided, in combination with a brief reference to the international regulations that aim to prevent the loss of more lives.

The term "spontaneous liquefaction" was invented by Terzaghi & Peck in 1948, as they were the first to research and study the properties and behavior of the soil. Since then, a lot more scientists have researched similar topics, mainly because of the high frequency of accidents and the extreme risk of the phenomenon. At the beginning, most of the studies were focusing on the problem of soil engineering and soil liquefaction. However, the technological development of recent decades has led to the use of numerical methods for determining the nature of the cargo liquefaction phenomenon. Below, is a brief presentation of the major experimental and numerical studies that have been carried out the recent years.

2.1 IMO bulk cargo regulation review

The problem of the transportation of bulk cargoes was first reported at the 1960 Safety of Life at Sea (SOLAS) International Conference, which is when the first edition of the Code of Safe Practice for Solid Cargoes (BC code, 1965) was published. By that time the code was just advisory. However, this code did not ensure the safe transport of dangerous goods. This led to the creation of a new committee from the IMO some years later, on September 2003, that was responsible about the Dangerous Goods, the Solid Cargo and the Containers, the so-called "DSC Sub-Committee". The new code was named "International Maritime Solid Bulk Cargoes Code, IMSBC Code" and it is the review of the BC code. The IMSBC Code was first established on 4 December 2008, and from the 1st of January 2011, it is mandatory under the provisions of the SOLAS Convention. Although the Code is mandatory, even today the paragraphs 11 to 13 remain merely advisory (International Maritime Organization, 2002).

2.2 Models for the assessment of soil's liquefaction

One of the first models that are still used is the Finite Element Method (FEM) that is a numerical technique which aims to solve boundary condition problems, including structural analysis or fluid flow. This method uses element equations from different subdomains to create a larger and more complex equation. The advantage of the FEM is that it can actually analyze a very complex geometry problem and have access to information like the stress, displacement and pore water pressure throughout the matrix. It can actually be used when a site investigation cannot be carried out, but information is needed. Nowadays engineers are able to even predict the behavior of the soil in an area under particular circumstances. They are also able to study the behavior of the same soil under different conditions only by changing different input conditions.

A specialized program has also been developed for the studying of liquefaction in Kyoto University in 2011. The Finite Element Analysis Program for liquefaction Process (FLIP) is basically being used for soil-structure systems that may face an earthquake. An advantage of the program is that it can be used for environments that consist of ground, fluid (sea or water), and structural systems. It is also possible to add a vertical and horizontal motion at the same time. The applicable equations are based on the equilibrium state of soil structure systems, the mass balance of pore water, and dynamic wave equation of fluid. The program is widely used for seismic performance evaluation and seismic assessment in new structural designs. It has so far proven trustworthy as its results shown good consistency with laboratory tests.

Another software that is being used widely nowadays is PLAXIS. Developed at the Technical University of Delft, was intended to analyze the soft soil river embankments of Holland. Soon the program was expanded to cover a broader range of geotechnical issues. Plaxis is equipped with features that can deal with various aspects of the complex geotechnical problems. Specifically, it is used for the analysis of deformation, stability and flow in geotechnical engineering. The input procedures enable the enhanced output facilities to provide a detailed presentation of computational results. Its results have been proven trustworthy and its use a lot simpler than other software (Brinkgreve, Broere, & Waterman, 2004).

2.3 Research on cargo liquefaction

Until recently, the complexity of the problem of cargo liquefaction did not allow the scientists to produce helpful results. However, the last years many achievements have been made in order to understand better and predict the phenomenon and its results.

One of the first researches by Rebouillat and Liksonov (2010), studied the modelling of the solid-fluid interaction in partially filled liquid containers. The phenomenon of sloshing was used as well as numerical approaches in order to predict the wave amplitude, frequency and pressures. Moreover, the stability of a container during the effect of sloshing was researched

Koromila, Spyrou and Spandonidis made some of the first steps in the understanding of cargo liquefaction. Koromila (2013) carried out experiments with a shaking table to investigate the behavior of sand and olive pomace under roll and sway movement. As it was proven, there is a critical moisture level, below which the sample would not move inside the tank. Furthermore, the result of cargo liquefaction in a bulk carrier was examined, proving that the alternate or inhomogeneous loading is safer for the vessel's stability than the homogenous loading. Following these results, Spandonidis and Spurou (2013) examined the behavior of granular materials in a two dimensional tank, without considering the moisture content of the sample. In this study, the particles were treated like discrete interacting objects and the results that were produced were in good agreement with the experimental data. Furthermore, it was proven that the material with the smaller particle size and the higher density tended to flow more easily .

At the same time, Zhou et al. (2013) and Zhou et al. (2014) tried to understand the aspects that lead to the liquefaction of nickel and iron ore through experiments. Their results revealed that the moisture content as well as the acceleration are two important factors for the appearance of liquefaction. They also proposed, that cargoes should not be accepted for loading if their moisture content is more than 31%. Another group of roll experiments was executed by Chen (2013) in different amplitudes and frequencies.

As the mechanical properties of the samples in different moisture content were compared, it was proven that, when the sample was liquefied, there was a phase lag between the vessel's and the cargo's movement. This phase lag would lead to the capsizing of the vessel. Similarly, Guan et al. (2014) executed as well model experiments in a platform focusing on the behavior of nickel ore. Specifically, the nickel ore was examined when its moisture content was 35% and its dynamic heeling moment was measured. The basic conclusion of this research was the fact that the phenomenon of liquefaction can be divided in three stages.

A numerical simulation methodology was carried out from Zou, Shen and Xi (2013) for the sloshing motion of fluid in a rectangular tank. As it was proven, the predictions of the behavior of the fluid sloshing were verified by the experiments. Furthermore, the results showed that the excitation amplitude and the excitation frequency affect the pressure on the wall of the tank from the liquid. They resulted to the conclusion that the collapse of the shear resistance of the fluid in combination with the increasing heeling moment, acquired from the fluid sloshing, can lead to the capsizing and sinking of a vessel. Another parametric study was developed to illustrate the phenomenon of sloshing of nickel ore slurry inside the cargo holds, based on numerical simulations (Zhang, Wu, & Hu, 2016b). Between the conclusions it was proven that the maximum of averaged moment amplitude happens in a excitation frequency around 4.8rad/s, which is close to the resonance frequency. Furthermore, when the rolling of the vessel is larger than 10 degrees, then the mean moment amplitude tends to deviate from the linear behavior because of the effect of the viscosity of the fluid.

Another group of researchers was focused on the effect of a baffle in a tank. Some of the first studies examined the pressure variations in both baffled and unbaffled rectangular tank numerically and experimentally. It was proven that the effects of the baffle are more clear in shallow water and accordingly the pressure is reduced with the use of a baffle (Akyildiz & Erdem Ünal, 2006). Another study, analyzed the variation of pressure and the free surface elevation with different baffle's height, based on the finite volume and the volume of fluid (VOF) methods. The results were then validated by the experimental results (Jung, Yoon, Lee, & Shin, 2012). A more recent research, examined the effect of a longitudinal baffle inside the holds, on the sloshing of nickel ore slurry. Between the results, it was proven that the dynamic viscosity changes when baffle's height differs and the peak viscosity continues to increase as the baffle height keeps increasing. Furthermore, it was stated that the movement of the water is more violent than the nickel ore slurry. As the baffle height increases, it decreases slightly the sloshing of the nickel ore slurry because of the block effects. (Zhang, Wu, & Hu, 2016a).

One of the most recent studies on sloshing of nickel slurries, compared the behavior of the sample with three different moisture contents. It was proven that the external excitation and the frequency are important factors that affect the sloshing-induced moment. The increase in the excitation amplitude, as well as in the frequency, results in the larger moment amplitude and phase lag. Moreover, another important factor of sloshing of the nickel ore slurry is its viscosity. When the viscosity is higher, the flow properties of the slurries become worse and the formation of the accumulation is easier which may lead the vessel to start listing (Zhang, Wu, & Hu, 2017).

2.4 Tests for evaluation of the cargo

The evaluation of the likelihood of liquefaction to occur is a necessary first step for many projects to assure the safety of the sample. The main experimental methods that have been developed and are still used to reduce the risk of liquefaction are listed below:

- **The Standard Penetration Test (SPT).** This test is still being used due to its simplicity and low cost. This test that is basically used for soil testing procedures can give consistent results in fine-grained sands, but it is not that consistent in materials like coarse sands or clays. It is the most commonly used as it is applicable in areas with difficult access for vehicles. The way that this test is being executed is the following. A tube is needed, which should have thick and durable walls to bear the test environment. This long tube is placed at the bottom of a borehole. Then a heavy hammer is used to hit multiple times the top of the tube. This way the desirable soil can be reached and tested. The person who is responsible for the operation has to count the number of hammer strikes until it drives the sample tube 6 inches at a time. Each test can drive the tube up to 18 inches deep in the soil. The last part of the procedure is that the tube is extracted and if it is needed a sample of the soil is pulled from the tube. The borehole is drilled deeper, and the test can be repeated. Often many errors, like counting ones, can occur and bring untrusted results. What it is important after the whole procedure is the number of hammer strikes needed for the tube to penetrate the second and third 6 inch depth. This is called the 'standard penetration resistance' and it is symbolized by the 'N-value'. As a result, it is possible to measure the cyclic strength, which is presented as the number of cycles of load that is required for liquefaction of the soil. The SPT test is best suited for granular materials.
- **The Cone Penetration Test.** CPT follows basically a similar philosophy with the SPT, but the procedure and the equipment that is being used differs a lot. It was first developed to investigate soft soils. The cone penetration test can be completed from the ground surface, and it usually lasts from thirty minutes to three hours. In this case, a steel cone that the penetration test rig will push into the ground is needed. It can go even in twenty meters depth if it does not find any hard layer. The steel cone also has attached an electronic measuring system that records the resistance and the friction inside the soil. While the cone is being pushed inside the ground, the soil will have different levels of resistance. This resistance can be recorded with the sensors that exist in the tip. While some sensors record the resistance at the cone tip, some other sensors in the friction sleeve, record the sleeve friction along a 100mm length. There are also cones with sensors for the recording of the water pressure inside the soil. Another advantage of the electric cones is that they also have a temperature sensor, so as to calculate the exact position of the zone of saturation, which is of great importance in stability issues. At the end, all these measurements will be used to check the soils' properties, and its response as the cone is pushed through it. All these data give a profile of the soil layers, which is often called a 'trace'(Komihana & EARTHQUAKE COMMISSION, n.d.). Engineers are

being advised to use both techniques whenever it is possible as the results will be a lot more trustworthy.

- **Measurement of in-situ shear velocity Vs.** Shear wave velocity is a crucial parameter in order to assess and analyze a soil. The method of in-situ shear wave velocity is being used as it has two basic advantages. First, the velocity can be measured with non-intrusive methods, and second it is also possible to measure the velocity of coarse soils. This is also why many times this specific method is being used instead of the SPT or the CPT, that may be interrupted because of the coarse soils particles.
- **Becker Penetration Test.** This test started being used in Borah Peak for the assessment of coarse grained soils as they were too hard to be tested with another method. The advantage of this test, in comparison to the others, is the large diameter that the used device has. This is, in fact, a double acting hammer that will drive a pipe quickly inside the ground. The test records the number of strikes that are required to drive the last 300 mm of the casing and relates it with the strength of the soil. It is important that every time the recorded number of strikes must be adjusted to the energy of the hammer in order to give a trustworthy assessment of the soil strength. The results that the Becker Penetration Test will give can be reliable only if the total bearing component of resistance is known. (Dejong et al., 2016)

CHAPTER 3: PHENOMENON OF LIQUEFACTION

The term "liquefied" was used for the first time on 1918 by Allen Hazen describing the failure of the Calaveras Dam in California. Back then, liquefaction was only connected to the soil liquefaction.

Soil liquefaction can be described as a phenomenon in which a soil-like material is suddenly transformed from a solid dry state to an almost fluid state as it loses strength and stiffness due to applied stress. This stress could be an earthquake or any other sudden change in stress condition which results in a behavior similar to liquid (Castro, 1975).

Even though at the end of the 20^{th}-century liquefaction of soil was a well-known phenomenon another type of liquefaction appeared to raise a worldwide concern. The cargo liquefaction on vessels suddenly was becoming a significant danger for the marine world. Although, according to the word “liquefaction” it was expected to concern cargoes with a high moisture content it was soon proven that any granular cargo that is being transported with a moisture content could liquefy and lead to the loss of a vessel and of many lives. The number of accidents that occurred the last 20 years due to liquefaction demonstrates the importance of understanding and dealing with this phenomenon.

3.1 Granular Materials

It is essential at this point to describe and perceive the properties of granular materials. A granular material is a mixture of distinct particles, such as sand, coffee, sugar or powders. Even though many would think that granular materials can be described easily, this has proven wrong. Their behavior is amazingly complex, and this is why so many questions regarding their characteristics are still unanswered. Their behavior is not identical to the behavior of solids, liquids or gases but a mixture of all these (Figure 1). The properties of granular materials always depend on the size of the granules, the size distribution, the weight, the density of the material and the surface of the granules (Mitarai & Nori, 2008, p. 1).

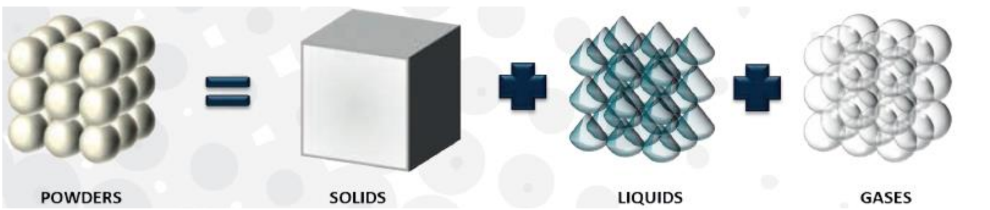


Figure 1 Powders are bulk assemblies consisting of solids, liquids and gases (Freeman, 2015)

Powders are a special category of granular materials. Many times their properties differ a lot from other granular materials due to their small particle size. The range of a powder’s density is larger than the range of a typical coarser granular material. Even if its density is low when it is being placed inside a tank, while being transported compaction will occur, leading to a higher density. (Rowe & Roberts, 1995)

Another important mechanical property of the powders is their clumping behavior. Often grains stick to each other due to the development of the Van der Waals force between the molecules. This force also affects granular materials with smaller grains but in this case, due to the size of the grains, the force's effect is smaller and its result insignificant. (Freeman, 2015)

Compressibility is also a property of powders. When a powder is being stored in a container and a stress is applied it will force the particles of the powder to move closer and its volume will change. The same number of particles will now fit in a smaller volume. Compression, unfortunately, is uncontrolled as it is not always intended and can occur even during the transportation and the storage of a powder. This is why also the flow of a powder is so hard to be explained as it is a complex issue. Compressibility is also connected to another property of powders, flowability, the ability of powders to flow. The flowability of a powder can usually be affected by the physical properties of a material or can change when a powder goes through some processes. The flow properties of a powder can determine if and how a powder can be mixed with another powder and how these powders will behave together. (Freeman, 2015)

Another important property of powders is their permeability. The variation of granular materials in particle size and shape results in the existence of gaps between them. Through these gaps air can move. Powders with larger particles have a higher permeability as the gaps between the particles will be bigger. As it has been proven there is a critical gap-grain ratio that affects the properties and the behavior of each material. In particular, when the gap-grain ratio of a material is greater than the critical ratio, then the particles tend to approach each other, while when it is smaller they tend to move away (Terzaghi, K., Peck, R. & Mesri, 1996). The gap-grain ratio also affects the density of the cargo. When a material that has a low density (i.e., the gap/grain ratio is large) is disturbed and is being saturated (i.e., the voids present between the particles are filled with water), the particles from which it is composed tend to approach each other and remove the water from the voids. If this disorder is not intense or is applied slowly, the water is evaporating, as it is removed from the voids and thus particles approach each other without the occurrence of liquefaction. On the contrary, when the disorder is intense, fast and repeated, the water does not evaporate and thus the pore pressure increases, resulting in liquefaction. Permeability is also the property that helps to identify the materials that are most likely to transform from a solid-like behavior to a liquid-like one.

Lastly, the ability of the particles to absorb water is crucial. When a liquid is being added to a powder, it tends to cover the surface of the particles like a coating. When this happens, it forms the so-called liquid bridges between the particles that prevent the free movement of each particle. The appearance of water in the powder can significantly change the behavior of the material and its productivity. Other properties of granular materials that also affect their behavior are jamming and unjamming, fragility, loss of kinetic energy, frictional shearing, and compaction.

As shown above, the behavior of powders is really complex and depends on many different mechanical and physical properties of the material.

3.2 Cargo Liquefaction

Cargo liquefaction is a phenomenon that can be observed both in granular materials and in very fine ore materials/ non-granular materials. In each category, the liquefaction can be explained differently.

Granular materials are one of the most common types of cargo among bulk carriers. Even by observing the material one can notice that is a mixture of smaller and larger granular particles. As already mentioned, the phenomenon of liquefaction occurs in bulk cargoes that usually contain a moisture content. Between the smaller and the larger particles of granular exists not only air but also water. When the material is in the dry state, these particles will be contacting each other. This contact results in frictional forces between the particles which produce shear strength and cohesiveness for the cargo.

During the transportation the cargo is facing vibrations from the waves, from the ship movements and other agitations, resulting in its gradual arrangement and compression. These movements will urge the grains to be arranged at the optimum density. The result of this arrangement and gradual compression of the load is the reduction of its volume and increase of its density. Thus, gaps between the particles become smaller, and the available volume for air and water decreases. Water is incompressible, unlike air that can be compressed, and therefore, when compressing the material, water will be expelled from it (Figure 2). As a result, the pressure of the water pore increases and results in the separation of the granular particles away from each other. The granular particles that are not in contact anymore are losing the frictional forces that used to exist between them. Losing the friction between its particles and its shear strength, the material is starting to act like a liquid. The appearance of the viscous behavior usually occurs quickly after the loading procedure. In many incidents, it has been observed that only a part of the cargo has been liquefied. (Gullen & Norwegian Hull Club, 2015)

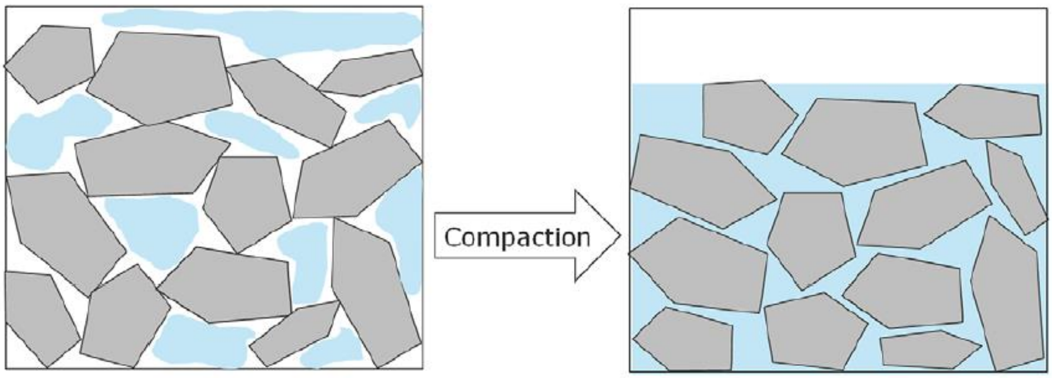


Figure 2 Liquefaction as a result of cargo compaction (Gullen & Norwegian Hull Club, 2015)

On the other hand liquefaction of the non-granular cargoes, such as nickel ores or iron ores, is caused based on another causation. Even so, the results of the liquefaction of clay-like materials are the same as the ones of the granular materials' liquefaction. In both situations, vessels are facing the hazard of the free surface effect that can lead even to the loss of the ship.

Liquefaction of very fine materials is the result of the fatigue of the material. During its transportation, the cargo is under a cyclic motion because of the vessel. As a result, the cargo loses some of its shear strength and its cohesiveness is being reduced significantly. Again, the cargo will start behaving like a liquid. In comparison to the granular materials, the liquefaction in the clay-like materials needs more time to appear but usually occurs in the most significant part of the cargo. (Gullen & Norwegian Hull Club, 2015)

Besides the above-mentioned ways that liquefaction occurs, there is an even rarer and at the same time more dangerous form of liquefaction; the formation of the wet base. More specifically, according to the International Maritime Solid Bulk Cargoes Code (IMSBC code), there is the possibility that during a voyage the moisture contained in the cargo moves to the lower levels of the cargo. This movement will result in a dry surface and a wet base where the moisture will exceed the Flow Moisture Point (FMP), meaning that the load will liquefy. This can happen even if the Transportable Moisture Limit (TML) is not exceeded before loading. The granular material should have high grain permeability, so the moisture can pass to the lower levels, to develop a wet base at the bottom of the cargo.

3.3 Moisture Migration

A phenomenon that is being connected to the liquefaction is the moisture migration of the cargo and its results.

As mentioned, before the loading of a ship, the cargoes may appear "dry" but in fact contain a significant amount of moisture. During loading, the cargo will compact, and this compaction will continue during the trip. All these movements will lead to the rearrangement of the cargo that can also result in the phenomenon called moisture migration. Moisture migration is called the movement of moisture inside the cargo holds. What has been observed many times in vessels is that the moisture of the whole cargo is the same at the beginning and the end of a voyage but the moisture content of different parts of the cargo have changed significantly. To understand how moisture migration is connected to liquefaction, it is crucial to explain how and why it is happening.

The atmosphere consists of a mixture of oxygen (20%), nitrogen (78%) and 2% of other gases, including water in the form of water vapor. The pressure exerted by the atmosphere depends in part on the pressure exerted by water (that the atmosphere contains) in vapor form and this percentage of the total atmospheric pressure is called 'water vapor pressure'. As the amount of water in the atmosphere increases, the water vapor pressure increases proportionately. At a specific temperature, the air can only contain a maximum amount of water vapor and the pressure exerted at this critical point is called "saturation vapor pressure" at a specific temperature. If the water vapor at a specific temperature is higher than the water vapor of the critical point, then the super saturation state will be caused and the water will be deposited from the air in liquid form probably like droplets.

As already mentioned, air - containing water vapor - is contained between the particles of the cargo. The vapor pressure of this air tends to equilibrate with the moisture content of the material. What happens is the following. In a part of the cargo, the pressure of the air between the particles may be higher than in another part of the cargo. This difference of pressure leads to the flow of water vapor from the high-pressure region to the low pressure in order to balance the pressure difference. The flow will lead to the water vapor moving from the center of the load to the outside. This water movement will cause the air vapor pressure to decrease at this point but the balance conditions will be restored as more water will start to move from the inside of the granules to the "space" between the granules to maintain the initial vapor pressure. (UK P&I CLUB, 2010)

So if we have a temperature difference between the inside and the outside of the ship's tank, then the moisture will move due to the above mechanism. Such movement of moisture may also occur when a part of the load is heated for some reason such as insect attack or micro-biological activity. In all of these cases, the moisture will migrate from the cold to the hot part.

Moving humidity is not a phenomenon that results only from the difference in water vapor pressure. If the load starts to warm up, then there is a tendency for the moisture to migrate in all directions and move away from the heated zone. However, there will still be a tendency for the hot air to rise upward from the heated zone and to replace it with colder air coming from the sides or below. Hot air while moving upward will carry moisture along with it. This will lead to a vertical movement of moisture. This results in the movement of moisture vertically upward and much more water moving to the top of the load. If it is not possible to remove the water that has migrated there through ventilation, then more damage is expected in the upper layers of the load.

All this movement of moisture can lead to the increase of moisture content in part of the cargo. Under these conditions, water may concentrate on specific parts, like the edges of the holds or on the top of the cargo. This will result in the appearance of liquefaction even if it is only localized.

3.4 TML and FMP

At this point, it is crucial to explain two fundamental terms that are being used in the research for liquefaction very often.

Flow Moisture Point (FMP) is called the lowest moisture level at which liquefaction may appear. If the cargo is loaded with a moisture content above the FMP, then the cargo can liquefy any time during the journey, depending on the vibrations caused by the engine room, the motions of the ship and the effect of the waves on it, and hence the degree of compression of the load. The moisture flow point depends on the volume of voids between the cargo particles in the maximum compression. As the void volume depends on the size, shape, and consistency of the surface of the individual particles from which the load is made, the numerical value of the FMP varies considerably depending on the mining location and processing facilities. Therefore, the FMP can only be predicted by laboratory tests in each case (Munro & Mohajerani, 2016a).

Transportable Moisture Limit (TML) is called the maximum moisture content of the cargo for which the load is considered safe for transportation. TML is equal to the 90% of the FMP as defined by laboratory tests. This difference between the varying moisture limit and the moisture flow point lies within the margin of security required for safe loading, as it is illustrated in Figure 3 (Munro & Mohajerani, 2016a).

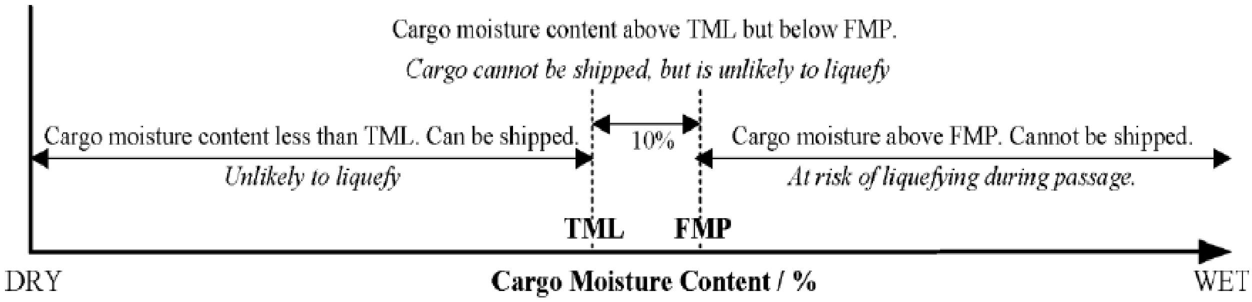


Figure 3 The TML and the FMP. Group A cargoes can only be shipped at moisture contents (Timothy Paul Rose, 2014, p. 16)

3.5 Ship Stability

The reason why so many vessels have been lost due to liquefaction is that cargo liquefaction affects their stability.

Any object that floats in the sea, like a vessel, receives an equal force of its weight from the water. The weight of the vessel is usually symbolized by the letter W, and it acts downward at the center of gravity of the vessel. This force is equal to the buoyancy force that acts at the center of buoyancy, which is the geometric center of only the submerged volume of the vessel. In a vessel that is stable the forces of weight and buoyancy act at the same vertical. When an external force appears in the vessel, for example from waves or from the wind, the center of buoyancy shifts to the side when the center of gravity stays in place. The horizontal distance between B and G is called the righting lever, and it is symbolized as GZ. The righting moment (W × GZ) that will appear will cause a list to the vessel and reduce its stability (Τζαμπίρας, 2015).

When looking into a vessel's stability, its metacenter (M) is considered as well. It represents the point where all vertical forces that act in the vessel intersect. For small angles it does not move. The ship's stability is represented by the vertical distance of M to G. This is called the Metacentric Height (GM), and for heavier loads, GM increases.

This shows that GM and GZ depend on the exact location of the center of buoyancy which changes according to the type and the loading of the cargo inside the holds. When the holds are being loaded with a high-density cargo, then the center of gravity of the vessel will be lower than if we were loading a low-density cargo. The lower center of gravity will make the ship more stable. While this vessel will be more stable, higher transverse shearing accelerations may act on the cargo, increasing the possibility of cargo to shift.

Another way by which the stability of a vessel can be illustrated is by the 'stability curves'. These curves depict the righting lever (GZ) of a vessel for any angle of heel, and they provide information like the range of stability, the angle of vanishing stability, the maximum GZ and the initial GM, like it can be seen in Figures 4 and 5.

During her research, Koromila compared the stability curves of vessels before and after the phenomenon of liquefaction appears in their holds (Koromila, 2013, pp. 88–90). The red curve in the following figures shows the stability of the vessel before liquefaction when the blue one the stability after liquefaction.

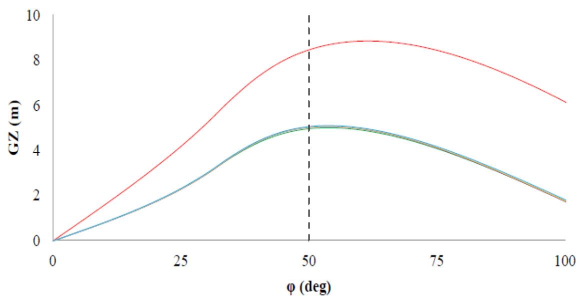


Figure 5 Illustration of GZ stability curve before and after liquefaction for a cargo with 3.6t/m3 density. (Koromila, 2013, pp. 87–90)

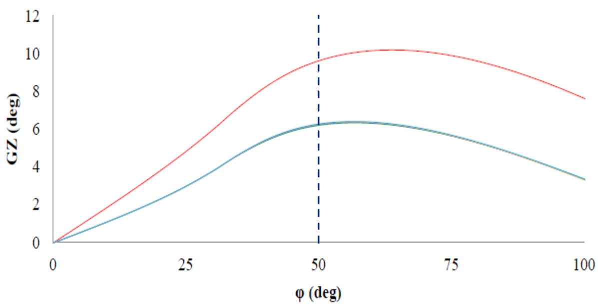


Figure 4 Illustration of GZ stability curve before and after liquefaction for a cargo with 5.6t/m3 density. (Koromila, 2013, pp. 87–90)

For a cargo, three main mechanisms can lead to its shift, the cargo liquefaction, the slope failure and the sliding that are illustrated in Figure 6. Within the research of this thesis the effect of liquefaction in vessels and why is it so dangerous once it occurs are examined.

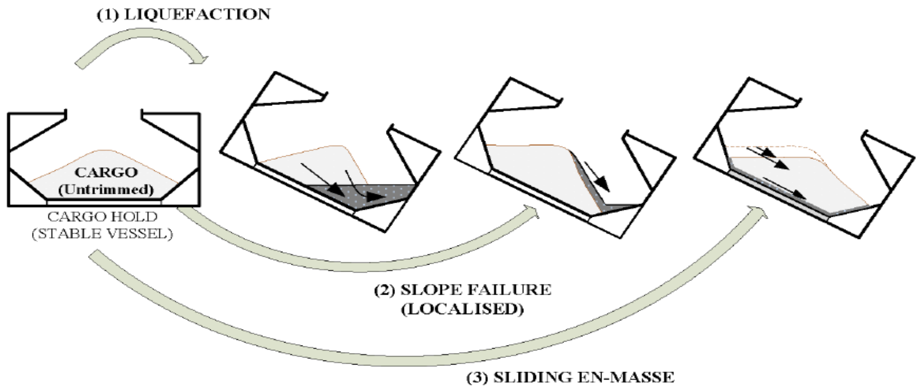


Figure 6 The three different types of cargo shift that may occur within a cargo hold. (Timothy Paul Rose, 2014, p. 24)

As already mentioned, the liquefaction of the cargo can appear either by creating a free water surface on the top of the cargo, or by creating a wet base at the bottom, or by causing the overall behavior of the cargo as a fluid. In the first case, when the amount of water that appears in the surface is low, the water tends to accumulate at the places near the sides of the hold. On the other hand, when the amount of water is more, the water spreads throughout the surface of the cargo and covers it entirely. The effect of this free surface that will appear can be either the reduction or the total loss of GM. This causes the cargo, which is now more like a liquid, to start moving to the side of the hold when the vessel rolls. When the vessel rolls on the other direction not all of the cargo will flow back to the other side. Every time more and more cargo will move to one side, causing a build-up on this side of the vessel. The concentrated cargo that will lead to a dangerous angle of heel for the vessel which may also cause its capsizing (Bureau Veritas, London P&I Club, & TMC Marine, 2017). This phenomenon is illustrated in Figure 7.

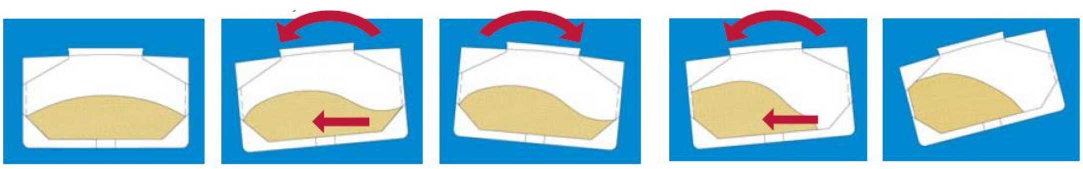


Figure 7 When the cargo liquefies it starts shifting from the one side of the hold to the other. This behavior of the cargo creates a dangerous angle of heel in the vessel. (Bureau Veritas et al., 2017, pp. 7–8)

There is also the case, in which the water will move to the bottom of the hold creating a wet base and making the cargo to move like a liquid. This form of liquefaction will lead to the shifting of the drier cargo that is on the top which may create a big list in the vessel and reduce its stability. In the third case, if the whole amount of cargo behaves as a fluid, its Roll motion will affect ship’s stability. The cargo will move from one side of the ship to the other during its transportation, and this will cause the ship to develop a tremendous transverse slope and suddenly overturn.

Thus, liquefaction will affect the stability of the vessel, and this is why the metacentric height of a vessel should be carefully considered when the vessel carries materials that may liquefy. When the GM value is bigger, it will result in shorter rolling periods and higher accelerations which will also help the appearance of liquefaction.

Except for capsizing, the change in the behavior of the cargo from solid to liquid will also affect the pressures on the cargo hold boundaries, as it is illustrated in Figure 8. The values of pressure from the liquid will be a lot higher making the cargo holds inappropriate for such loading. Higher pressures could also lead to the failure of the hull as its hold are not designed to face flooding.

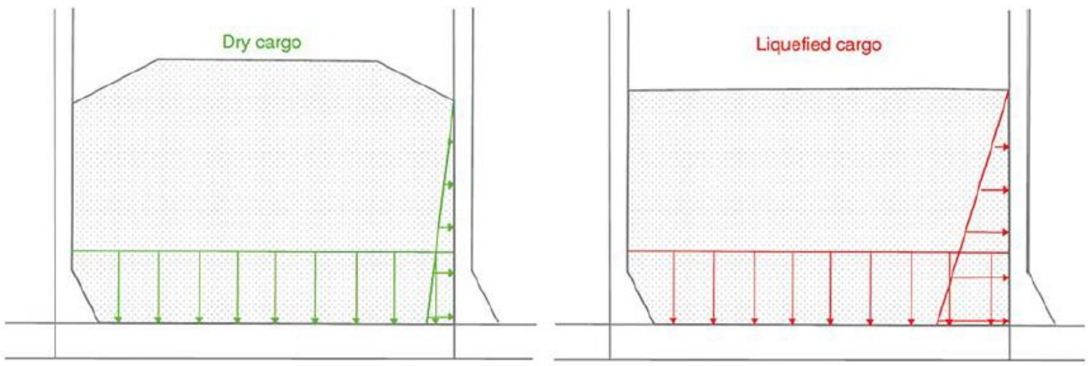


Figure 8 Pressure on bulkhead when the cargo is dry and when it is liquefied. (Gullen & Norwegian Hull Club, 2015)

CHAPTER 4: MARINE ACCIDENTS

As mentioned before, liquefaction, that results in the movement of the cargo inside the holds, creates free surface moments that often leads to the loss of ship's stability (Zou, Shen, & Xi, 2013). In the worst scenario, the ship can develop a severe list and suddenly capsize.

At first, liquefaction of cargoes like granular materials or very fine materials was not considered to be an essential and critical issue. Within the last decades though after the loss of approximately 130 lives, liquefaction is considered to be a major hazard for bulk carriers. The liquefaction risk is now a big concern for the marine companies, the whole maritime community, and the industry stakeholders.

As it has been observed most of the times the cause of such accidents is the failure of shippers and crew to comply with the tests and certificates required to verify that the cargo to be loaded is safe for transporting (Jonas, 2010). Another reason is the environment where the cargo is being stored before loading. It is usually open areas that are exposed to all weather conditions (Gullen & Norwegian Hull Club, 2015).

In the table below a list of the major accidents of vessels carrying nickel ore is presented. (COLAK, ISIACIK, SATIR, 2014; Intercargo, 2017)

Table 1 List of major accidents due to liquefaction of Nickel Ore (COLAK, ISIACIK, SATIR, 2014; Intercargo, 2017).

a/a	**Vessel's name**	**Year of the accident**	**Fatalities**	**Cargo**
1	Mega Taurus	1988	20	Nickel Ore
2	Sea Prosped	1988	10	Nickel Ore
3	Oriental Angel	1990	0	Nickel Ore
4	Padang Hawk	1999	0	Nickel Ore
5	Hui Long	2005	0	Fluorspar
6	Jag Rahul	2005	0	Nickel Ore
7	Black Rose	2009	1	Iron ore
8	Asian Forest	2009	0	Iron ore
9	Nasco Diamond	2010	22	Nickel Ore
10	Hong Wei	2010	10	Nickel Ore
11	Jian Fu Star	2010	13	Nickel Ore
12	Vinalines Queen	2011	22	Nickel ore
13	Trans Summer	2013	0	Nickel Ore
14	Harita Bauxite	2013	15	Nickel Ore
15	Bulk Jupiter	2015	18	Bauxite

Taking a closer look at these incidents

- **Mega Taurus**. The first reported accident can be found back in 1988. The Mega Taurus was a handysize bulk carrier that was built in 1980. Her deadweight (DWT) was 30.413 metric tons. On December 16, 1988, while she was traveling from Taiwan to Japan carrying nickel ore, she faced rough seas. The cargo started shifting leading to the capsizing of the ship and an accident with no survivors. (Shouzhi & Wang Jing & Co, 2011)
- **Sea Prosped**. The same year the Sea Prosped vessel carrying as well nickel ore from Indonesia had the same fate leading to 10 fatalities. (Shouzhi & Wang Jing & Co, 2011)
- **Padang Hawk:** From the 17th until the 23rd of July 1999, the bulk carrier Padang Hawk was loading her holds with nickel ore from Kouaoua, New Caledonia. After the vessel was loaded with nickel ore and started her journey, she faced bad weather with rough seas. She started listing heavily up to 15° port. Nevertheless, the ship finally made it to reach the port safely in Townsville on the evening of 28th of July. After the incident, the investigation revealed liquefaction of the cargo in four out of five holds of the ship and water was obtained in the surface of the nickel ore in cargo number 1, like it can be seen in Figure 9. Also, cargo in some holds behaved like water, following the vessel's movements. (Australian Transport Safety Bureau, 2000)
- **Jian Fu Star:** On the 27th of October 2010 the vessel capsized while carrying Nickel ore from Obi Island, Indonesia. With 13 casualties this was the first of the three accidents that took place in less than 39 days with 44 fatalities and raised the awareness about the risks of liquefaction (Panama Maritime Authority, 2011b).

Figure 9 Photos of dry and liquefied ore inside the cargo holds (Roxburgh Environmental Ltd)

- **Nasco Diamond:** The same time, in October 2010 Nasco Diamond arrived at Kolonodale port, Indonesia to load nickel ore. During the loading, the cargo was exposed to heavy rain. Even though the captain denied at the beginning to sail with the cargo, as it looked like mug, at the 4th of November, the ship finally sailed with 55,000 tonnes cargo in her holds. Only five days later the ship started developing a 3° list and slurry started being observed in some holds. Despite the efforts of the crew members to confront with the free surface effect the loss of the vessel was fast. As it revealed, tests before the loading showed that the moisture content was 30.8%, close enough to the TML limit of the 30.25% (Panama Maritime Authority, 2011c).

- **Hong Wei:** The third of these accidents happened some days later on the 3rd of December 2010. The vessel had departed on the 28th of November from the port Kolonodale. The chief engineer was not informed if the cargo that was loading was appropriate for carrying or not. At the beginning of the voyage the weather was good, but after some days the wind force became very strong. On the 2nd of November, a list of the vessel that started only from 3° was drastically increasing, leading to the activation of the alarm and finally to the sinking of the vessel. Half of the crew was lost in the ocean. After the accident, the investigation showed the following regarding the cargo. The moisture content of the nickel ore before loading was at 31.5% when the was FMP 37% and the TML 33.25%. Even though the moisture content was lower than the TML, the loading procedures lasted approximately ten days. During this period the moisture content (MC) of the nickel ore may have increased leading to its liquefaction (Panama Maritime Authority, 2011a).
- **Trans Summer**: Many causes led to this incident back in 2013. On 15th of July 2013, The Trans Summer arrived at Subaim port in Indonesia to load nickel ore. The chief inspected the cargo. They did not verify the conditions of cargo stockpiles, nor were aware whether the cargo stockpiles would be covered by tarpaulins to prevent wetting. Even though the crew members executed the can test it was proven that they had collected a sample only from the middle of the cargo, resulting in incorrect results. Also, the crew accepted the loading of the vessel even though the moisture content was out of the limits. At the 9th of August the vessel left the port, and only five days later the tragic loss of the ship happened. As it was revealed later before loading its moisture content was 33.87% when its TML 34.79%. Between loading and the beginning of the trip, the rain increased the moisture content of the cargo and led to such unfortunate event, that can be seen in Figure 10 (The Hong Kong Special Administrative Region & Marine Department, 2015).

Figure 10 The marine vessel Trans Summer sinks off the coast of Hong Kong during Typhoon Utor in August 2013. Photo: HKG Flying Service (http://gcaptain.com/nickel-ore-liquefaction-eyed-in-emerald-star-bulker-sinking-off-philippines/)

- **Harita Bauxite:** The Harita Bauxite, a Handymax bulk carrier was loaded on the 3rd of February 2013 with nickel ore at Obi Island in Indonesia. Reports say that a can test was carried out in every cargo. On the 10th of February, loading was completed, and she sailed one day later. After four days of traveling the vessel had to stop at sea to perform some repairs in the engine room. After stopping, the vessel sank in less than 30 minutes with 15 crew members losing their lives. Old papers of the ship proved that the moisture content of the cargo at the 9th of February was 34.32% and its TML 36.59% (Panama Maritime Authority, 2013)

During 2017 there have been reported two more accidents with the suspected cause to be the liquefaction of the cargo.

- **Stellar Daisy** was originally built as a very large crude carrier (VLCC). On the 31st of March, 2017, she was carrying iron ore across the South Atlantic Ocean to China. From the reports that were drafted by the two crew members who were rescued, it was described as there was a loud sound and then the ship suddenly began listing. Very soon the ship was lost. The causes of the accident are not clear yet, but many are reporting that cargo liquefaction caused by excessive moisture in the iron ore cargo could be a possible reason for the loss. (“GISIS: Marine Casualties and Incidents”)
- **Emerald Star:** Some months later, on the 13th of October, Emerald Star loaded with nickel ore from Indonesia sank in the waters of the Philippines. 16 crew members were rescued whereas 10 lost their lives. Like in Stellar Daisy accident, the causes of the accident remain unknown. Before her last hours the ship traveled through bad weather that made her roll and pitch heavily. Researchers believe that the weather in combination with the nickel ore made the ship listing sharply before she capsized. (“GISIS: Marine Casualties and Incidents”)

CHAPTER 5: CARGOES THAT MAY LIQUEFY

The cargoes that may liquefy during their transportation are a lot and their properties vary. According to INTERCARGO's report, the last ten years the most accidents that happened due to liquefaction are connected with the transportation of unprocessed ores, like nickel ore or iron ore fines (Intercargo, 2017). Unlike other cargoes, they are taken directly from the ground of open mines, which are exposed to different weather conditions and they are rich in minerals. Their form usually consists of a heterogeneous mixture of fines, like clay, and coarse particles, like stones. In addition, the condition of their storage before loading can also affect their moisture content. The way that nickel ore is stored in the countries of origin (mainly Indonesia) is critical as in these areas the humidity is high and intense rainfalls appear from November to February.

Below is the list of materials that are in Group A of the IMSBC code and may liquefy.

Table 2 List of cargoes that may liquefy according to the IMSBC code.

Cargoes that may liquefy		
Aluminium fluoride	Iron concentrate (pellet feed)	Pyrites (cupreous, fine, flotation or sulphur)
Alumina hydrate (can also be B)	Iron concentrate (sinter feed)	
Aluminium smelting/remelting byproducts, processed (can also be B)	Iron ore (concentrate, pellet feed, sinter feed)	Pyritic ash (can be B)
		Pyritic ashes (iron)
Blende (zinc sulphide)	Iron ore fines	Pyritic cinders
Calcined pyrites (can also be B)	Iron oxide technical	Sand, heavy mineral
Cement copper	Lead and zinc calcines (mixed)	Scale generated from the iron and steel making process
Chalcopyrite	Lead and zinc middlings	
Chemical gypsum	Lead concentrate	Silver lead concentrate
Clinker ash, wet (can also be B)	Lead ore concentrate	Silver lead ore concentrate
Coal (can also be B)	Lead ore residue	Slig (iron ore)
Coal slurry	Lead silver concentrate	Spodumene (upgraded)
Coke breeze	Lead silver ore	Zinc and lead calcines (mixed)
Copper concentrate	Lead sulphite	Zinc and lead middlings
Copper nickel	Lead sulphite (galena)	Zinc concentrate
Copper ore concentrate	Manganese concentrate	Zinc ore, burnt
Copper precipitate	Manganese ore fines	Zinc ore, calamine
Copper slag	Metal sulphide concentrates (can be also B)	Zinc ore, concentrates
Fish (in bulk)		Zinc ore, crude
Fluorspar (can be also B)	Mineral concentrates	Zinc sinter
Fly ash, wet	Nefeline syenite (mineral)	Zinc slag
Galena (lead sulphide)	Nickel concentrate	Zinc sludge
Ilmenite clay	Nickel ore	Zinc sulphide
Ilmenite sand (can be also C)	Nickel ore concentrate	Zinc sulphide (blende)
Ilmenite (upgraded)	Peat moss (can be also B)	Zircon kyanite concentrate
Iron and steel slag and its mixture	Pentahydrate crude	
Iron concentrate	Pyrites calcined (can be B)	

5.1 Nickel Ore

5.1.1 Nickel Ore Reserves

Intercargo has described the nickel ore as the deadliest cargo in the world (Poulsen, 2013). An understandable characterisation when taking into consideration the accidents and the fatalities that have been caused by nickel ore liquefaction.

As in most of the incidents the vessels have been obtained to carry nickel ore, the thesis focuses on this specific material. Within the last decade, the demand for nickel ore has increased significantly as it is the main component in the process of stainless steel.

Table 3 Nickel basic characteristics (www.nickelinstitute.com).

Name:	NICKEL
Chemical Symbol:	Ni
Atomic Number:	28
Atomic Weight:	58.71
Melting Point:	1453 ºC
Boiling Point:	2730 ºC
Density:	8.90 g/cm^3 at 25 ºC
Curie Temperature:	253 ºC

Nickel belongs in the eighth group of the periodic table, and it is the fifth most common element on the earth. It is ranked in the 24th place between the elements that exist in the earth's crust with an estimated concentration of 0.008% (Zografidis, 2010)

The use of nickel can be traced back to 3500 BC. Some reports from China, dated back in 1500BC refer to the 'white coper', which is assumed to be an alloy of silver and nickel. During the fifteenth century, German miners in Saxony were trying to extract copper from nickel ores. The nickel was finally isolated and reported as a chemical element in 1751 by Axel Fredrik Cronstedt. During the 20th century, the discovery of some ore deposits in countries like Russia and South Africa made large-scale production of nickel possible. After the World War I and World War II the significant increase of steel demand resulted in rising of nickel demand.

In the last years many countries are competing for conquering the first place in the ranking of nickel production. What is though important is not only where the largest nickel ore production is but which countries still hold significant nickel reserves. While there are countries that have a massive production of nickel thanks to their sizeable nickel reserves, some other countries have a smaller production of nickel, but they have high reserves of the metal. Subsequently, we will refer to the countries that hold the highest nickel reserves worldwide based on the United States Geological Survey's most recent report.

1. Australia: Australia has the largest nickel reserves that go up to 19 million Metric Tons (MT), but many years it does not have the largest production of the metal.

2. Brazil: In the second place is Brazil with reserves around the 10 million MT. During 2016 the country faced a reduction in the nickel production, but it is still included in the ten largest nickel producers worldwide.

3. Russia: Russia which had the world's second-largest nickel production in 2016, holds the number of reserves at 7.6 million MT.

4. New Caledonia: Even though New Caledonia has a smaller production of nickel ore it holds approximately the same amount of reserves as Russia at 6.7million MT.

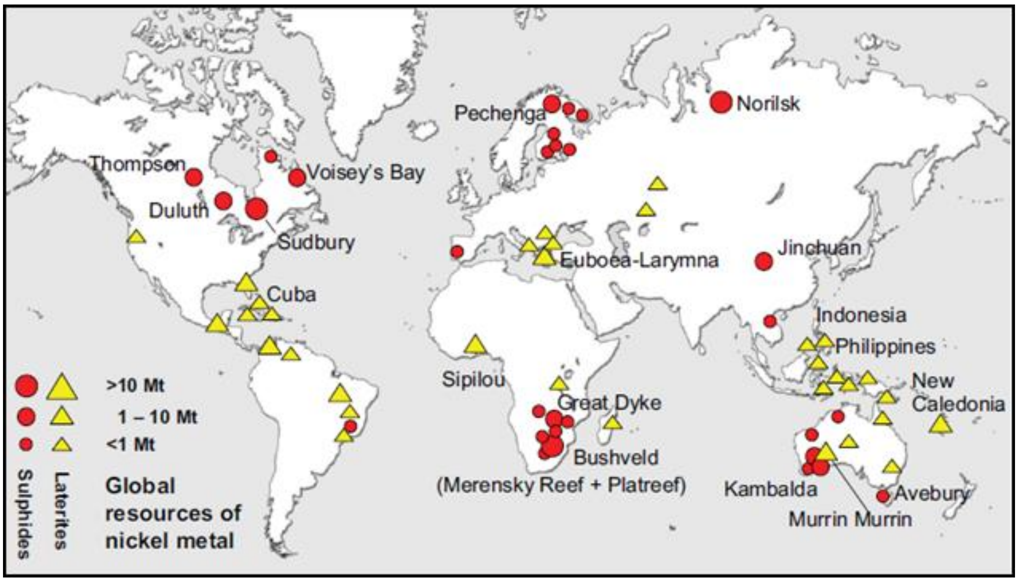


Figure 11 Map of Nickel Sulphide and Laterite Deposits
http://www.goldendragoncapital.com/map-of-nickel-sulphide-and-laterite-deposits/

As can be noticed in the map above (Figure 11) Greece is one of the few countries in the European Union with significant nickel deposits in its subsoil. In Greece exist poor ferronickel alloys (lateritic type) with an average nickel content of around 1 %. The annual production of the Greek company LARCO has fluctuated in recent years between 1.9-2.3 million tons a year. The exploited fields are located in central and northern Euboea, in Lokrida, in Central Greece, and in Kastoria region.

Nickel has a great affinity with cobalt and iron. This is why they coexist in many fields, and why they can replace each other in many applications. Some of the most important physical properties are its magnetic behavior and its resistance to high pressures. At room temperatures, it has properties similar to steel. Nickel is not oxidized in air and is a good catalyst. Its importance as a metal lies in the fact that when used as an alloying element with other elements, it increases the strength, hardness, and resistance to alloy corrosion. Other factors that make it a valuable asset are its elasticity as well as its excellent thermal and electrical resistance.

One of its basic properties is its ability to react directly with carbon monoxide to form a complex carbonyl which is particularly volatile at ambient temperature. At certain temperatures, it is resistant to corrosion in the air, seawater, and non-oxidizing acids. Another property of nickel is its resistance to alkali erosion (Jordan & Swanger, 1930).

5.1.2 Nickel Ore Properties

Primary nickel is usually taken from Lateritic nickel ore. Lateritic ore or laterite is a product of the long-term disintegration of tropical rocks after many fluctuations of wet and dry periods. Because of the way the lateritic ore is forming, laterite deposits are usually found close to the surface like a soft claylike material, where nickel is concentrated in strata as a result of weathering.

It has a rusty dull brick color, which is the characteristic of laterite soils, as it is rich in iron and iron oxides. Nickel ore has a non-homogenous form, unlike other minerals, and consists of very fine clay-like particles and at the same time of larger pieces, like rocks. It is important to mention here that only 2% of the nickel ore is nickel as it also contains other elements like cobalt, silver and iron oxides (Κατζαγιαννάκης, 2013).

Laterite nickel deposits do not pollute the environment like sulfide ores do, as they do not contain sulfur but their mining can be harmful to the environment. Due to the nature of the lateritic ore, the variety of process options is restricted. Being oxides, laterites are not feasible to conventional concentration processes where large amounts can be extracted. Furthermore, laterite nickel contains 35 to 40 percent of water as moisture and chemically bound in the form of hydroxides. Therefore, the operations of drying the moisture and removing the water is critical. The majority of laterite smelters around the world produce a crude ferronickel. This product is very useful and after removing impurities such as silicon, carbon, and phosphorus, is marketed as an alloying agent in steel manufacturing business.

Other important classes of ore are Sulfides. Canadian ores are sulfides that contain nickel, copper, and iron. The essential nickel minerals are pentlandite, pyrrhotite, Chalcopyrite, cubanite. Some gold, silver, and the six platinum-group metals also are present, and their recovery is important. Cobalt, selenium, tellurium, and sulfur may be recovered from the ores as well.

In order to release the nickel minerals, Sulfide ores are being crushed and ground. During this process, the ore is blended with particular reagents and being agitated by mechanical devices that produce air bubbles. As these rise through the mixture, the sulfide particles adhere to their surfaces and are collected as a concentrate containing 6 to 12 percent nickel. The waste material, or tailings, is frequently run through a second cleaning step before it is discarded. (www.brittanica.com)

5.1.3 Extraction of Nickel Ore

With nickel found in two radically different types of ore, it is expected that the mining methods differ. As mentioned before, the processes depend on whether the ore is a sulfide or laterite. As the extraction of nickel from ore is similar to copper in many cases the processes and equipment that are used are similar as well. In the case of sulfides, the reaction of oxygen with iron and sulfur in the ore supplies a portion of the heat required for smelting. Sulfide deposits are usually mined by underground techniques in a manner similar to copper, although some deposits have been mined using open pits in the early stages. The mining of laterites is an earth-moving operation, with large shovels, draglines, or front-end loaders extracting the nickel-rich strata and discarding large boulders and waste material. The ore is loaded into trucks at the face, as would be the case in an open pit, and hauled to the smelt.

The biggest nickel ore mining process is taking place in Indonesia and the Philippines. When laterite is mined, little processing takes place (Figure 12). Even though there are many different mining procedures around the world, usually the operation consists of the following. The nickel ore is usually being extracted, sorted by size, stored in stockpiles and then shipped. (The Swedish Club, 2012)

The extraction of nickel is generally difficult because of their complex mineral composition. The variety of ores and the differences in their chemical composition in combination with the lack of a particular nickel mineral that can be recovered by conventional physical or physicochemical methods, represent the main cause of the limited exploitation of laterites. More difficulties are presented by the fact that other metals coexist in the ore, such as iron, cobalt, chromium, which can not be exported economically. (Τζουβελάκης, 1981)

Figure 12 The process of loading the Ores from open mines.
(Gullen & Norwegian Hull Club, 2015)

5.1.4 Uses of Nickel

The most famous use of the nickel from the old years was the production of coins. Today more than 300,000 uses of nickel are known. The most important of all is its use in the production of stainless steel but also generally in the production of steels, where more than 70% of the world production is consumed. (Κατζαγιαννάκης, 2013)

Nowadays, we use Nickel-containing materials in our everyday life such as in food preparation equipment, mobile phones, medical equipment, transport, buildings, power generation – the list is almost endless. Below is a list which summarizes the most common applications of nickel (Figure 13).

- Production of stainless steel, special steel and special alloys
- Production of steel and iron
- Treatment of the metal surface
- Manufacturing of batteries using positive nickel electrodes
- Magnets production
- Manufacturing of electronics
- Production and use of welding alloys
- Production and use of materials for the contact of silver-nickel
- Production of carbonaceous steel

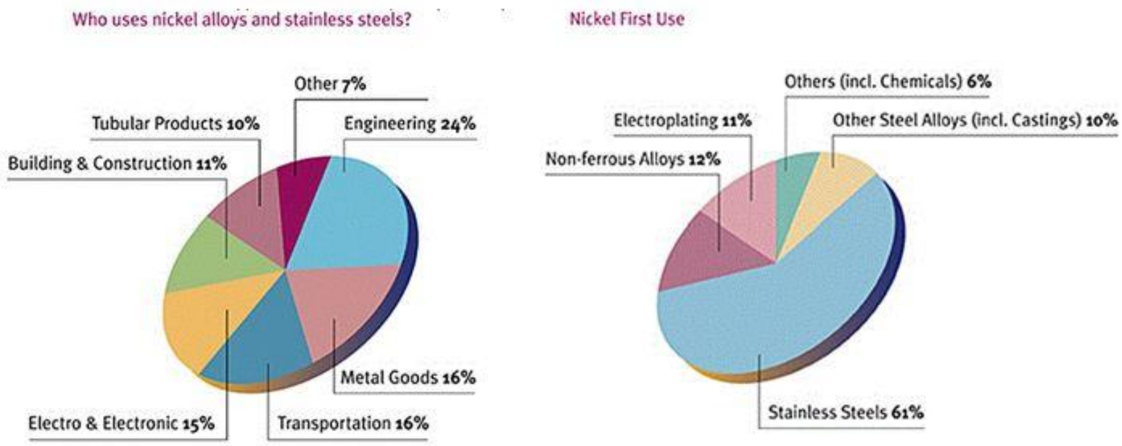


Figure 13 Uses of nickel from Nickel Institute https://www.nickelinstitute.org/

The wide variety of the final products is the result of the variety of industrial processing methods. Hence, the products can be divided into the following two categories:

- **Category I: products with Ni 99% or more.**

- Nickel cathodes (approximately 99,96% Ni).

- Nickel Pellets that are produced by the carbonylation process.

- Nickel powder

- Nickel briquettes

- Washers

- **Category II: products with Ni below 99%.**

- Ferronickel ore (20-29% Ni with the exception of Nippon Mining with Fe-Ni 60% Ni, about).

- Nickel oxide sinter (75-90% Ni).

In the chart below (Figure 14) can be obtained the price of nickel in the last decade. Nickel prices have been in the doldrums after reaching spectacular highs ten years ago. As it can be observed after 2007 and 2010 when the prices were extremely high, today the price is a lot lower. High prices and high demand gave nickel miners good reason to produce more and more nickel, and nickel supply increased. Eventually, China's nickel demand – as well as demand from the rest of the world – slowed when the global economic crisis hit in 2008. Since now was a lot more nickel being supplied than needed, prices collapsed. Then for the past several years, there's been too much nickel and prices have stayed low. However, the picture might change now from having too much nickel to having too little.

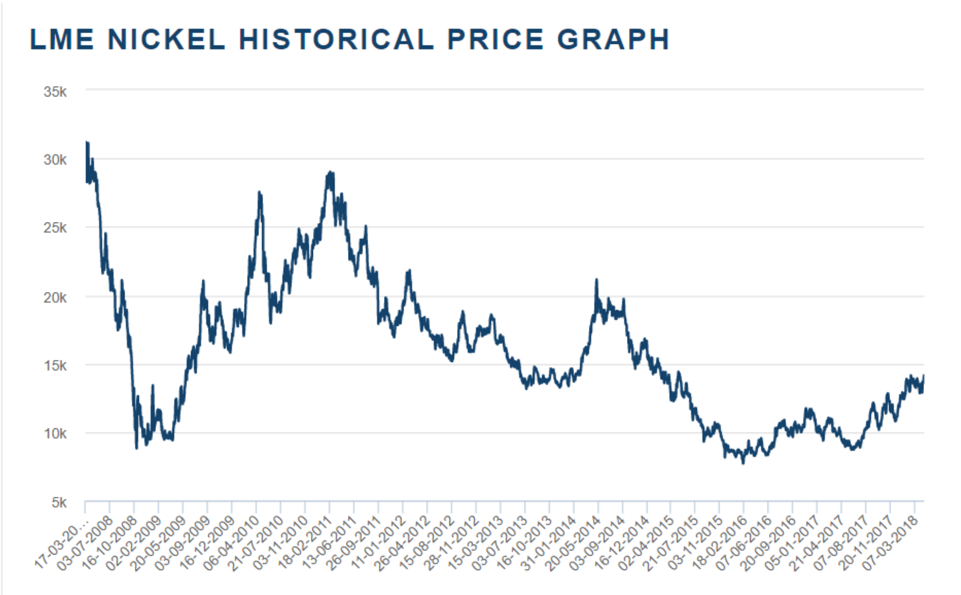


Figure 14 Prices of nickel for the last decade (2008-2018) from London Metal Exchange Market (https://www.lme.com/)

The samples of nickel ore used to execute the experiments were provided by the Greek General Mining and Metallurgical Company LARCO. LARCO, which has been operating since 1963, is the biggest mining company in Greece and one of the five largest producers of ferronickel in the world.

LARCO has mines in Euboea Island, in Agios Ioannis area and Kastoria, near the Albanian borders. Their smelting plant is located in Larymna, and its annual production reaches the 20.000 tonnes of ferronickel per year. From Larymna port the product is being transferred.

5.1.5 Materials tested

To carry out the experiments, two different samples of nickel ore from Kastoria and from Euboea area were chosen to be tested. In this way, it can be checked if there will be any differences in the behavior of these two samples. Below are photos that show some of the elements concerning both the stoichiometry and the chemical composition of the materials in question. The chemical analysis was carried out in the laboratory of the School of Naval Architecture and Marine Engineering with the scanning electron microscope (Figures 15 to 18). The company provided further information about the two samples and specifically about their density. The lateritic ore from Euboea has a specific gravity of 1.896 kg/m^3 while the nickel ore from Kastoria has a specific gravity of 1.589kg/m^3.

5.1.5.1 Sample from Kastoria

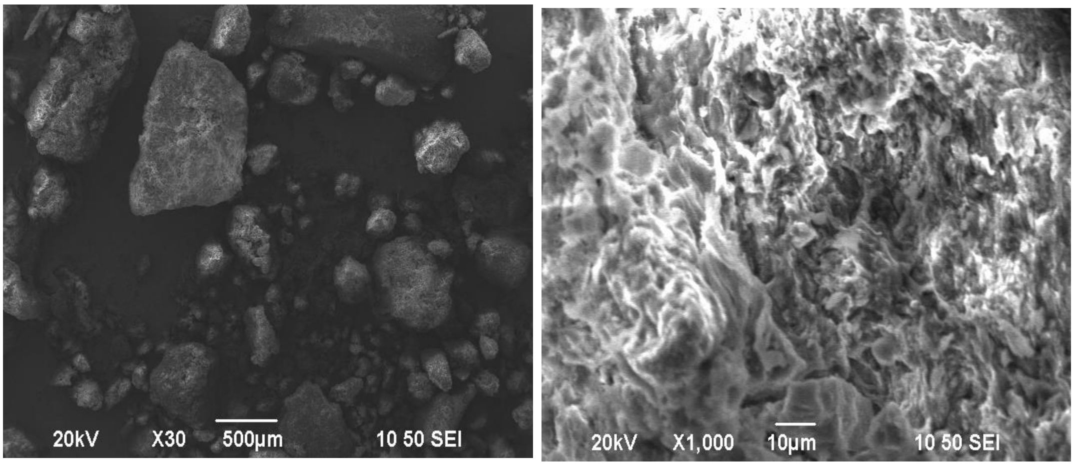


Figure 15a,b Representative images from sample analysis of the nickel ore from Kastoria in the optical microscope.

Element	Weight%	Atomic%
C K	2.94	5.50
O K	43.78	61.47
Mg K	10.49	9.69
Si K	15.49	12.39
Fe K	25.51	10.26
Ni K	1.79	0.68
Totals	100.00	

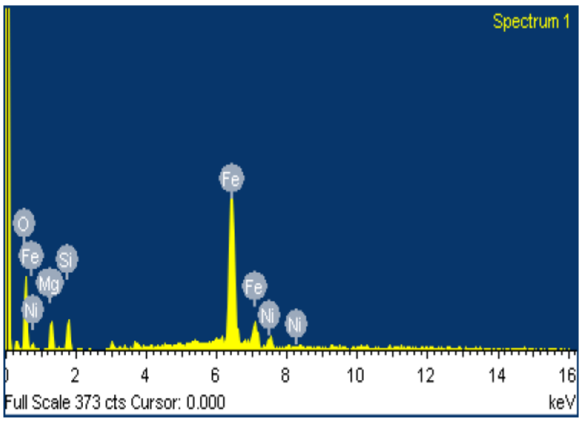
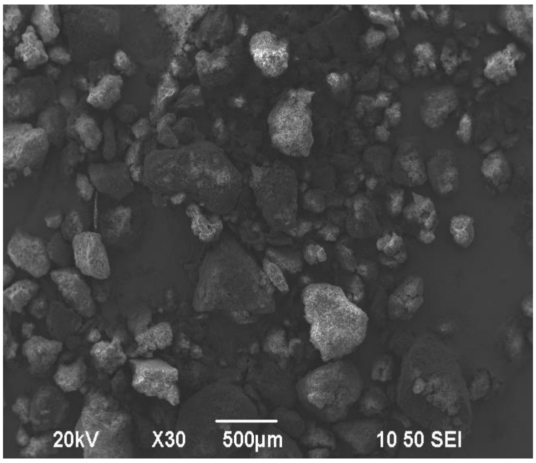


Figure 16a,b Chemical Analysis of the sample from Kastoria

5.1.5.2 Sample from Euboea



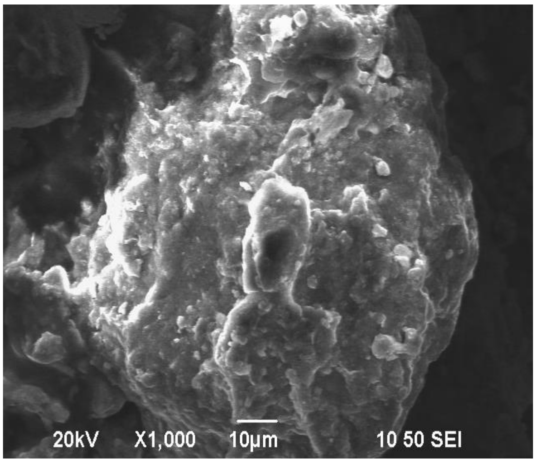


Figure 17a,b Representative photos from sample analysis of the nickel ore from Euboea in the optimal microscope

Element	Weight%	Atomic%
O K	34.58	52.32
Mg K	4.08	4.06
Al K	2.22	1.99
Si K	37.43	32.26
Fe K	19.63	8.51
Ni K	2.06	0.85
Totals	100.00	

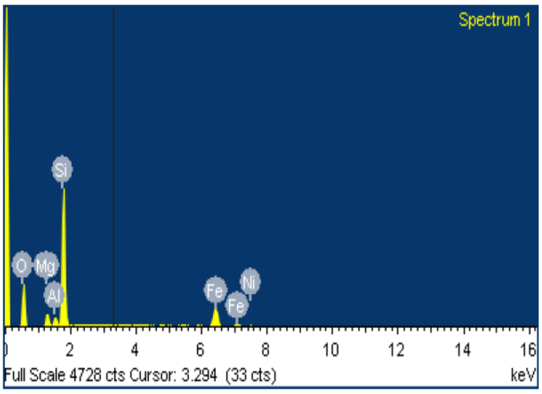


Figure 18 a,b Chemical analysis of the sample from Euboea

To sum up, after going through the reports of all these accidents that were caused by the cargo liquefaction and combine them with nickel ore's properties we can make a list of the reasons that make this cargo still so dangerous.

- Many times nickel ore is delivered directly from excavation to the vessels.
- Mines situated in remote locations making it hard for surveyors and experts to attend them. Moreover, it is not easy to arrange for cargo samples to be tested independently due to the lack of reliable laboratories in such countries.
- Stockpiles exposed to heavy rainfalls (Figure 19).
- 'Solar drying process' even if it is executed it can be ineffective.
- Physical properties sometimes vary from gravel to mud.
- Often it is necessary to send samples that are suspected for liquefaction overseas for testing.
- The crew is often unexperienced and untrained to execute the requested tests correctly.
- Once the cargo is liquefied, the loss of the vessel can happen in less than 30 minutes.
- Once the cargo is liquefied, there are no certified ways and solutions to deal with the problem.
- Insufficient knowledge of the characteristics of nickel ore as a cargo and its propensity to become fluid when the moisture content is high, and it is subjected to sufficient physical stress (Munro & Mohajerani, 2016b)

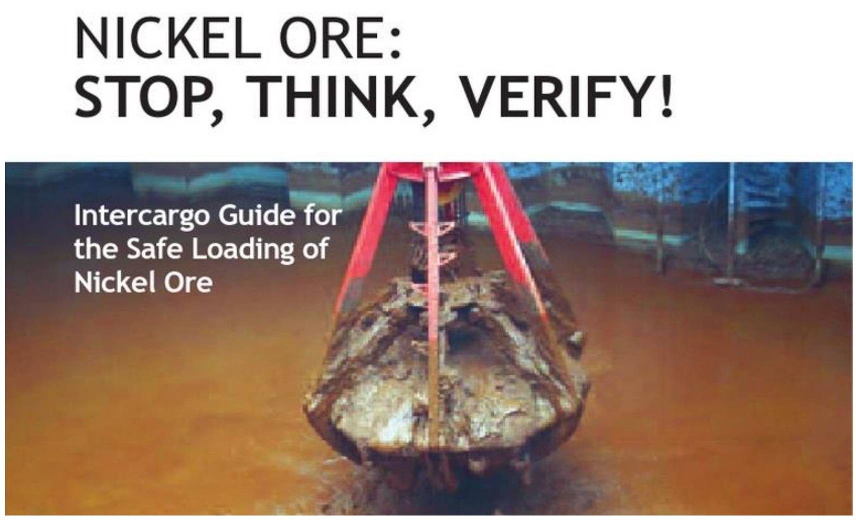


Figure 19 Intercargo guide for the safe loading of Nickel Ore (Intercargo, 2012)

5.2 Iron Ore

Similar to nickel ore the liquefaction of iron ore is the cause of many accidents the last decade. Since 2006, there have been approximately eight reported bulk carrier incidents possibly caused by the iron ore cargo shifting.

Iron Ore is an extremely important raw material, especially considering its essential role in the steel industry, which is the world's largest metal industry. In the last years, China has emerged as a leader in steel consumption. After China, Japan and Korea are following the largest consumption of steel. However, iron ore production takes place in a different part of the world, mainly in countries like Australia, Brazil, Mexico, the United States of America, Canada, Russia and South Africa. Thus, its transfer from producer countries to demand countries is carried out by special-purpose vessels and it is proven to be very risky (YI, 2014) .

Iron is a metallic element that composes approximately 5% of the Earth's crust. When being clean, it has the characteristic dark gray color of the metal. However, because of its potency, it is easily oxidized, resulting in a red, orange or yellow color. These elements are iron oxides. Iron oxides are called iron ores. Iron ores could be described as mixtures of ferrous minerals contain minerals in various proportions. Iron ores are usually being classified based on their mineralogical, chemical and mechanical composition.

Depending on the mineral form of iron, they are classified as oxides, oxygenated and titanium iron ores. The most important category is the oxides. Between them, a big role has hematite (Fe_2O_3), magnetite (Fe_3O_4), goethite (FeO (OH)) and limonite (FeO (OH)) n (H_2O) ($FeCO_3$). Generally, ores containing high quantities of hematite or magnetite (greater than about 60% iron) are called "natural ore" or "direct shipping ore", meaning they can be fed directly into iron-making blast furnaces. Especially Hematite is known as "natural mineral", and in some cases, its iron content reaches 66%.

What should be also mentioned here, is that the presence of harmful elements in the iron ores such as Cu, Zn, Pb, As, S and P is of great importance. Phosphorus should be at very low levels (below 0.045%) with a P: Fe ratio of less than 0.00075. The type and content of mineral and harmful elements play a decisive role in the metallurgical processing stage. (Τρίχος, 2011)

The biggest resources of iron ore in the world occur in iron-rich sedimentary rocks that are known as banded iron formations (BIFs). These rocks are almost exclusively of Precambrian age (i.e. greater than 541 million years old). BIFs occur on all continents except Antarctica. Usually, they are mined as iron ores but, most importantly, they are the source rocks for most of the large, high-grade concentrations of iron ore currently mined throughout the world.

Iron ores are the basic element for some important products, such as Pig ore, Sponge iron, Mill Scale or Iron Ore concentrates.

Iron ore concentrates are produced either by dry or wet process. In the first method, the iron ore is dried, resulting in a sufficiently low moisture content but increasing the possibility of its ignition due to the reaction of sulfur with oxygen. In the second method, to remove the Sulfides, the ore is wetted with water, and its moisture content is increased. The same effect has on the likelihood of liquefaction during cargo's voyage.

Sponge iron or Direct Reduced Iron (DRI) is being produced from iron ore and used in the production of steel. For its production, the iron ores need to be heated to low temperatures without being allowed to come into contact with air. This iron derivative is separated from the magnets and thus has a low moisture content. Consequently, when transported in large quantities, if water enters it, it is likely to oxidize and cause spontaneous combustion and/or toxic fumes.

Another product of nickel ore that is usually dangerous to liquefy is the Mill Scale. It is a material that is being carried in bulk carriers, like Iron ore fines. This material belongs to the Group A as a cargo and therefore cannot be accepted for loading without its moisture content being checked from the crew. Usually, when this product is liquefied, it is created a wet base, resulting in the surface of the cargo being dry and shifting more easily.

Iron ore is a heavy load, it has a fairly low stacking rate of 0.29 to 0.80 m3 / t, while its density is 1250-3448 kg / m3. The moisture content contained there is around 0.16%. However, if it is stocked in the countryside, moisture content increases due to air or rain.

At the beginning of 2010 after the accidents of BLACK ROSE and ASIAN FOREST (Figure 20), the Ministry of shipping in India (Ports Wing) published a report with the investigation of these casualties and with recommendations for the future of the iron ore Transportation. In both accidents, the loss of the vessels that caused by the sifting of the cargo inside the holds was a result of many unfortunate reasons.

Figure 20 A view of the tilted Chinese ship M.v.Asian Forest from Coast Guard ICGS Sankalp which rescued the ship crew from few nautical miles away from Mangalore. Photo: R. Eswarraj (http://www.thehindu.com/news/cities/Mangalore/Sunken-ship-complaint-filed/article16888395.ece)

Below is a list of the reasons that led to the loss of the vessels. It is obvious that the basic reasons were the same in both accidents.

- The cargo loaded on the ship was wet due to the rain and the master did not stop the loading procedure even when it started raining.
- No or wrong documentation was submitted about the flow moisture limit or the Transportable moisture limit of the cargo.
- In both accidents, the port had no control over the loading operation as they left the Stevedores responsible for this procedure.

- The area where the cargo was being stored before shipment was at a relatively low area causing water accumulation. Beside the same being open, thus making the cargo wet before it is brought to the jetty
- The test report that was given to the captain was old, so he could know the actual status of moisture in the cargo.
- The captain and the crew had insufficient knowledge about the regulations.
- During the trip, the vessel faced rough sea and it was raining. The vessel had high metacenter height. As a result, the vessel rolled and pitched excessively which led to the liquefaction of the wet cargo. (The Ministry of shipping (Ports Wing), 2010)

After these casualties, awareness has been raised about the loading and carrying of the iron ore so as to prevent similar accidents. In 2014, Yi Lu in the University of Auckland executed tests in order to understand and examine if iron ore liquefies under specific conditions. They executed experiments with the cyclic triaxial test in three different samples. They mostly applied techniques of soil mechanics and tests that are usually being used for soil liquefaction. Nevertheless, they realized that the mechanism of liquefaction is the same. What changes though, is the material that is being liquefied. As it was proven, the shear resistance to liquefaction is a lot higher in ores like iron ore than in soil sands. (YI, 2014). Furthermore, the engineering properties of iron ore differed from the properties of the soil sands because of the density and the particles distribution. Another important conclusion of this research was that a liquefaction failure could not be observed in a roll movement that does not exceed the five degrees.

Other interesting results about iron ore liquefaction come from the RMIT University in Melbourne, Australia. Michael C. Munro and Abbas Mohajerani tested the iron ores fines under cyclic loading in order to explain the phenomenon of the on board liquefaction. During the experiments, they executed they were trying to monitor the water and air pressure, the moisture migration and also the changes in the physical properties of the iron ore. After the experiments, they reached the conclusion that while iron ore is being transported moisture migration is happening due to the ores' good drainage. This leads to the separation of the fine particles together with moisture. This mixture of moisture and fine particles is usually moving to the surface of the cargo inside the holds. Pore pressure will start increasing in these areas causing liquefaction. (Munro & Mohajerani, 2018)

As it was proven, liquefaction is possible to occur in specific spots of the cargo and not in all of it. Lastly, another important observation was that when the gross water content of Iron ore fines is 9.5%, which is 1.5% less than the TML the segregation, moisture migration, and the increase of pore pressure starts.

5.3 Bauxite

Some years ago on the 2nd of January 2015, the loss of 'Bulk Jupiter' brought the attention to a cargo that until then had never been reported to cause any marine accidents. The vessel sank in the South China Sea carrying 46,400 tons of bauxite.

Bauxite holds its name from the French village 'Les Baux' where it was first found and recognized as containing aluminum. Bauxite can be described as a soft, white, grey or reddish brown material with an earthy luster (International Maritime Organization, 2002). However, these properties of the material have nothing to do with bauxite's value or usefulness. And that can be explained as bauxite is almost always processed into another material with physical properties that are distinctly different from bauxite.

Bauxite is the main source of aluminum, with aluminum being the third most abundant element in the earth's crust. Almost all of the aluminum that has ever been produced has been extracted from bauxite. Today large reservoirs of bauxite can be found near the surface as flat layers in deposits that extend many square kilometers. It can usually be found in tropical areas like Africa, Australia and South America.

After the mining of bauxite and before loading for shipping, bauxite can be categorized into one of three categories:

1. Direct Shipped Ore (DSO): Going through the screening process and crushing to remove bigger pieces and any piece of organic contamination.
2. Beneficiated ore: ore is crushed, screened and washed to remove fines.
3. Dried for handleability. (Global Bauxite Working Group, 2017)

According to the IMSBC code, the transportation of bauxite evolves no hazard. It belongs in the Group C and it is a non-soluble and non-combustible cargo.

As mentioned before, the loss of Bulk Jupiter in 2015 was an unexpected and tragic accident. The vessel faced rough seas in her last trip, and the only survival of the accident claims that inside the holds had been formed pools of water. Furthermore, the slurry cargo was moving from one side of the hold to the other which caused an a-typical movement of the vessel in combination with a rapidly increasing list. During the trip, the vessel was rolling more and more heavily until she developed a list of 45 degrees. (Bahamas Maritime Authority, 2015)

Later that year, the investigation report from the Bahamas Maritime Authorities identified the causes of the accident. The basic reason that led to the loss of the vessel was that the cargo in the holds had an increased moisture content of 21.3% when the recommended moisture content from the IMSBC code is only 10%. This could be explained by the fact that the cargo remained exposed to rainfall for several days during the loading procedure. Moreover, an independent inspection was not requested by the Master to verify the properties and the moisture content of the bauxite before loading.

Approximately, one year ago on April 2017, the Global Bauxite Working Group published a report about the behavior of bauxite while it is being transported with vessels. As they examined and tested many different samples of Bauxite, they tried to understand the mechanism of its failure. After many experiments in extreme conditions, no sign of liquefaction was observed during its transportation. Although no liquefaction was observed, the authors have demonstrated that

Figure 21 Failure Mechanism of Bauxite cargo (Global Bauxite Working Group, 2017)

bauxite cargoes can undergo other potential instabilities that are connected with the moisture content of the cargo. Specifically, the failure mechanism of bauxite is the dynamic separation (Figure 21), and it is explained briefly next. While the bauxite is being transported, as it is illustrated in Figure 22, many vibrations from the sea and the vessel create forces that are also affecting the cargo. These forces usually result in the compaction of the cargo. Although, if the moisture content of the bauxite cargo is above or close to critical then the dynamic separation can occur. During this process, the cargo is being separated in two different phases, liquid and solid with the slurry phase perching at the top of the dry cargo (Figure 23 and 24) (Global Bauxite Working Group, 2017). Even though finally the process has some differences from liquefaction its results are unfortunately the same causing the instability and even the loss of vessels.

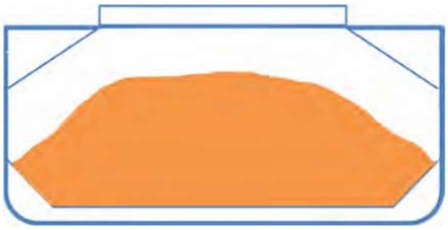


Figure 22 Bauxite cargo in holds (Global Bauxite Working Group, 2017, p. 83)

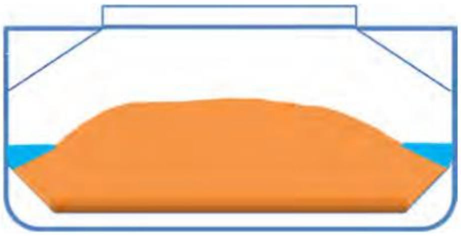


Figure 23 Initial stage of cargo instability due to dynamic separation (Global Bauxite Working Group, 2017, p. 83)

*F*igure 24 Final stage of cargo instability due to dynamic separation (Global Bauxite Working Group, 2017, p. 83)

CHAPTER 6: REGULATIONS

The last decade several regulations have been established globally and nationally to secure the loading, transporting and unloading of the cargo. Most of the regulations are trying to prevent marine accidents and incidents and protect the human lives as well as the environment. Such regulations are the International Convention for the Safety of Life at Sea (SOLAS), the International Safety Management Code (ISM Code), the Code of practice for the safe loading and unloading of bulk carriers (BLU Code), the International Maritime Dangerous Goods Code (IMDG Code), the Dangerous Bulk Material Regulations, the Canadian Code of Safe Practice for Solid Bulk Cargoes, the International Marine Solid Cargoes Code (IMSBC code), etc.

6.1 The International Maritime Solid Bulk Cargoes Code

As mentioned before, the IMSBC code contains regulations about different hazards. The most important hazards for the bulk carriers are the ones that are related to the loss of the stability of a vessel due to its cargo improper distribution or movement inside its holds during the transportation. The primary aim of the International Maritime Solid Bulk Cargoes Code (IMSBC Code) is to ensure the safe transportation of solid bulk cargoes on vessels. In each chapter, it provides information about how every cargo should be treated, what dangers exist in the carriage of different type of cargoes and specific instructions about the tests that should be executed to check whether the cargo is appropriate for loading.

In the IMSBC code information can be found about most of the cargoes that are being transported nowadays. Briefly, there are included the properties, the characteristics, the risks and requirements for loading, the stowage factor, the segregation as well as any further important information for the transporting, cleaning and the ventilation of this specific cargo.

The code refers to a large number of cargoes, for which a specific code has been assigned, the Bulk Cargo Shipping Name (BCSN), which identifies the cargo during its transportation by sea. This code should always be completed with a United Nations (UN) number if the cargo is dangerous and with the word "WASTE" if the cargo needs further processing. If the load has a UN number, then it should be classified.

In addition, according to the code each cargo is being categorized in one of the following groups. Group A, which includes the cargoes that can be liquefied if loaded on board with a moisture content greater than the variable limit, Group B, which includes cargoes that involve a chemical hazard when they are carried on a vessel and Group C, which includes cargoes that neither liquefy during transportation, nor can cause a chemical hazard. In the code, are specific paragraphs for the safe loading and transport of loads A and B, as well as for bulk solid waste.

For the secure transportation of the cargo, the master of the vessel should be informed about the cargo’s properties before loading. All the information for the cargo should be included in a special form. This form should contain information about the BCSN code of the cargo, the group (A and B, A, B or C) that belongs to, its class according to the IMO, the total amount of cargo that is about to be loaded, the UN number, the stowage factor, the load handling procedures that are required, the rest angle, the moisture level (TML) and if it is possible for the cargo to liquefy. Also it should contain the possibility of creating a wet base, the toxic and non-flammable gases that can be produced by the cargo, the flammability, the toxicity, the erosion ability, the self-heating properties of the cargo, the properties of flammable gases when in contact with water, the radioactive properties and any other load information required by the national authorities. (International Maritime Organization, 2002, p. 21). Lastly, the cargo information should declare whether the cargo is dangerous for the environment.

In order to accept the cargo for loading the master shall order a proper check of the cargo, in addition to the necessary tests and the certificates of the cargo. Special certificates should be provided to the master in case the cargo that is about to be loaded is hazardous loads or can be liquefied. In particular, loads belonging to group A should only be accepted for loading when their moisture content is less than the transportable moisture limit (TML). The loading should not take place if the TML of the cargo is lower than the moisture content of the cargo.

6.1.1 Instructions for the sampling and testing of cargoes

Below, the three methods of the IMSBC Code that are used for testing the materials that may liquefy, are described:

1. The flow table test. This test provides the moisture content of the cargo, with the flow moisture point of the sample and the transportable moisture limit of the material. This test is suitable either for fine materials with a maximum grain size of 1mm or for materials with grain size up to 7mm. The quantity of the sample that is needed for the flow table test may vary depending on the material. It can be between 2 to 3 kg that has to be selected from different parts of the cargo being shipped in order the test to have more accurate results.

2. The penetration test. In this simple test, the material being tested needs to be placed in a cylindrical vessel that is vibrated. During this test, the sample is subjected to vertical vibration for 6 minutes. By this way, the flow moisture point is determined by the penetration depth of an indicator. The penetration test is suitable for mineral concentrates and coals up to a top size of 25 mm. The IMSBC Code also provides specific information about the dimensions of the cylindrical vessels. After the penetration test has been performed the authorities can check if the liquefaction will take place. Specifically, if the depth of penetration after the 6 minutes is less than 50 mm, it is judged that liquefaction did not take place. Otherwise, if it is more than 50mm, it is judged that liquefaction took place and further measurements need to be done.

3. The proctor/ Fagerberg test. This test method can be used for both fine, and relatively coarse-grained ore concentrates and similar materials up to a top size of 5 mm. For performing the Proctor apparatus, the authorities need a cylindrical iron mould with a removable extension piece and also a tool guided which they can use for the compaction of the sample inside the mould.

Generally the IMSBC code advises the authorities to perform the tests in a place where the samples will be protected from extreme temperatures, air currents and humidity variations. Also, the material preparations and the test should be complete in a reasonable space of time for more accurate results.

Finally, even if after these tests the master is not ensured about the condition of the cargo, the IMSBC code recommends to execute an extra very simple test, which is called the Can test. For this test, all that is needed is a cylindrical can which he has to fill until the half with the sample. Then he needs to strike it on a hard surface like the floor very fast for 25 times at one- or two-second intervals. After that, he needs to examine if it is visible on the surface of the sample any sighs of free moisture or liquid. If this is the case, then arrangements should be made and additional laboratory tests should be executed on the material before loading. If samples remain dry, then the sample is acceptable for loading.

Even though all of the tests mentioned before could verify the situation of the cargo, their results can only be correct if the procedure of the sampling has been executed correctly and according to the guidance. As it has been proven, the incorrect sampling of ores has led to many accidents of vessels as the cargo is being accepted with wrong moisture content. Specifically, what should be done according to the Section 4.6 of the IMSBC Code is the following:

- Sampling should only be executed by people that have been trained for these procedures and know the applicable principles and practices of sampling.
- For cargoes that belong to the Group A, the responsible person for the sample should visit with the master of the vessel and inspect the stockpiles where the cargoes are being loaded
- Before the sampling, a visual inspection of the shipment should be carried out. If a portion of the cargo appears significantly from the rest of the cargo, then it should be tested separately.
- Samples should be gathered from the whole cargo considering the characteristics of the cargo like the type of material, the particle size distribution, the composition of the material and its variability, the manner in which the material is stored, the chemical hazards that the material could cause, the characteristics like the moisture content, TML, bulk density/stowage factor, angle of repose, variations in moisture distribution throughout the consignment which may occur due to weather conditions, natural drainage, variations which may occur following freezing of the material.
- It is also important to take care of the cargo while the testing procedures are being carried out so as the weather conditions not to change the moisture content or other properties of the cargo.
- Samples should be taken from the full depth of the stockpiles.

There is a specific plan for the stockpile before the loading, and it is divided into areas, that can be from 125t to 500t, depending on the amount of the whole cargo (Figure 25). The sample should be collected from approximately 50cm below the surface of the above area of the stockpile. (Captain Paul Walton, 2015). Sub-samples should be taken in a uniform pattern as it is illustrated in the photo below.

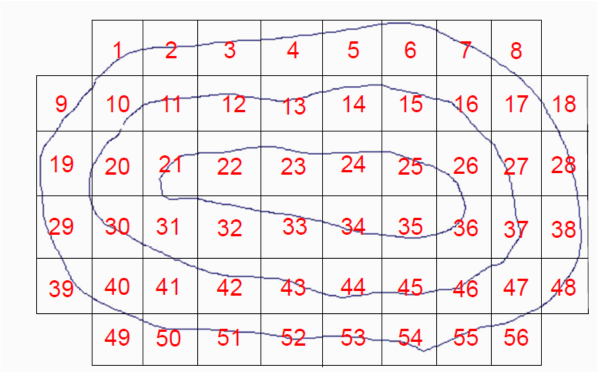


Figure 25 Sampling Procedures in open mines following a specific pattern (Captain Paul Walton, 2015, p. 34)

6.2 Important Guidance for the prevention of liquefaction

6.2.1 The International Safe Management Code

The International Safe Management Code, issued by the IMO, aims to establish an international standard for the safe management and operation of ships and has been adopted and incorporated into SOLAS. Therefore its provisions are mandatory. One of the basic rules of the ISM Code is that each ship should have an operational safety management system. Regarding the bulk cargo transportation, it is important to assess all the potentially dangerous situations and their risks and also plan the appropriate procedures to face them. More specifically (UK P & I, 2010):

1. Carry out a detailed risk assessment before loading the cargo

2. Make the appropriate stability calculations after loading the cargo and before leaving the port

3. Captain to know port boats for the scheduled voyage of the ship

4. In case of a problem during the trip, there is direct contact with the shipowner

5. In the event of liquefaction occurring, the master must proceed to the nearest port

6.2.2 Canadian Code of Safe Practice for Solid Bulk Cargoes

In 1984 the Canadian government established the Canadian Code of Safe Practice for Solid Bulk Cargoes. The Code aims to create a standard procedure for the safe stowage and transportation of solid bulk cargoes, with the exception of grains that is covered by another code. This code incorporates all the recommendations contained in the latest version of the IMSBC code, in conjunction with specific Canadian requirements, in particular regarding the safe carriage of ores.

Special references are included in the Code for the protection of personnel and the ship as well as for cargoes that can be liquefied. Loads that can be liquefied according to the code are ores, certain coals and other materials that have similar properties to them. At the same time, the code gives specific instructions about how the ores should be loaded in the vessels that are travelling to and from Canada. Finally, Annex E of the

Code refers to the sampling procedures that are necessary in order to check the cargo correctly. It is also followed by an addition that emphasizes the responsibilities of the harbor master before and during the loading of the cargo in order to ensure that the all the regulations are being followed.

6.2.3 Lloyd's Register checklist

In the recent years, many classification societies around the world together with marine organizations, Intercargo, the International Group of P&I Clubs, the International Chamber of Shipping (ICS) are publishing a lot of newsletters and reports to raise the awareness of the problem of liquefaction and to find practical solutions.

Lloyd's Register in cooperation with Intercargo and UK P&1 Club published a newsletter based on the IMSBC code with the basic information about cargoes that may liquefy. It also informs the master of the vessel and the crew what is being required to accept the cargo and what they should do to reduce the risk of liquefaction. Interestingly, the newsletter includes a checklist that that simplifies the supervision of the whole procedure, from the inspection of the cargo, the loading and then its transportation inside the holds. The Figure 27 a, b shows the checklist that the master needs to fill up (Lloyd's Register, UK P&I CLUB, & Intercargo, 2013).

Checklist

Before accepting and loading a cargo, ask yourself the following questions:

1. Has the shipper delivered the cargo information and documentation listed in the Code under 'Assessment of acceptability of consignments for safe shipment; Provision of Information', including the correct Bulk Cargo Shipping Name (BCSN), and provided a declaration that the cargo information is correct? ☐

2. Have you consulted the relevant IMSBC Code schedule to find out the cargo's general and specific hazards? ☐

3. If the cargo is listed as Group A, have you followed all procedures relating to the safe carriage of cargoes which may liquefy? ☐

4. If the schedule indicates the cargo is Group B has the shipper provided a statement that the chemical characteristics of the cargo are, to the best of his knowledge, those present at the time of loading? ☐
   a) If the cargo is classified as 'dangerous goods in solid form in bulk' does the Master have a special list, manifest or stowage plan identifying its location, are there instructions on board for emergency response, and does the ship have a Document of Compliance for the Carriage of Dangerous Goods? ☐

(Continued on the next page)

Checklist (continued)

5. Whatever the cargo Group, have you taken the recommended precautions to remove or minimise the cargo's hazard, including:
   a) preparing recommended safety equipment and procedures? ☐
   b) activating any cargo monitoring equipment ready for loading? ☐

6. Have the Master and Terminal Representative agreed a Loading Plan to ensure that the permissible forces and moments on the ship are not exceeded during loading or unloading? This should include the sequence, quantity and rate of loading or unloading, the number of pours and the de-ballasting or ballasting capability of the ship. ☐

7. Are there instructions to suspend the loading or unloading operation if the ship's limits are exceeded, or are likely to be exceeded if the operation continues? ☐

8. Are you monitoring the cargo loading or unloading procedure, is the ship's draught being monitored and recorded in the logbook, and have any significant deviations been corrected? ☐

9. Before sailing on the loaded passage, have you considered other factors, such as the ingress of water, which could affect the cargo during the passage? ☐

Figure 27a,b Checklist and flowchart for accepting and loading solid bulk cargoes (Lloyd's Register et al., 2013, p. 16)

6.2.4 Nautical Institution guidance for nickel ore

On December 2013 the Nautical Institute also published a newsletter with the title 'The deadliest cargo', referring to the nickel ore. The report was focusing on the way that the vessel Harita Bauxite was lost due to liquefaction of the cargo and the reasons that led to this accident. It was also pointed out which elements can be improved to prevent accidents like this and also how important is the right training and knowledge of this topic from the master and the crew (Poulsen, 2013).

6.2.5 DNV GL's research for liquefaction

Two years later, in 2015 DNV GL, also published a detailed newsletter about the phenomenon of liquefaction. It contains a detailed explanation about how liquefaction can occur both in granular and non-granular materials. Also, it refers to the cargoes that are most likely to liquefy and inform the crew about the risk of nickel ore, iron ore and bauxite. The report gives specific instructions about every step of the procedure from the testing of the moisture content of the cargo to its transportation. (Gullen & Norwegian Hull Club, 2015)

It also refers to the allowance from IMSBC code of carrying cargo with a moisture content higher than its TML from special fitted vessels. Additionally, the newsletter proposes to apply some changes in the conventional bulk carriers to ensure their safety and stability.

6.2.6 The Swedish Club guidance

The Swedish Club published an interesting report in 2012, in which they tried to explain how liquefaction occurs and how the crew and the companies should deal with this problem. They also answer to what should be done in two urgent situations.

- What should be done in case it is raining during the loading of the cargo on the holds?

It is very often that bulk cargoes are stored in stockpiles between the procedures of sampling and loading and are being exposed to weather conditions like rain or snow that can affect their moisture content. A cargo that had been accepted for loading can turn into to a danger for the life of a vessel as it may be eager to liquefaction once its moisture content raises. The Master of the vessel is being advised to stop the procedure of loading if it is possible during the rain. Also, it is important that the Master asks an expert or a surveyor to execute more tests of the cargo to check its moisture content again and be sure that is below its TML. This procedure between sampling/testing and loading should not last more than seven days. (The Swedish Club, 2012, p. 3)

- Discharging or sailing with the unsafe cargo

In case a vessel loads cargo without its necessary documentation there is the chance that the cargo is unsafe and the master will need to order the discharging of it. The problem is that the discharge may cause many troubles to the master, the company and even the harbor. This is due to the lack of exact regulations about how this situation should be treated. The company will lose a lot of money in their process of discharging and also terminals and shippers may not be willing to accept the discharged cargo. As a consequence, many bureaucratic difficulties may. Usually, in situations like that, there is a lot of pressure on the masters of the vessels as no one wants a bigger cost or delay.

In case that the cargo can be discharged, there is the opportunity to let it dry. However, this procedure may take up to some days, and it also requires personnel that will take care of the cargo and regularly move it and turn it over. In the past, when sights of liquefaction became visible to the master and the crew, and the unloading of the cargo was not possible, many suggestions were made for reducing the risk for the vessel and its crew. Some of these suggestions were sailing with reduced speed, staying closer to land, and change of route so as to avoid bad weather conditions. Although these suggestions could reduce the risks for the vessel, there is no guarantee of their effectiveness. From what we already know, there have been reported accidents that happened very suddenly and during calm weather.

Another suggestion is to restrain of the cargo surface. This can be achieved either by placing bagged cargo on top of the holds or by strapping the cargo. These are solutions that have been introduced to prevent the shifting of grain cargo, but their efficiency in liquefied cargo is questionable. This is because liquefaction may also appear on the base of a cargo hold and then these suggestions could not reduce the risk. (The Swedish Club, 2012, pp. 16–17)

At the end, if liquefaction appears, the Master is obligated to notify immediately the owners, who should ask for the help and advice of experts.

CHAPTER 7: IDEAS FOR LIMITING THE RISK OF LIQUEFACTION

While the scientific community is still trying to understand and explain the phenomenon of cargo liquefaction, from 2009 until today, many ideas have been proposed to reduce its risk and secure the vessel's and its crew safety. Below is a list with the proposals that have been suggested, as well as the opinion of people that are working in the marine industry and were willing to help in this research.

7.1 The first special vessel for Nickel ore

From around 2009, ClassNK started trying to create a specially constructed vessel for the transportation of nickel ore since so many lives were lost due to its liquefaction. They researched a lot to understand the properties of the nickel ore and its behavior during shipping. Only two years later, in 2011, the Japanese classification society ClassNK presented to the marine world the idea of the first specialized vessel for the transportation of nickel ore. They developed a specific hull structure, and the vessel was designed to meet the necessary stability requirements.

In March 2012, they released the newsletter 'Guidelines for the Safe Carriage of Nickel Ore' with information about this special vessel. Soon the governments of Panama and Japan approved the use of these special vessels, flagged with their administrations. Nowadays, they have earned the approval not only of INTERCARGO but also of the wider maritime industry. In September 2012, they were honored with the "Safety Award" at the Lloyd's List Global Awards.

Figure 28 Jules Garnier 2. The first specialized vessel for carrying Nickel Ore. https://www.marinetraffic.com/

The special vessel that they constructed is called Jules Garnier II (Figure 27) with deadweight 27,200 tons. It is the first vessel in which ClassNK applied the new requirements in its construction. Longitudinal bulkheads are being used in the cargo holds to ensure not only stability but also structural strength even in the case that they cargo may liquefy (Hull Department ClassNK, 2013).

7.2 A chemical solution for the liquefaction of minerals

At the end of 2010, the same time that ClassNK was looking for a structural solution to the problem of liquefaction M.Popek faced the problem from a different perspective. Being inspired by the way that soil liquefaction was being faced he proposed the use of polymer materials to absorb the water from the wet cargo. He executed experiments, and the results showed that by adding the polymers the cohesion and the internal friction angle were affected. In the end, the use of polymer materials will prevent the drainage of water happening from the cargo's pores and as a result will obviate the sliding and shifting of cargo inside the holds or when it is being stored before loading. Here it is important to mention that the polymer materials that were proposed for use are based on natural renewable resources, and there is no concern for their environmental pollution. (Popek, 2010)

7.3 A Safety Inflated Device

A different solution was proposed and also studied in 2013 which involved the use of Safety Inflated Devices. These devices can be placed in the outer surface of the cargo holds in both port and starboard sides. Every time they can also be placed in another position/ hold. The advantage of the Safety Inflated Devices is that they can be easily installed also in existent vessels and their cost and weight are low. As it was proven in research (Zografakis, 2013) the use of these devices could prevent the capsizing of vessels even when liquefaction occurs in all the holds. Also, their effectiveness raises when they are being submerged entirely. Finally, they could increase the stability of the vessel being placed closer to the stem.

7.4 DNV's proposals for transportation of ores

Following NK's example, DNV GL published a newsletter as well, referring to some structural changes that could prevent accidents that are caused due to the liquefaction of the cargo. One of their proposals was the longitudinal bulkheads that could make the holds narrower and the effect of the free surface on the stability smaller. Even though this solution could ensure the increase of the stability, it would lead to the loss of holds' volume as well as to the increase of the weight and cost of the structure.

DNV also emphasized the special requirements for ore carriers. As they claimed because of the high filling level inside the cargo holds, there is the need to increase the strength of the hull to comply with the criteria for cargo liquefaction (DNV GL, 2015). In Figure 28, they illustrate the critical areas of the midship section.

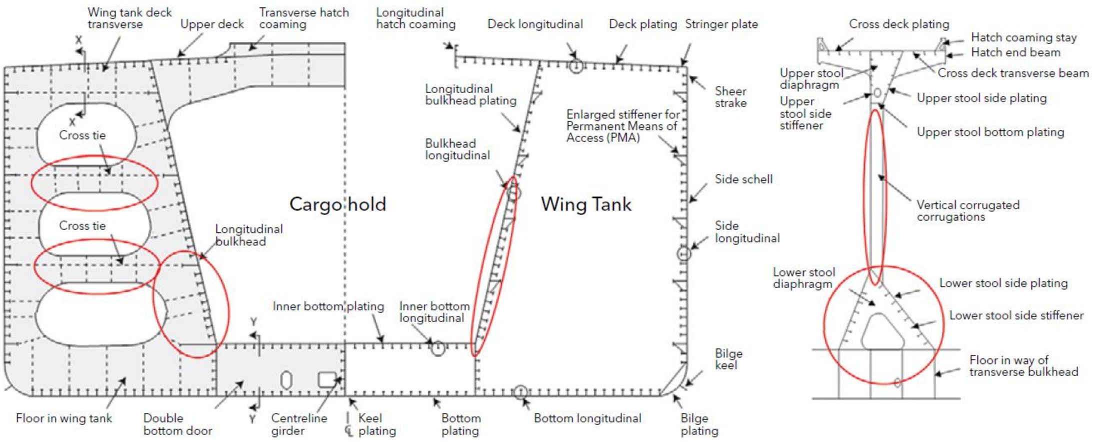


Figure 29 Ore carrier: Areas of special attention (DNV GL, 2015)

In the newsletter, they include the following guidelines for a safer vessel:

- For the longitudinal bulkheads, the use of a thicker plating or steel with higher yield point is required since the stiffeners that are supported by the web frames in the wing tank, and the increased loading lead to higher shear stress in the lower part of web frames. Increased strength in the cross ties is also required as they will experience high compressive forces.
- For the lower stool, since the pressure is increased, either the scantlings will need to be increased, or the diaphragms may need extra support. The strength of the transverse corrugated bulkheads is basically relied on the loading conditions. In case the vessel has been designed for homogenous loading then its stability needs to be checked for the worst case scenario, which is the liquefaction of the cargo in one hold and no liquefaction in the neighboring hold. Also, what is of great importance is the height that the cargo is reaching after loading inside the holds, because of the corrugations. When we load a low-density cargo, then the filling height is higher than when we load a high-density cargo. In this situation, the force on the corrugations will be higher and the center of pressure will less favorable for the corrugation bending (DNV GL, 2015).

7.5 Some innovative solutions

At the same time, Stefan Kirchner proposed an innovative solution to limit the risk of vessel's capsizing due to liquefaction of its cargo. The suggestion was the use of an ultralight honeycomb structure inside the holds of the vessel. This would restrict the shifting of the cargo in the holds. He also proposed the lattice to be constructed from a light material and to be able to be removed from the cargo holds quickly before the unloading. (e.g. with an excavator which would be used to remove the dry cargo). (Kirchner, 2015a) Another suggestion was to add in the cargo a non-reactive Drying Filler Material. This way the (empty) space inside the cargo holds (regardless of the amount of cargo that would be transported) would be reduced and the movements of the material inside the holds would be limited. Also, the drying properties of these materials could absorb humidity from the cargo and reduce the risk of its liquefaction. As far as the material that should be used, the thought of big items, such as wood pellets, sounded more suitable, but even the author expressed the need for more research and the construction of an appropriate artificial device. The only disadvantage in this solution was that before the unloading the material should be removed from the cargo. That increases the time and therefore the cost of transporting ores with these materials for sure (Kirchner, 2015b).

7.6 The use of coagulants inside the holds

Just one year ago, in March 2017, a group of students from the University of Strathclyde presented their thesis with the title 'Liquefaction Risk Management'. During their research, they tried to come up with solutions on the phenomenon of liquefaction. They examined the feasibility of structural, mechanical and chemical solutions and tried to come up with ideas that would be applicable to all vessels and not only to newbuildings. The basic idea, they examined detailed, was adding by a sprinkler system inside the cargo holds coagulants. From the materials they tested, they concluded the Sodium Polyacrylate to be the most effective (Seng et al., 2017). They also designed the onboard system for the use of this additive chemical considering its properties. The proposed system is considered to reduce the risk of liquefaction and prevent the capsize of vessels. Studying the cost of this solution they understood that it would overcome the possible financial benefits in all cases except unrealistic situations, like the really low price of the chemical. Nevertheless, their solution from another perspective has proven applicable and effective in terms of protecting the lives of the seafarers.

7.7 The expert's opinion

Within the research on the topic of liquefaction, specialists were contacted and asked for their opinion and their ideas on this critical issue.

- Mr Dimitris Dedepsidis is the Customer Service Manager of Bulk Carriers in the Region of South East Europe and Middle East for DNV-GL. During the interview, he expressed his concerns about the phenomenon of liquefaction as he believes not enough research has yet been done on the topic. He believes that the best way to avoid the problem is to follow closely the guidelines of the IMSBC Code for the storage, sampling and loading of the cargo. As he mentioned, the problem of liquefaction is multidimensional and the solutions that have been proposed so far not satisfying. He is not in favor of adding chemicals to the cargo to absorb the water as he believes that they can either affect the chemical composition of the cargo or increase the cost and delay the procedure as they will need to be removed from the cargo as well.
One of the ideas he expressed was the use of Ore Oil Carriers. These vessels have narrow holds that extent approximately on the half of the breadth and though the effect of free surface in case of liquefaction will be eliminated (Figure 29) (Appendix A).

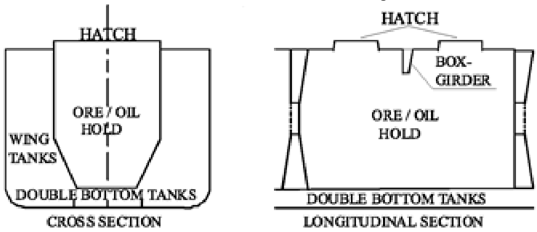


Figure 30 The holds of Ore/Oil Carriers https://www.cultofsea.com/general/types-of-combination-carriers/

- Mr Pontikos Dimitrios has been a captain for more than 30 years and even more a fleet manager in the company Alkyon Shipping Ltd. During his trips, he had carried iron ore as a cargo many times. As he explained during our interview, the company that he is working in is not accepting nickel ore for transportation as they know how dangerous it can be for the safety of the vessel. As he explained, when they were carrying iron ore, he was always executing the can test so as to be sure himself that the cargo was safe. He believes that the crew nowadays is informed about the phenomenon of liquefaction but not about how to deal when the problem occurs. He also expressed his concerns about the structural changes that have been proposed over the years as he is not sure if they are worthy it.

CHAPTER 8: INVESTIGATION THROUGH EXPERIMENTS

In the context of this diploma thesis, a series of experiments were carried out in order to understand the phenomenon of liquefaction and the critical values of various parameters (width, frequency, duration of stimulation and humidity levels of the sample). The goal of the experiments is to observe and compare the behavior of nickel ore before and after liquefaction and to investigate the results of nickel ore liquefaction for vessels.

For each of the test materials, a series of experiments for roll and sway movements was performed. Furthermore, for every sample, the experiments were executed with different percentages of moisture, from a really dry state until the sample is muddy and watery. In both samples of nickel ore, the moisture content was fully controlled and ranged between 0% and 45% of the material's total weight. A test was also executed with a sample of nickel ore in the exact condition the company delivered it in order to check its safety.

For each sample with a different percentage of moisture, a series of experiments was performed by changing the excitation of frequency and amplitude each time.

At the beginning of the experiments, the amplitudes and frequencies were determined. Since the company that provided the sample is carrying the nickel ore in the Aegean Sea, the samples were tested in conditions that vessels usually face in the Mediterranean Sea. For this purpose the 'Wind and Wave Atlas of the Mediterranean Sea' was used. These results were adapted based on the model scaling and the restrictions of the shaking table.

According to the Atlas for the Mediterranean Sea, the Spatial Distribution of mean value of the wave (Hs) ranges between 0.6 and 1.4 m and the spatial distribution of the mean value of the period of the waves (Ts) ranges from 5.5 to 7 seconds.

For sway experiments, the frequency range extends from 0.6 to 1.5Hz (with 1.5 Hz corresponding to the frequency of the machinery vibrations), with a 0.1Hz step, and the amplitude ranges between 1 and 10 cm. The choice not to test higher frequencies is based on the fact that such conditions are rare at the Mediterranean sea, and for an initial approach to the phenomenon of liquefaction, such a study is not necessary. For roll experiments, the frequency is the same as above, with the angle extending from 1° to approximately 10°. Unfortunately, at the procedure of calibration, it became obvious that the shaking table, in a dynamic movement, could not perform in large angles. For the first sample, the duration of each experiment, in both movements, was two minutes, in contrast to the second sample in which the duration varied from 30 to 60 minutes. In this way, the effect of the amplitude and frequency could be meticulously examined. Finally, the experiments were recorded with a simple camera for their necessary analysis.

8.1 Shaking Table

The experiments are carried out in the Hydrodynamics Laboratory of the School of Naval Architecture and Marine Engineering of the National Technical University of Athens with the help of the Shaking Table that can be seen in Figure 30.

Figure 31 The shaking table in the School of Naval Architecture and Marine Engineering.

The first shaking table was created to study earthquakes, it was built in Japan at the end of the 19th century and was moved by hand. At the beginning of the 20th century, at Stanford University in the USA, developments were made with the introduction of an electric motor that could produce a more sophisticated oscillatory motion in one direction. Moreover, the movements of the test piece were recorded with mechanical pencils.

Today, at the National Technical University of Athens there are two shaking tables, one at the School of Civil Engineering and one at the School of Mechanical Engineering. It is worth mentioning, that for the study of cargo liquefaction and sloshing, there are only a few shaking tables around the world. In fact, this specific shaking table was the first that was ordered to have such specifications. After that, orders were made by Korea, France and Brazil.

It is remarkable that this device is an innovative system regarding its type. Its ability to simulate the vessel's movements (heave, surge, sway, roll, pitch, yaw) and its frequency range define it as pioneering.

The specific shaking table can carry a maximum load of 2 tons. The maximum displacement and velocity in the heave movement are +/- 30cm and 50cm / sec respectively, in surge and sway movement are +/- 30cm and 30cm / sec respectively, while in roll, pitch and yaw movement +/- 30deg and 0-15deg / sec respectively. Finally, the frequency range and maximum acceleration on each axis are 0-8Hz and 0.3g respectively.

For the experiments, a tank was used and placed on the top of the shaking table. The tank was set on a Plexiglas base, that was screwed on the shaking table. The characteristics of the shaking table, as well as the tank, are shown in the tables below.

Table 4 Basic dimensions of the tank that was used in the experiments.

Tank	
Length (cm)	34
Width (cm)	23
Height (cm)	20
Thickness (cm)	15
Material	Plexiglas with 1,19gr/m3 density

Table 5 Basic dimension of the shaking table that was used for the experiments.

Shaking Table	
Length (cm)	124
Width (cm)	110,2
Weight (kg)	147,45
Thickness (cm)	3,88
Material	Aluminum with 2,7gr/cm3 density

At the bottom of the shaking table, a triangular base exists. On each side of the base two hydraulic pipes and a pneumatic arm, made of aluminum, are hinged. Hydraulic arms are double-acting with a gate on each end providing hydraulic fluid for both the extension and the retraction of the piston. Special valves are positioned on these arms to control the oil flow. The pneumatic pipes, on the other hand, are designed to support the heavy weight of the experiment table.

The two hydraulic arms, along with a pneumatic one, are joined with a base (110.50x41.00x2.00cm) which is embedded in the floor of the workshop. The oil pump system supplies the hydraulic arms with the oil. The arrangement uses a water based cooling system to ensure low oil temperature. Moreover, filters placed in the oil tank provide high quality oil.

All the measurements taken during the experiments, are recorded in an electrical control panel. In this panel, there are indications of temperature and filters' operation, as well as an emergency shutdown button.

In conclusion, it should be mentioned that the machine is handled via a computer and the use of the ANCO company's Trireme V11 program. A detailed description of the experimental device and the software used, can be found in the thesis of N. Kalloumenos (2013) "Experimental Study of Free Liquid Surface under Vertical Excitement". (ΚΑΛΟΥΜΕΝΟΣ, 2013)

8.2 Calibration Process

At the beginning, the calibration of the machine was necessary, so as to ensure the table's proper function.

The first part of this process is to ensure that the position of the table is horizontal and parallel to the floor. To achieve this, a LASER was used. Specifically, it was placed on a staircase proximately at the height of the shaking table, and was supported with a clamp horizontally. The ladder was placed, so as the LASER to be aligned with one of the four corners of the shaking table. Following, each hydraulic arm was moved, in order to achieve the table's horizontal position. The footprint of the LASER beam should appear at the top edge of each side of the table. Then, three small metallic pickets were placed on the top of the shaking table in a triangle position. The goal was similar with above, the footprint of the beam should appear at the bottom edge of all three pickets.

Every time, in order to change the position of each hydraulic arm, the following procedure was executed. Using the Trieme program, the machine was turned on and placed in Zero Position by pressing the 'Pump to Zero Position' button. From this position, the offsets of one or more Actuators on the 'Calibrate Actuators' tab could be changed in order to move the table.

The next step was to check if the bank returns to the same starting position after performing several tests. Through the 'Run Test' tab, tests were executed in different movements like heave, pitch, roll or yaw and with different amplitudes. Each time the final and the initial position were compared. After the execution of several tests in heave movement, it was obvious, that the table's final position had not changed significantly from its original position. In contrast, during the pitch, roll and yaw movements the table did not return to its original position, but to a position that differed from it by 1-3 mm.

In the second part of the calibration process, the goal was to ensure that the shaking table was executing the command that was inserted in the Trieme program. In order to check this, each move was examined separately. First, tests in heave motion were performed. In order to record the exact movement of the shaking table, the laser GLM 80+R60 from BOSCH Company (Figure 31) was used. In its screen, appears the maximum and the minimum distance that is measured from a specific point. In this way, the final move that the shaking table was executing could be compared with the command that was inserted in the program.

Figure 32 Photo of the laser that was used for the calibration process

Tests in sway and roll move were also executed. What could be observed was that there was a deviation in all three movements, but that deviation was proportionate with the amplitude of the table's movement. For this reason, charts were created that depicted the movements that the shaking table was executing in comparison to the commands that were inserting in the program. For each move, three complete tests were executed, each of which performed movements from a very small amplitude to the maximum amplitude that was allowed by the program.

The third and most time-consuming task was the dynamic calibration. At this stage, the goal was to ensure that the machine in dynamic tests executed the commands that were inserted in the program. From the first tests it was obvious that the higher the frequency of a test was, the bigger the deviation between the movement of the shaking table and the command in the program. At this point, many experiments in sway, roll and heave motion were executed. In every movement, tests performed in different frequencies and amplitudes, and with the BOSCH laser in every test the exact movement of the shaking table was recorded.

After these tests, equations that would describe the movement of the shaking table in every frequency were produced. By this way, it was known what command to insert to the program Trieme in order the shaking table to execute the desirable movement.

8.3 Description of the experiments

In the next paragraphs, the preparation, the execution and the results of the experiments are described.

8.3.1 Preparation for the experiments

Before the execution of the experiments, it was necessary to dry the amount of the sample that would be used, in order to control the moisture level of the sample. The procedure was the following. A part of the sample was loaded in a container and weighed on a scale. The container was then placed in the oven in an invariable temperature. After one hour the sample was weighed again in order to check how much the weight was reduced. The same procedure was repeated until the weight of the container was stabilized.

After this procedure was completed for both samples of nickel ore, it was observed that the amount of water that each sample contained was different. The sample from Euboea did not contain a lot of water as its weight stabilized only after 1 and a half hours and in a container of approximately 9kg; the amount of water was only 150grs. On the other hand, the sample from Kastoria contained more water. This was something that could be also observed as the color of the sample before and after the drying procedure was slightly different. The second sample needed more than 2 hours in order for its weight to stabilize.

After both samples were dried, they were sifted. The goal was to use the nickel ore in the form of sand, as the stones that there were in the samples were not able to absorb water (Figure 32).

Figure 33 a, b, c Weighing, drying and shifting the sample of Nickel Ore

After the drying and shifting of the sample, water was added to test different humidity levels. According to the relationship given by the IMSBC code, the moisture content could be calculated.

$MC\% = mwater/msand \times 100$ (Appendix 2 1.1.4.4., IMSBC Code)

It is important to mention, that after every experiment the sample was blended in order to have a homogenous surface.

8.3.2 Scale Effect

Even though many scientists have studied the phenomenon of cargo liquefaction, minimum research has been done regarding the scale effect of moisture migration or cargo behavior. This probably can be explained due to the difficulties associated with applying complex scaling laws to this specific problem, like scaling of accelerations, of particle size or of the density of the sample. Nevertheless, some years ago it was proven that the scaling actually affects the behavior of a material. It was found that a critical size of tank does exist and after that, the sample behaves in a very similar way irrespectively of the container's size. Friction is considered to play a very important role in the smaller sizes, and this is how the difference in the dynamic behavior can be explained. Furthermore, in the same research, it was proven that the critical angle from which the material starts to shift depends on the width of the tank. The smaller the tanker, the larger the critical angle before the material starts moving. (Spandonidis & Spyrou, 2013)

8.3.3 Ship scaling

Having completed the description of the experimental process, and before proceeding with the analysis of the results, it is advisable to briefly refer to the dimensions of the tank and compare it with what is expected in realistic scenarios for bulk carriers' holds.

In order to correlate the real vessel's dimensions and conditions that it may face, with the tank's that will be used, an appropriate scaling law should be applied. This matter, however, is still quite uncertain. In this work we applied geometrical scaling and we calculate the excitation frequency of the model form the relation,

$$\omega 1 \cdot \sqrt{\frac{l1}{g}} = \omega 2 \cdot \sqrt{\frac{l2}{g}}$$

ω1: angular frequency of the tank

ω2: angular frequency of the ship

l1: width of the tank (0.31m)

l2: width of the ship

g: Gravity Acceleration (g = 9.81m / sec2)

For a typical ship size, such as a Panamax ship, with a width of around 35m, the frequency of the sea that will probably face, could be found through the Atlas. With the equation above we can also calculate the frequency that the tank will face during the experiments.

Concerning the correspondence to the amplitude of excitation, it is given by the equation below.

$$\frac{\zeta 1}{l1} = \frac{\zeta 2}{l2}$$

ζ1: the amplitude of excitation of the experimental tank

ζ2: the amplitude of the ship

l1: width of the tank (0.31cm)

l2: width of the ship

Finally, in the roll movement, the angles of excitation of the tank corresponding to the angles of the transverse list of a real ship.

8.4 Experiments with the sample from Euboea

The first experiment was executed with the nickel ore before the drying and sifting procedure, just as the company provided it. The goal of this experiment was to observe how the material behaves inside the cargo holds when the company transports it in this condition. Experiments were executed in sway, heave and roll movements in frequencies that vessels usually meet in the Mediterranean Sea. What was noticed from the beginning was that the sample contained a lot of bigger and smaller stones. In the photos below the difference in the tank before and after the experiments is obvious. As it was expected, the sand moved on the bottom of the tank, and the bigger stones stayed on the top of the tank. The sample was observed to follow the movement of the tank. After the heave movement (Figure 33) the sample in the tank was concentrated in the center creating a hill in the middle of the tank.

Figure 34 a, b The dry sample that the company provided us with before and after the compaction due to the movement of shaking table.

After that, experiments in sway motion were executed. The amplitude of the sway motion ranged from 1 cm up to 10 cm. Working in the same frequencies like before no further difference in the sample was noticed. During the experiment, the nickel ore was not moving inside the tank which was expected since the bigger stones of the sample were on the top of the tank.

In the roll movement, we noticed as well no difference in the sample as well. What is worth pointing out is that even in a big incline of 30 degrees the material did not move inside the tank. This can be explained again by the fact that the big stones were on the top blocking the way of the smaller ones or of the sand to move.

After these first experiments, more tests were executed with the sample that had been prepared.

First, the material from Euboea was tested. For each test, water was added in the laterite to increase its moisture content. The sample was behaving as a dry material in all movements of heave, sway and roll, following the tank's movement, until its moisture content exceed the 18.0%. Until this point, the compaction of the material could be observed, that was though, decreasing with the increase of the sample's moisture content (Figure 34).

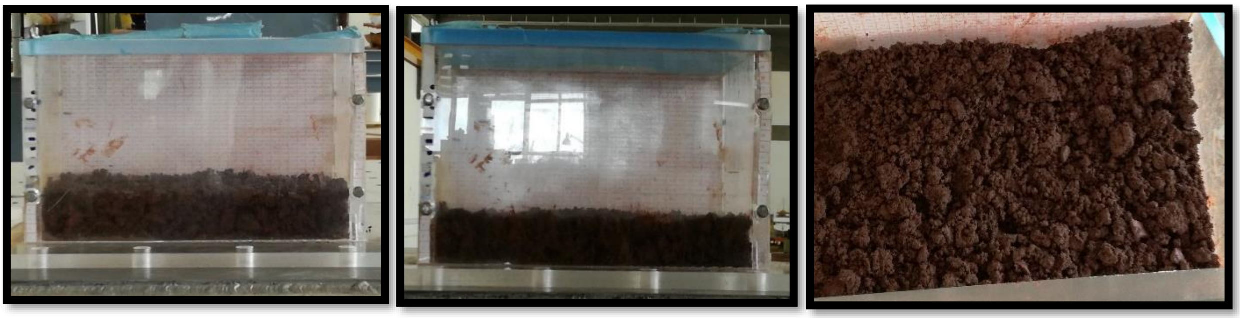


Figure 35 a, b, c The wet sample of Nickel Ore before and after the compaction.

When the moisture content of the sample was raised to 18.3% its behavior started changing. The material looked a lot like mud and it needed some time until it absorbed the water from the surface to be homogenous (Figure 35a).

Tests in heave and roll movement were executed. From the beginning of the experiment, the sample, that was on the top, was moving inside the tank. First, the movement was limited but as the time and the frequency were increasing the movement of the sample had a larger amplitude. In the photos below can the difference in the surface of the sample be observed, as at the end of the experiments the surface was covered with a layer of 'muddy water' (Figure 35 b, c). The same behavior was noticed when the moisture content of the sample was 20.3%. At the end of the experiments, a larger amount of 'muddy water' that was covering the surface (Figure 36 a, b).

Figure 36a, b, c Sample with 18.3% of moisture content before and after the heave experiments turning into a muddy material.

In figure 36, the before and after the experiments shot can be seen as well as the way the sample looked the next day. Between the figures b and c is a difference of 20 hours. As it is obvious, even more water has been moved on the top of the sample creating a small 'lake of water' over the drier sample. This is something that was noticed every time while conducting the experiments with this sample.

Figure 37 a,b,c Sample with 20.3% of moisture content before and after the experiments of roll movement turning into a muddy material. Also in the last photo can be observed the sample the next morning in which the water seems to have been raised in the surface.

Next, more water was added to the sample, in order to execute experiments with a moisture content of 22.5%. Even though the behavior of the material was the same, a larger amount of the sample was moving inside the tank. The material that was covering the top 3 centimeters of the sample inside the tank was moving like a liquid. At this point, a comparison was made between the results of the roll and sway tests. The difference was that after the roll experiments the amount of water on the surface was slightly higher than the amount of water on the surface after the sway motion (Figure 37 and 38). It is important to mention, that due to the limited movement of the shaking table for the roll experiments, the angles, in which the materials were tested, were up to 5°.

On the other hand, in the sway motion, the movement of the shaking table had a bigger amplitude, and the experiments executed in more extreme conditions. From this comparison it is expected that in more extreme conditions the roll experiments would have resulted in a larger amount of water on the surface of the sample. Finally, it is vital to mention that in both motions the sample was observed to move from the one side of the tank to the other and to slosh while the shaking table was moving.

Figure 38 a, b Sample with 22.5% moisture content before and after the sway experiments

Figure 39 Sample with 22.5% moisture content before and after the roll experiments

When the moisture content was increased up to 25.35 %, half of the sample inside the tank was sloshing and moving from side to side during the experiments (Figure 39 to 41).

Figure 40 a, b, c Sample with moisture content 25.35% before , during and after the sway experiments. It can be seen that inside the tank during the experiments the sample is shifting from the one side to the other.

Figure 41 a, b, c Sample with moisture content 25.35% before , during and after the roll experiments. Sample was behaving like a liquid.

Figure 42 The sample after hours of being stored in the tank. The water that was inside the sample created a lake on the top of the drier sample.

In the next group of experiments, when the sample's moisture content was 28.17%, the whole sample was moving inside the cargo, like a liquid. As can be seen in the photos, the sides of the tank were covered with mud after the experiments. Also, during the experiments, we could see the sample inside the tank moving like a wave, especially in frequencies higher than 1Hz (Figure 42 to 44).

Figure 43 a, b, c The sample with 28.17% moisture content before and after the sway experiments. As it can be seen in the last photo the sample was shifting in the whole height on the sides of the tank.

Figure 45 a, b At 1Hz frequency the sample was moving inside the tank creating waves.

Figure 44 a, b, c The sample with 28.17% moisture content before and after the roll experiments

In the last group of experiments that was executed, the sample contained 31.7% of moisture. Even at the beginning of the experiments, it was noticed that not all of the water had been absorbed by the material, and a small quantity was still on the surface. During the experiments, we realized that after the 1Hz the whole tank was covered with muddy water and the movement of the sample was hardly hitting the tank in every move of the shaking table (Figure 45 and 46).

Figure 47 a, b, c Sample with 31,7% moisture content before, during and after the sway experiments. The sample even before the experiments looked watery and it behaved like that during the experiments.

Figure 46 Sample with 31,7% moisture content before, during and after the roll experiments. At the end the muddy, watery sample had covered the whole tank.

8.5 Experiments with the sample from Kastoria

In the second part of the experiments, the sample from Kastoria was used and the experiments lasted longer, as the goal was to observe how each factor affects the phenomenon.

At the beginning the sample had 18% moisture content, and an one hour sway test was executed in 1Hz frequency and with a maximum amplitude of 6cm. At the end of the test, no water was found on the surface of the sample. The material was really dry, and it differed a lot from the way the sample Euboea looked, at the same moisture content.

Following, the moisture content of the sample was increased to 19.82%. The same experiment was executed and what was noticed after 55 minutes was that at some parts of the sample water could be observed on the surface. This was a surprising result as the material looked again too dry at the beginning. However, the amount of water that was observed on the surface was inconsiderable. Also, another observation was the trend of the material to make its surface smoother and horizontal (Figure 47 and 48).

Figure 48 Before the experiment at 19.82% moisture content.

Figure 49 After one hour of sway motion at 1Hz some unimportant spots of water can be observed.

The same sample was also tested 1 hour in a sway motion on frequency of 0.8 Hz at the maximum amplitude which was 7.5cm. After one hour, no sights of liquefaction were noticed and the same results were observed after the execution of roll experiment for one hour.

Subsequently, more water was added until the moisture content of the sample was 21.6%. At this point, after only 20 minutes of sway motion at the 1Hz frequency, water was observed on the surface of the sample. Nevertheless, the sample was not moving inside the tank during the experiments. At this point, it was obvious that the phenomenon of liquefaction did not

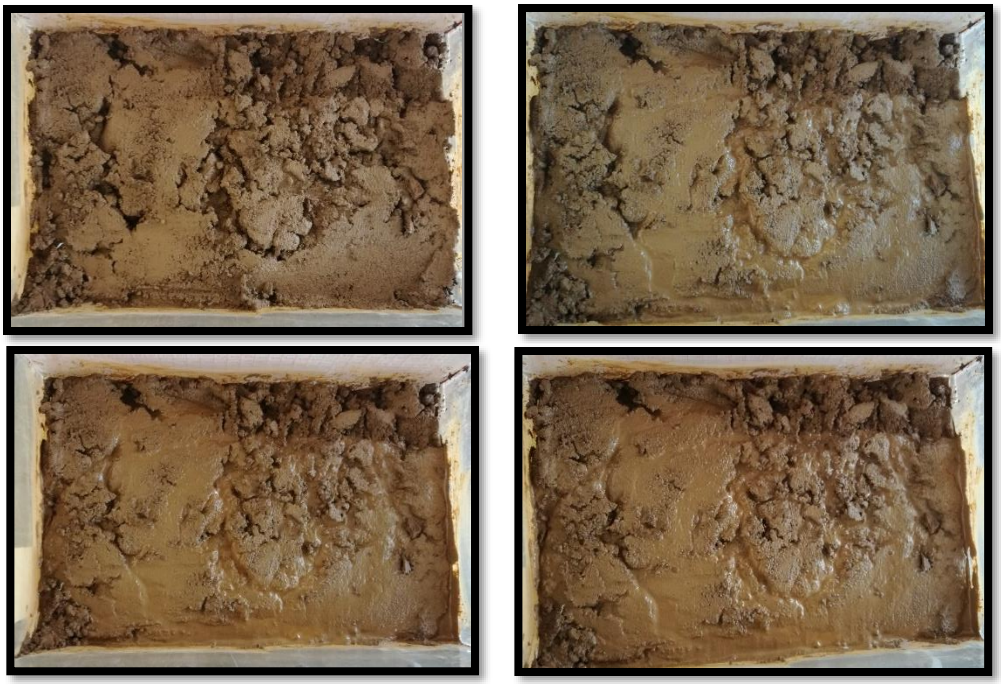


Figure 50 a, b, c, d The sample with 21.6% moisture content at the beginning of the sway experiment at 1Hz, after 20 minutes, after 40 minutes and after 1 hour.

evolve, meaning that the amount of water did not increase after the twenty minutes and did not cause any changes on the behavior of the sample during the experiments (Figure 49).

The same experiment was executed at 0.8 Hz and 1.2Hz and with an amplitude of 7.5cm and 5.3cm respectively, so as to observe the difference in the results and understand if the frequency and amplitude of the movement actually affects the results. In this test, after 35 minutes a small quantity of water could be observed at the edge of the tank, but nothing further changed in the behavior of the sample (Figure 50 and 51).

Figure 51 The sample with 21.6% of moisture content before and after the sway experiment at 0,8Hz. No difference could be observed in the sample.

Figure 52 The sample with 21.6% of moisture content before and after the sway experiment at 1.2Hz. No difference could be observed in the sample.

With the same moisture content of 21.6%, experiments in roll motion were executed with 4° at 0.8Hz. Even after 50 minutes, no sight of liquefaction was observed. The same happened when experiments were executed at 1HZ and 1.2Hz.

Following, the moisture content was increased to 23.42% and experiments were executed in sway motion. The Figure 52a shows the sample at the beginning of the experiments. For the test at 1Hz frequency, the results were the same like before; only a slight amount of water on the surface of the sample was observed. Still, the material was not moving inside the tank (Figure 52b).

Figure 53 a, b Sample with 23.42% moisture content before and after the sway experiments.

Figure 54 Sample with 26% moisture content before and after the sway experiments.

A slight difference in the behavior of the material was noticed when its moisture content increased to 26% (Figure53). During these experiments, the material was barely moving inside the tank after 45 minutes of testing. Still, the behavior of this sample was totally different from tests before as the material was a lot drier with the same percentage of moisture content. As it can be seen in the photos below, the material still looked dry after the experiments.

In the next experiments, the moisture content of the sample was 27.9%. The sample looked muddy and it was moving together inside the tank. After 40 minutes of experiments, water was observed on the surface which was mainly concentrated on the sides of the tank (Figure 54 and 55). Subsequently, the moisture content was increased to 29.7% (Figure 56). At this point, the behavior of the material changed, as it started shifting more intense inside the tank after 15 minutes, even though, at the beginning, it still looked dry.

Figure 55 a, b The sample with 27.9% moisture content before and after the sway experiments. The movement of the whole sample was now a lot more intense.

Figure 56 a, b The sample with 27.9% moisture content before and after the roll experiments. The amount of water that could be observed in the surface was more than after the sway experiments.

Figure 57 a, b The sample with 29.7% moisture content before and after 1 hour of sway experiments.

In the next test, the moisture content of the sample was 33.3%. Even before the test, the material looked muddy and the sample on the top was shifting from the beginning of the experiments. After an hour, water could be observed on the surface of the material. It is important to mention, that, during the experiment, the movement of the sample was becoming more intense as its moisture content was increasing (Figure 57).

Following, the moisture content of the sample was at 36%. At this point, it was obvious that the whole sample was moving inside the tank from the beginning of the test. As it can be observed in Figure 58, at the end of the sway experiment, the sample was totally liquefied and its surface fluidic and horizontal.

Figure 59 a, b The sample with 33.3 % moisture content before and after the sway experiments.

Figure 60 a, b The sample with 36% moisture content before and after the sway experiments. The whole sample behaved like a muddy thick liquid.

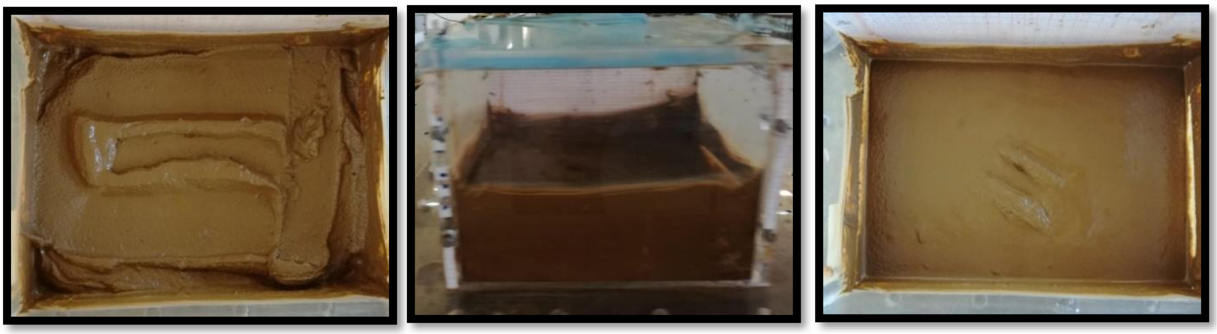


Figure 58 a, b The sample with 39.6% moisture content before, during and after the sway experiments. As it can be seen in the middle photo the sample was shifting from side to side inside the tank.

When the moisture content was raised to 39.6%, the sample could be described as a viscous liquid. The amount of water on the surface of the sample increased and its movements became more intense, as it was striking the sides of the tank. At the end of the experiments, the sample looked like a liquid (Figure 59).

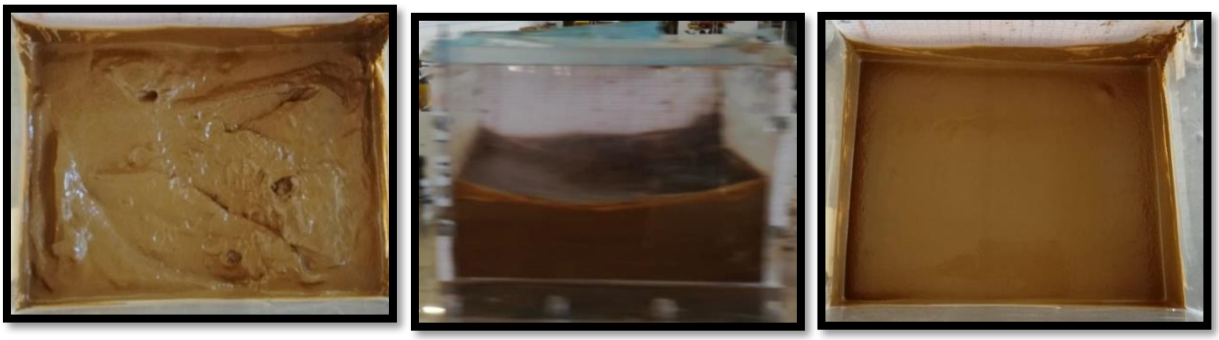


Figure 61 a, b, c, d The sample with 43.24% moisture content before, during and after the sway experiments. The sample was shifting in the whole tank during the experiments.

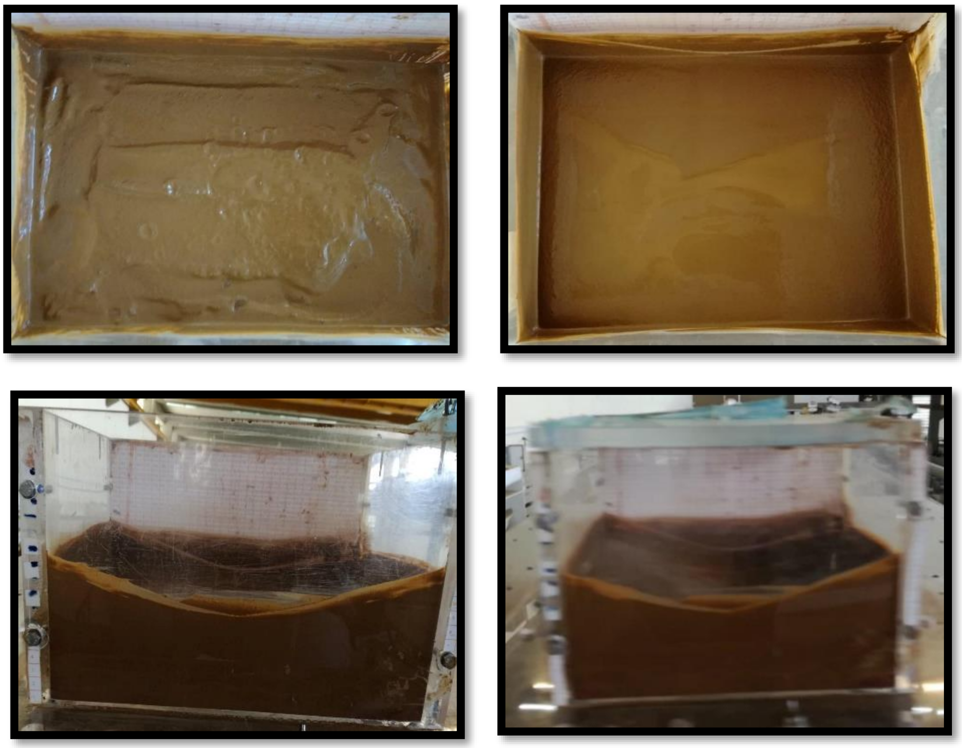


Figure 62 a, b The sample with 46% moisture content before, during and after the sway experiments. The sample was creating waves while the shaking table was moving.

The final experiments were executed with a moisture content of the sample of 43.24% and 46% (Figure 60 and 61). In this condition, the sample was behaving from the beginning of the test like water. It was creating waves inside the tank, and it was splashing on its sides.

Comparing the two samples it becomes obvious that their behavior is a lot different. Firstly, the second sample looked a lot drier when it contained the same moisture content as the first one. Furthermore, the second sample started moving inside the tank only after its moisture content reached the 26% while the first sample moved when its moisture content was around 18%. Another noticed difference was the way the sample looked when it was stored for a longer period inside the tank. As it was mentioned before, in the sample from Euboea, the water tends to move on the top when it was stored for a longer time. On the other hand, the sample from Kastoria did not show the same behavior when its moisture content was up to 27.9%. After hours of storage, only drops of water on the sides of the tank could be seen. Although, when its moisture content increased, the same behavior as in the sample from Euboea appeared.

CHAPTER 9: STABILITY ANALYSIS

Except the significance of the cargo what is also important for the safe voyage of a vessel is the loading procedure. The cargo is typically being loaded inside each cargo hold in a planned sequence following the ‘loading plan’. It is also possible that each hold of the ship will contain a different type of cargo. The most typical ways of loading according to the guidance of International Association Of Classification Societies (IACS) “Guidance and Information on bulk Cargo Loading and Discharging to Reduce the Likelihood of Over - stressing the Hull Structure”, are the following (International Association Of Classification Societies, 2003):

- **Homogeneous hold loading condition.** A homogeneous hold loading is when every hold of the vessel, in the full load departure condition, is being filled with the same amount of cargo, like it is demonstrated in the figure 62. This distribution is usually used in bulk carriers that are carrying low density cargoes, like coal and grain. However, in specific situations, high density cargoes like iron ore could also be carried homogeneously (Figure 62).

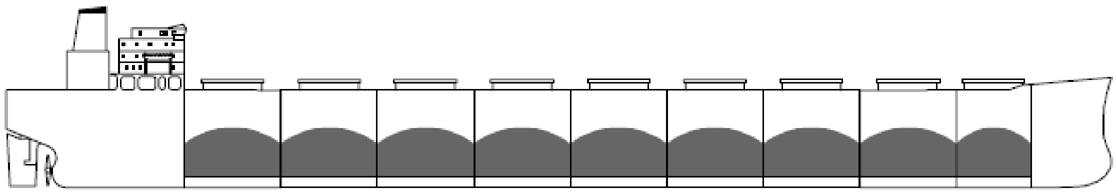


Figure 63 Homogenous loading in a bulk carrier (International Association Of Classification

- **Alternate hold loading condition**. Even though iron ore can be loaded with a homogenous hold loading, the alternate hold loading is usually being followed. It is used for heave cargoes and it is illustrated in Figure 63. Usually, large bulk carriers stow high density cargo in odd numbered holds when the rest of the holds are empty. By loading heavy cargo this way, the vessel’s stability is higher and more deadweight can be carried than when the homogenous hold loading is followed. To support the loading of the heavy cargo in the holds, the local structure needs to be specially designed and reinforced (Figure 63).

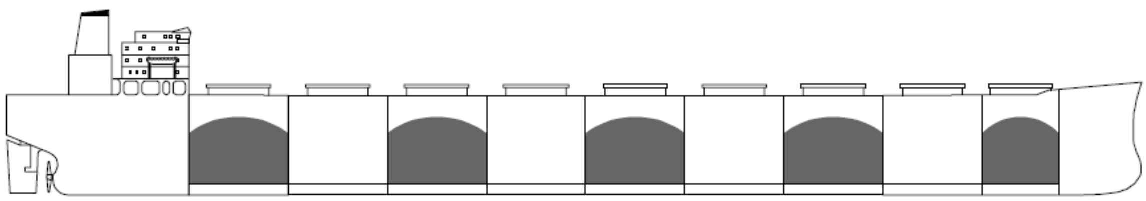


Figure 64 Alternate loading in a bulk carrier (International Association Of Classification Societies, 2003)

- **Block hold loading condition**. This way of loading can be described as the following. Two or more cargo holds that are next to each other can be loaded with cargo when the holds next to them could be empty exactly like it is illustrated in Figure 64. In many cases, this type of loading will be adopted when

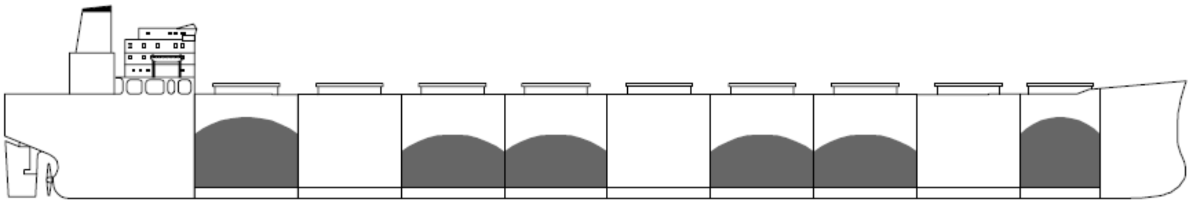


Figure 65 Block hold loading in a bulk carrier (International Association Of Classification Societies, 2003)

the ship is partly loaded. When the block hold loading condition is being followed, then the master should be sure about the stability of the vessel and avoid over-stressing the hull as well as not increase a lot the draft of the vessel (Figure 64).

- **Part hold loading condition.** When a ship is partly loaded, then its cargo is less than the maximum capacity of the vessel. This loading will lead many times to the reduction of the draught and hence to the reduction of the stability of the vessel. This type of loading could be used under two circumstances. One is when the ship's structure has been approved for the carriage of the cargo following the part hold loading condition. The second is when the vessel is provided with a set of approved criteria that clarify the maximum cargo weight limit as a function of ship's mean draught for each cargo hold (International Association Of Classification Societies, 2003).

9.1 Stability analysis of a vessel carrying Nickel Ore

After the execution of the experiments and the observation of its behavior in conditions similar to the ones that it is facing during its transportation, the stability of the vessel was examined. With the AVEVA Marine program, a stability analysis for a bulk carrier transporting the two samples of nickel ore that were used for the experiments was performed. The effect of liquefied cargo in the stability of the vessel was also tested in one or more holds. Finally, the result of a longitudinal bulkhead in the same bulk carrier was examined, not only in the transportation of dry nickel ore but also when the sample is liquefied. The main characteristics of the vessel, which was examined in AVEVA Marine program, as well as its tankplan, are listed in Table 8 and Figure 65.

Table 6 Main particulars of the vessel used in AVEVA Marine.

Length Overall	290.000 metres
Length B.P	280.000 metres
Breadth mld.	49.000 metres
Depth mld.	25.500 metres
Design Draft (moulded)	18.000 metres
Displacement at Load Draft	219003 tonnes
Lightship Weight	27264 tonnes

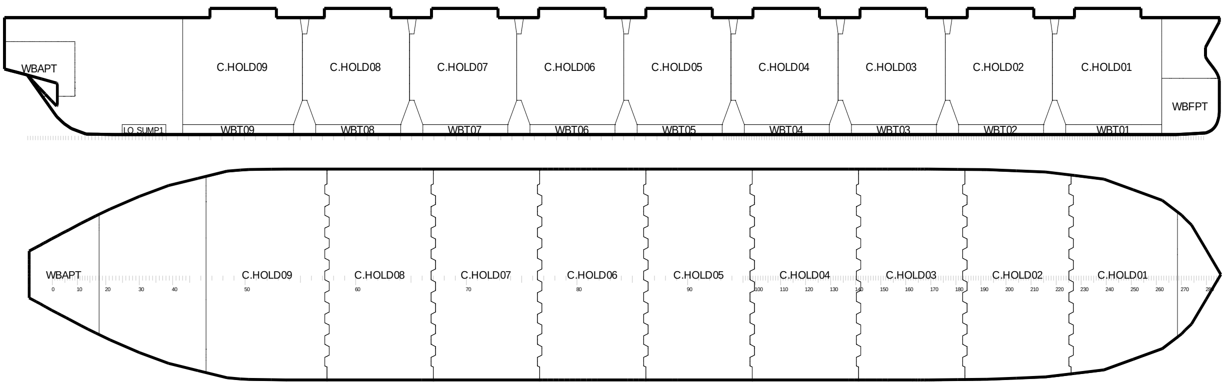


Figure 66 Tankplan of the vessel used in AVEVA Marine.

The stability of a ship carrying heavy cargoes was tested for two different powders, that have the same density as the two nickel ore samples that were used in the experiments. The density of the one sample is 1.589t /m3 and of the second sample is 1.896 t /m3. The stability of these conditions was checked before and after they were liquefied. Liquefaction, due to the high specific weight of such loads (such as nickel ore or iron ore), occurs by forming a free surface moment at the upper level of the material, a conclusion reached by the above experimental research, having as a test material the two samples of nickel ore. It is important here to remind that when liquefaction occurred, the whole sample was shifting inside the tank, behaving like a liquid.

According to IACS Guidance and Information on Bulk Cargo Loading and Discharging to Reduce the Likelihood of Over-stressing the Hull Structure, heavy cargo transport is usually being performed by alternate loading (for large ships, load placement only in the single-number hull).

Firstly, the effect of different loading conditions in the bulk carrier while it was carrying the two samples was tested. As it can be seen in the diagrams below, the homogenous loading leads to higher values for the righting lever curves in both samples, when the alternate hold loading seems to lower righting lever curves values. On the other hand, the Block Hold loading seems to give similar righting lever curves to the homogenous loading for heavier cargoes when for the lighter ones (sample with density 1.589gr/cm3) the righting lever values range between the values of the alternate and the homogenous loading. In the three different loading conditions, the draft in the longitudinal center of flotation (LCF) is approximately the same. For the nickel ore with density 1.589 gr/cm3, the holds 1,3,5,7 and 9 were loaded with cargo in the alternate condition, while for the nickel ore with 1.896gr/cm3 the holds 1, 3, 7 and 9 were used since the material is a lot heavier. Figures 66 and 67 show the different loading cases under consideration.

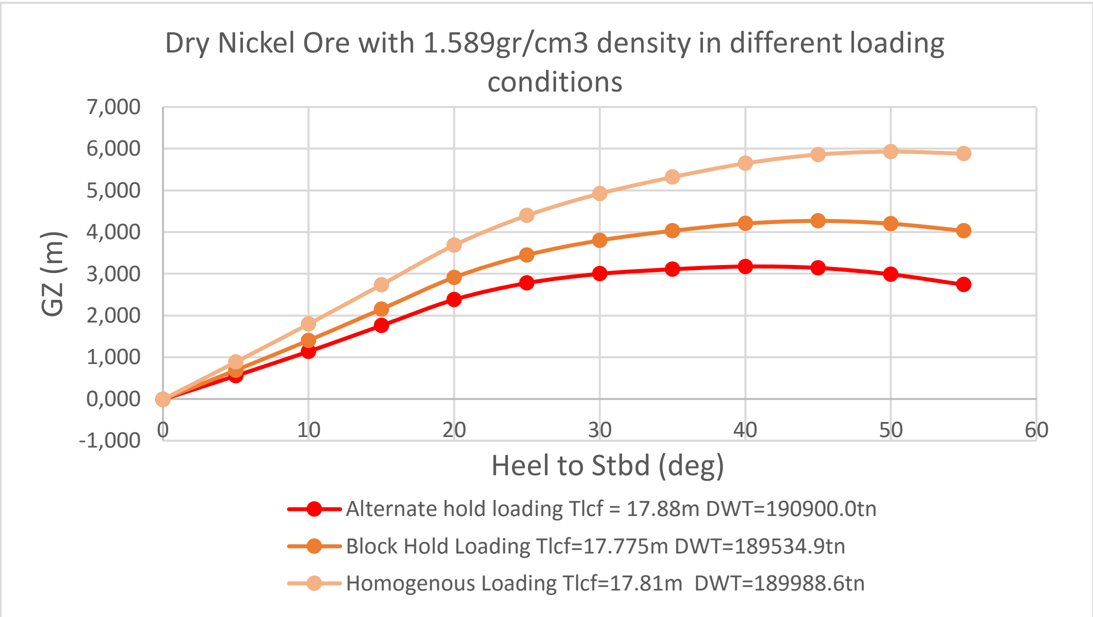


Figure 67 The stability curves of the vessel carrying dry Nickel Ore with 1.589gr/cm3 density in different loading conditions

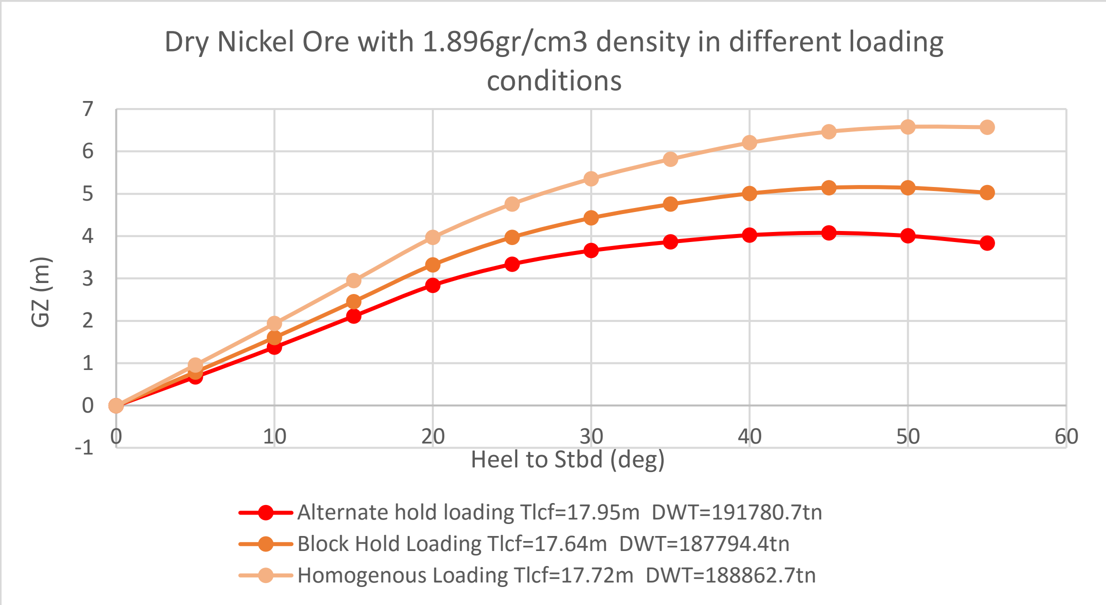


Figure 68 The stability curves of the vessel carrying dry Nickel Ore with 1.896gr/cm3 density in different loading conditions.

It becomes clear that, while the density of the transported cargo increases, the height of the ship's center of gravity decreases, thus increasing values of righting lever the ship becomes more stable (Figure 68). This is also illustrated in the diagram below, with the comparison of the two righting levers, when the vessel is carrying heavier and lighter nickel ore. As most vessels follow the alternate loading when it comes to the transportation of cargoes like nickel ore or iron ore, the comparison is referred to the alternate loading condition.

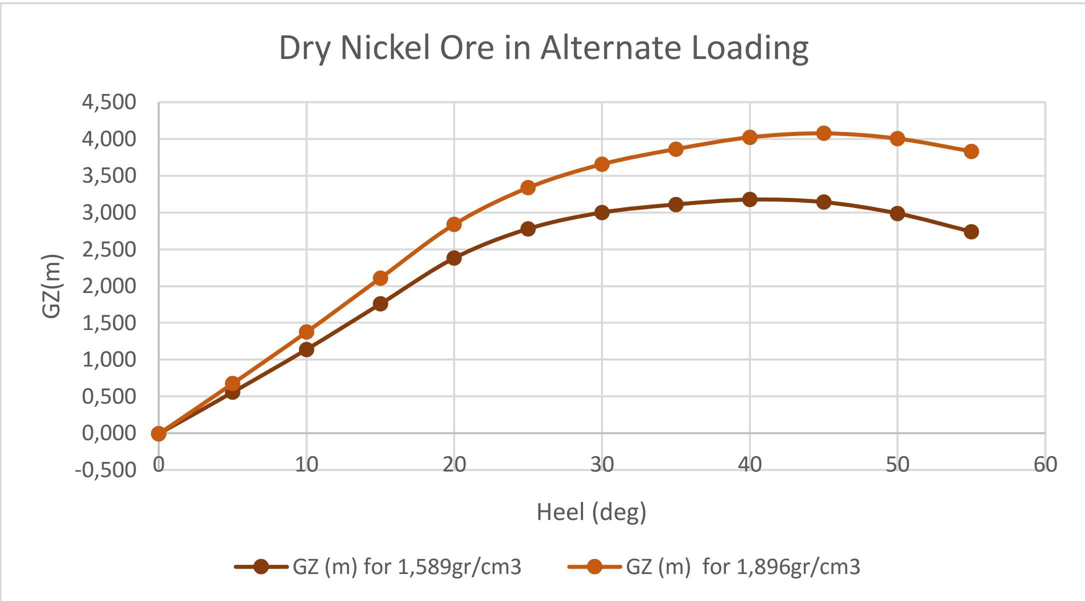


Figure 69 The stability curves of the vessel carrying dry Nickel Ore different densities in alternate loading condition.

Subsequently, the consequence of the liquefied cargo in the stability of the vessel was investigated. As was referred in the previous chapter, for both samples there was a specific moisture content range in which each material at the beginning of the experiments was behaving like a solid cargo, but at the end, its behavior was similar to a liquid cargo, as it was shifting inside the tank. Following, Figures 69 to 72 show how liquefaction in one or more holds can affect the stability of the vessel.

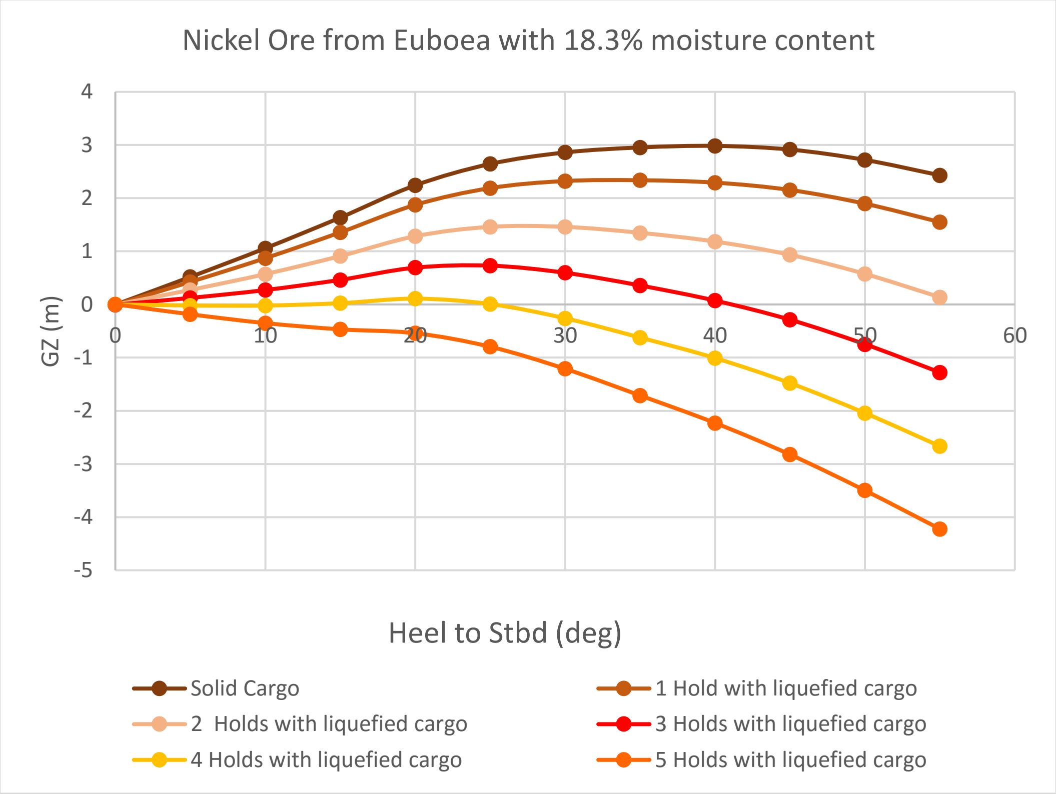


Figure 70 The stability curves of the vessel carrying Nickel Ore from Euboea with a moisture content of 18.3% while cargo is liquefied in one or more holds.

As it can be seen, the liquefaction of the cargo results to the reduction of the righting lever values. Although, when liquefied cargo appears in one hold, the vessel still complies with the regulations of the IMO (Appendix B). When liquefied cargo appears in two holds, then the vessel condition does not comply with the regulations anymore as the maximum value of the metacentric height (GM) is not obtained in an angle larger than 30 degrees. Nevertheless, all the other criteria are still satisfied. Furthermore, when four out of five holds contain liquefied cargo, the righting lever of the vessel has mainly negative values, and the same happens when all holds of the vessel contain liquefied cargo. The stability of the vessel at this point is lost, and the vessel will capsize. Similar were the results of the same cargo when its moisture content was higher, as it is illustrated in the diagrams below for moisture content 20.3% and 22.5%.

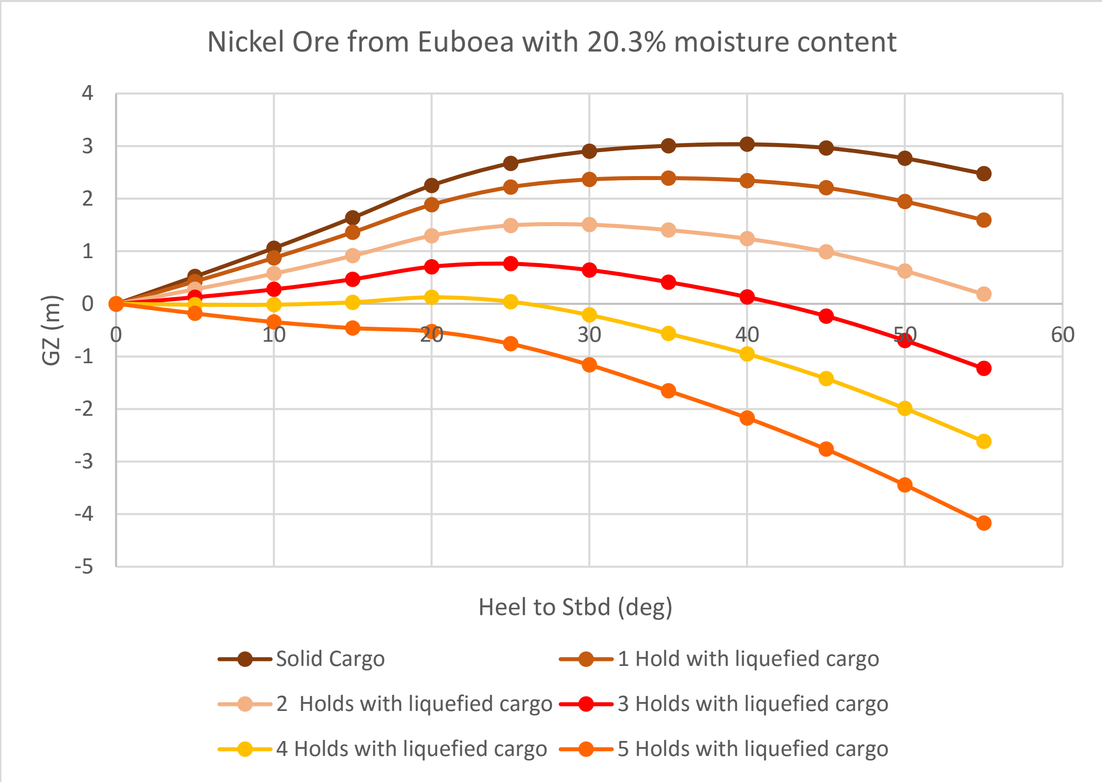


Figure 71 The stability curves of the vessel carrying Nickel Ore from Euboea with a moisture content of 20.3% while cargo is liquefied in one or more holds.

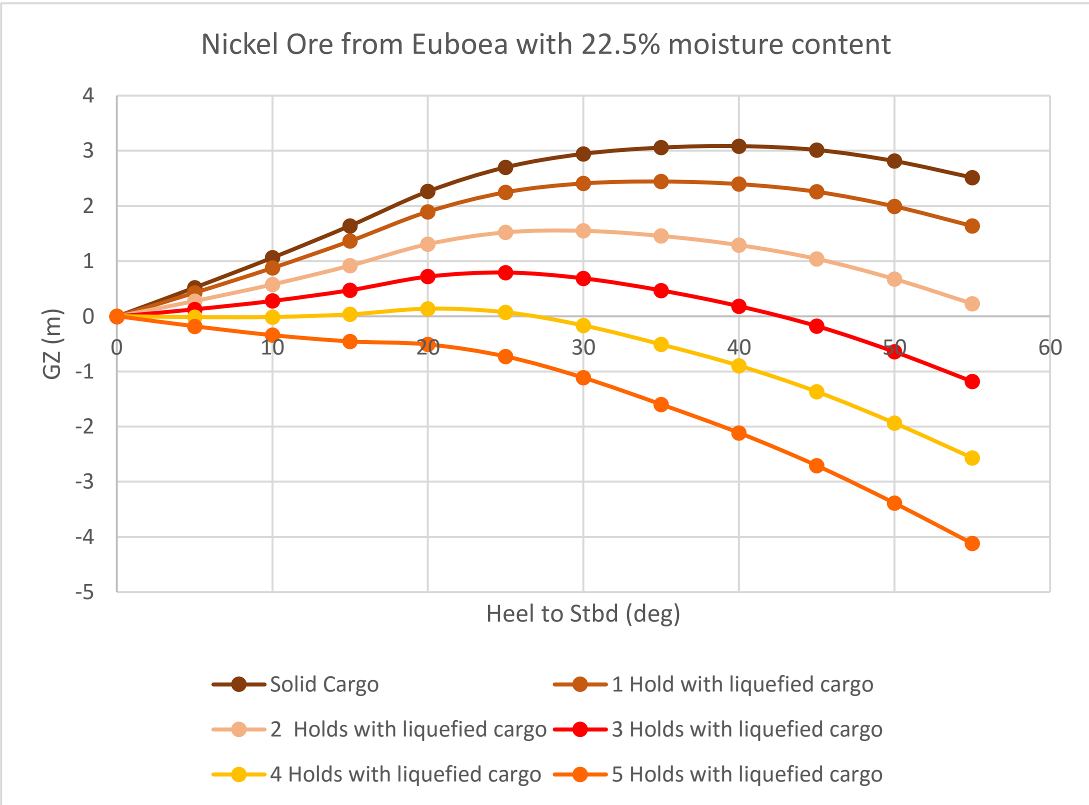


Figure 72 The stability curves of the vessel carrying Nickel Ore from Euboea with a moisture content of 22.5% while cargo is liquefied in one or more holds.

At this point, the appearance of liquefaction in different holds was examined, as well as the way it can affect stability of the vessel. The righting lever was calculated for different cases when the liquefied cargo was obtained every time in another hold. From the figure below two results are emphasized. Firstly, the effect of liquefied cargo in the holds 3, 5 and 7 is the same for the righting lever of the vessel. A similar effect seems to have the liquefaction of cargo in hold No 9, even though the values of the righting lever in this condition are a bit lower. Finally, the effect of liquefied cargo in hold No1 (the front hold of the vessel) seems to differ from the others. In this situation, when liquefied cargo is being observed only in hold No1 the righting lever curve, and consequently, the stability of the vessel is higher (Figure 72).

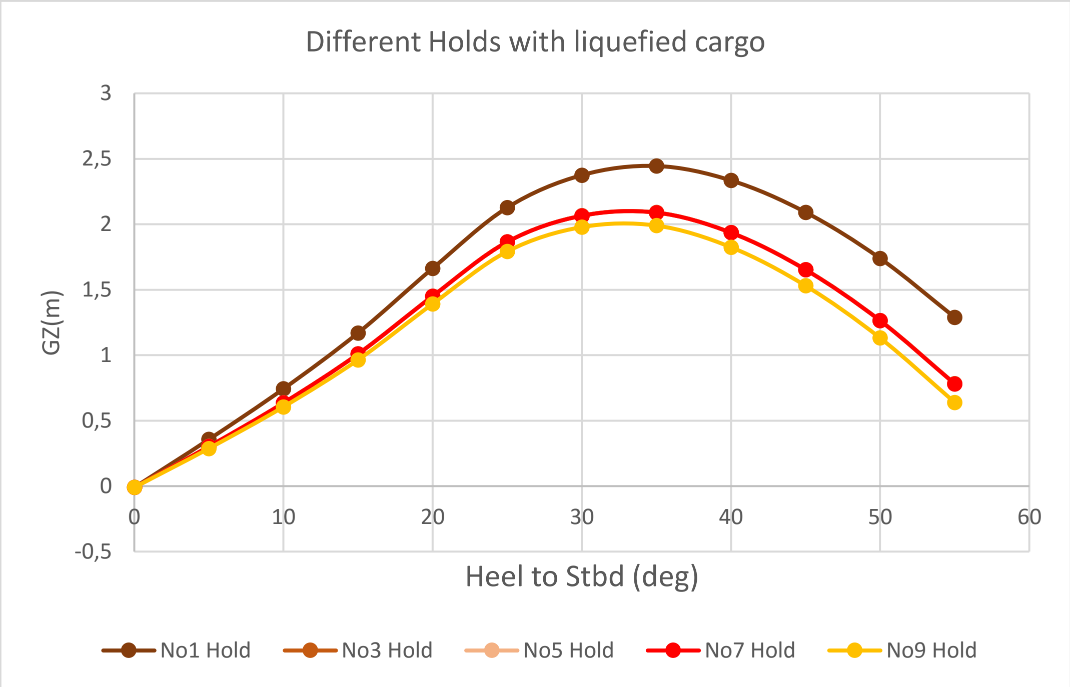


Figure 73 The stability curves of the vessel carrying Nickel Ore from Euboea with moisture content of 18.3% while liquefied cargo is obtained in different holds.

Afterwards, the same procedure is being followed for the sample from Kastoria. At this point, the righting lever curve of the vessel, when it is carrying liquid nickel ore but with Fixed Free Surface Moment (FSM) is also calculated. In the figures below, it can be observed the effect of the liquefied cargo in the stability of the vessel, that appears to be similar to the results from the previous sample. As it was also observed previously, (Figure 68), the values of the righting lever were higher for the sample from Kastoria since the cargo's density was heavier. As before, the appearance of liquefaction in more than one holds, leads to a condition that does not comply with the regulations (Figures 73 and 74). Also, it is worth mentioning that the righting lever of the vessel, when one of the holds contain liquefied cargo, is higher when the density of the cargo is 1.896gr/cm3 than when it is 1.589gr/cm3.

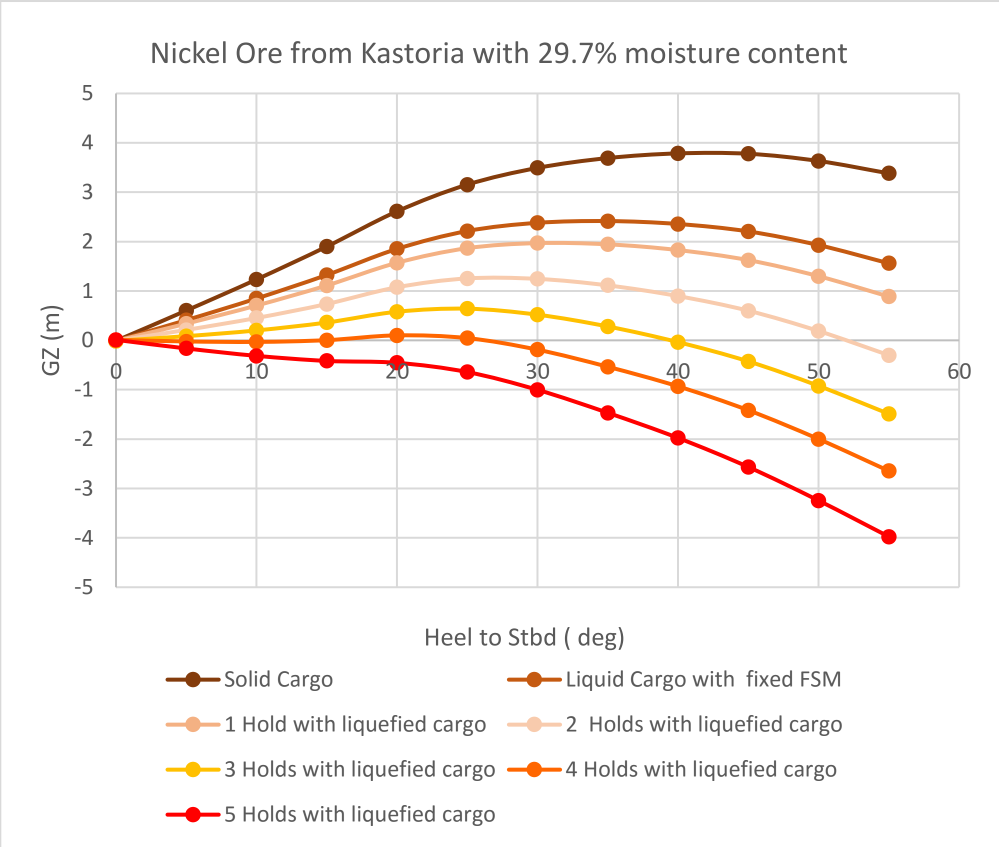


Figure 74 The stability curves of the vessel carrying Nickel Ore from Kastoria with moisture content of 29.7% while cargo is liquefied in one or more holds.

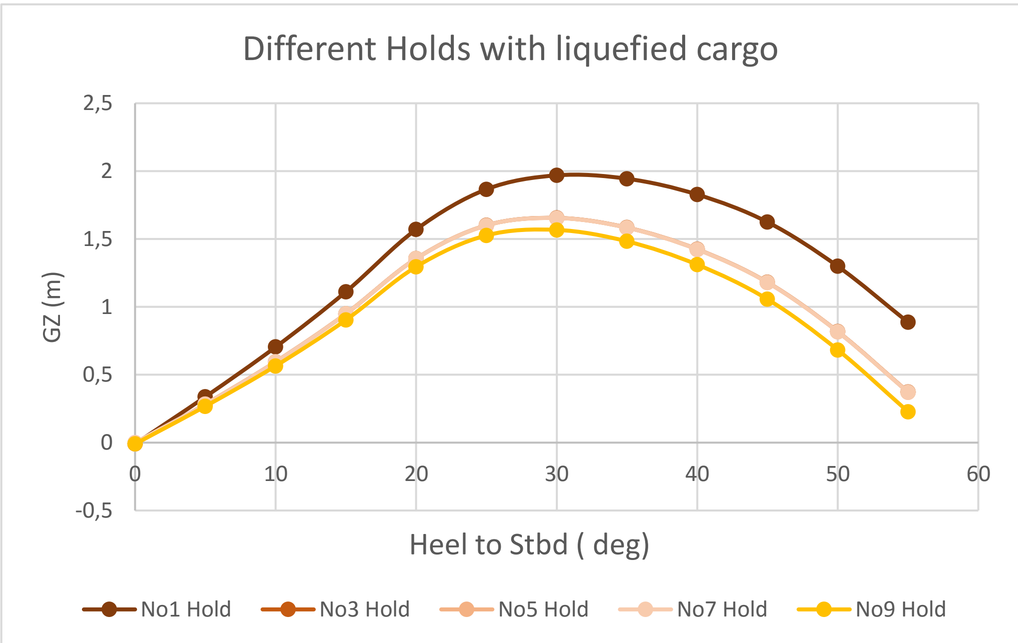


Figure 75 The stability curves of the vessel carrying Nickel Ore from Kastoria with moisture content of 29.7% while cargo is liquefied in one hold.

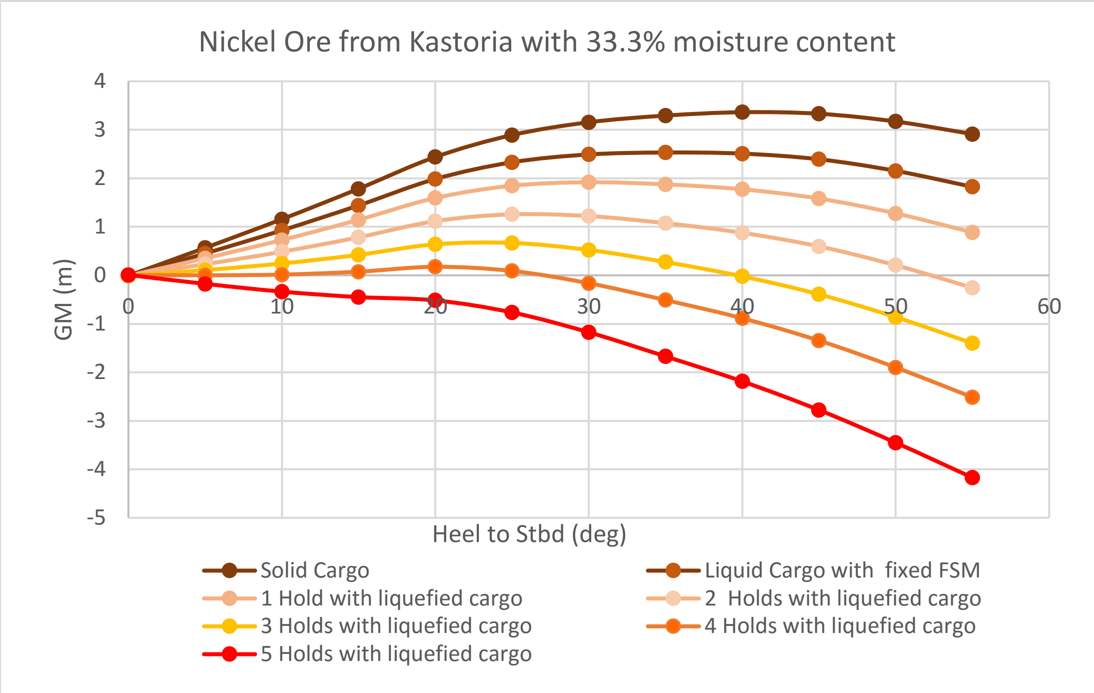


Figure 76 The stability curves of the vessel carrying Nickel Ore from Kastoria with moisture a content of 33.3% while cargo is liquefied in one or more holds.

The effect of the liquefaction of cargoes in different holds for the stability of the vessel was also tested once more. As can be seen in the figure 75, the results are the same with the ones in Figure 72, confirming that the liquefaction in hold No1 is the one affecting the least the values of the righting lever curve of the vessel.

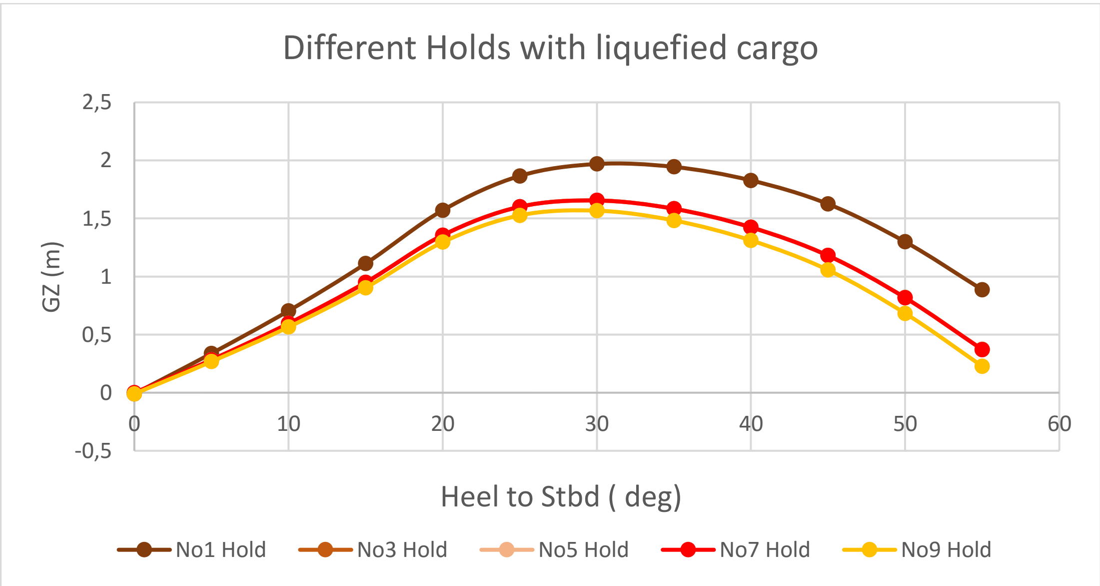


Figure 77 The stability curves of the vessel carrying Nickel Ore from Kastoria with a moisture content of 29.7% while liquefied cargo is obtained in different holds.

One last case that was examined in this part was which combination of holds with liquefied cargo could be proved the worse for the stability of the vessel. In Figure 77, it is illustrated the righting lever of the vessel when liquefied cargo is obtained in two different holds. As it is observed, the worst combination for liquefied cargo to appear is in holds No 7 and 9 that are the ones closest to the stern of the vessel. On the other hand, the righting lever curve of the vessel when liquefied cargo appears in holds No 1 and 3, that are closer to the stem, is the highest of all other combinations (Figure 76).

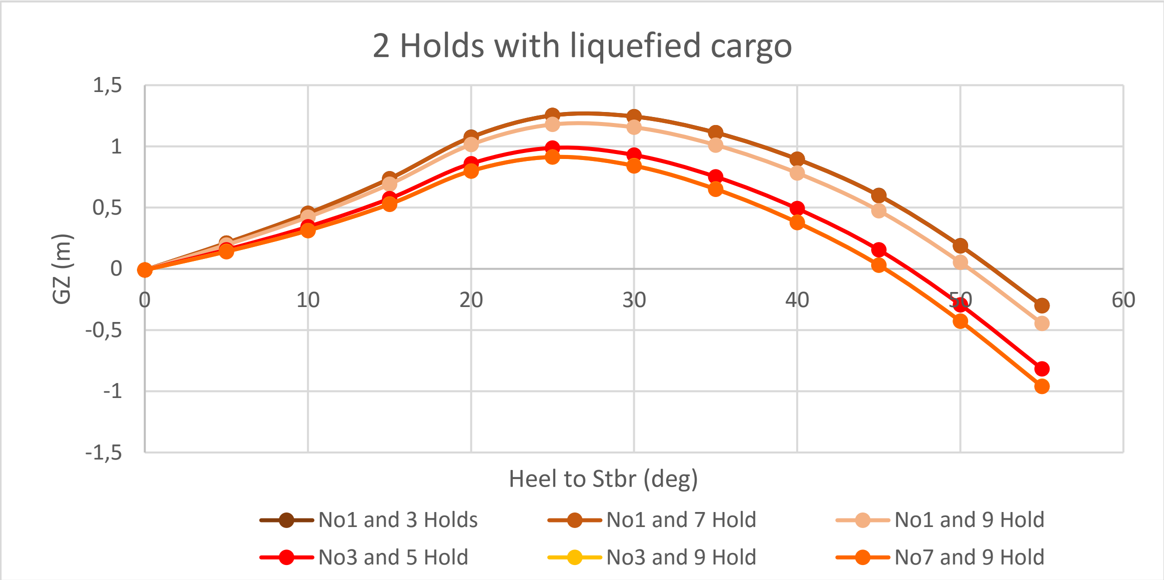


Figure 78 The st of the vessel carrying Nickel Ore from Kastoria with a moisture content of 29.7% while liquefied cargo is obtained two holds.

9.2 The effect of a longitudinal bulkhead in the stability of a bulk carrier

As it was mentioned before, ClassNK proposed and applied the use of longitudinal bulkhead in the bulk carriers to reduce the risk of liquefaction. With the intention of verifying the use and value of this solution, the effect of a longitudinal bulkhead in the vessel's stability will be examined. Using the AVEVA Marine, a longitudinal bulkhead was placed in the middle of the breadth of the same vessel that was used before. Its tank plan is illustrated in Figure 77.

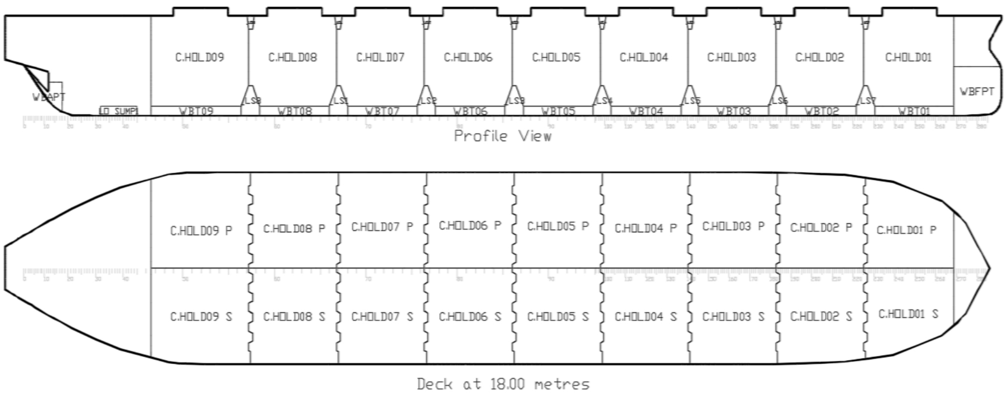


Figure 79 Tankplan of the bulk carrier with a longitudinal bulkhead.

Firstly, the stability of the vessel, while it is carrying dry Nickel Ore, will be examined and compared with its stability without the longitudinal bulkhead. In Figure 79, the righting lever curve of the vessel before and after the use of the longitudinal bulkhead while carrying Nickel Ore with 1.589 gr/cm3 and 1.896 gr/cm3 density is illustrated. As it was expected, the righting lever is higher with the use of the longitudinal bulkhead, but the difference is still unimportant (Figure 78).

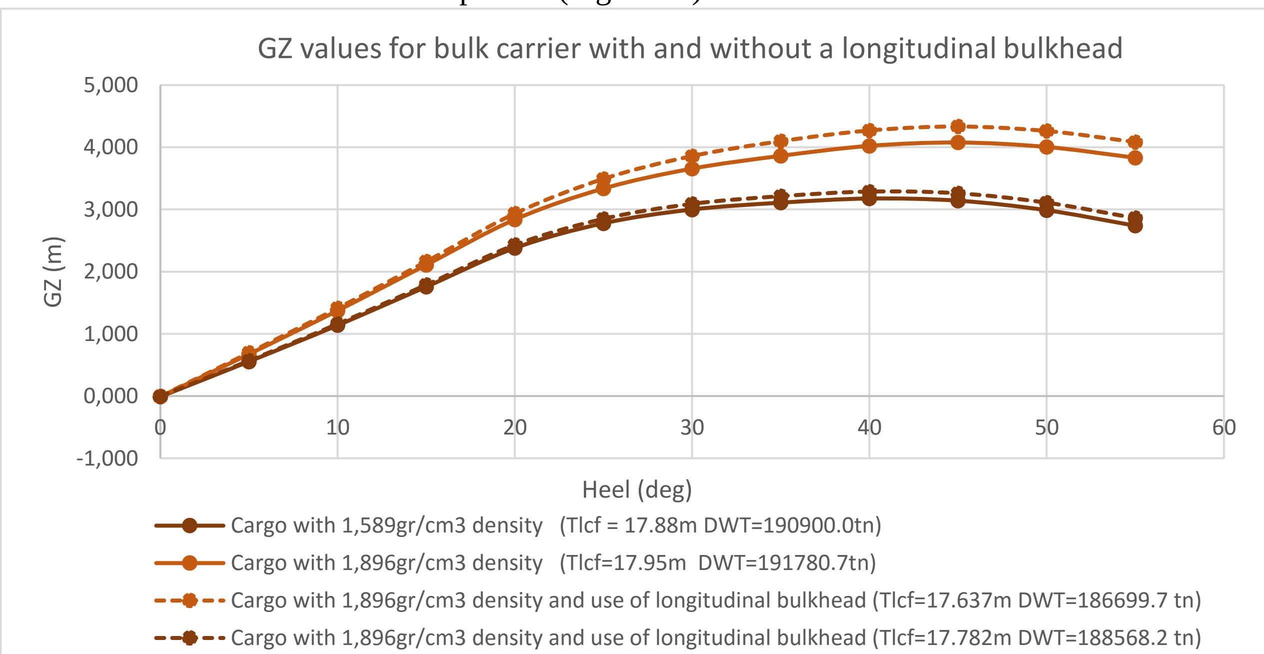


Figure 78 The stability curves of the vessel with and without a longitudinal bulkhead carrying Nickel Ore with 1.589 gr/cm3 and 1.896gr/cm3 density.

Following, the effect of the longitudinal bulkhead in the situation that cargo has liquefied will be examined. In Figures 79 to 83, it is illustrated the righting lever curves of the vessel when cargo in one or more holds is liquefied. In order to be able to compare these results with the results of the bulk carrier without the bulkhead, the assumption that a similar amount of cargo has been liquefied every time, is taken into consideration. Within this context, the liquefaction of cargo in one hold when the vessel does not have the longitudinal bulkhead, is equivalent with the liquefaction of cargo in one port and one starboard hold when the vessel has the longitudinal bulkhead. The first sample that was be tested is the Nickel Ore from Euboea with 18.3% moisture content.

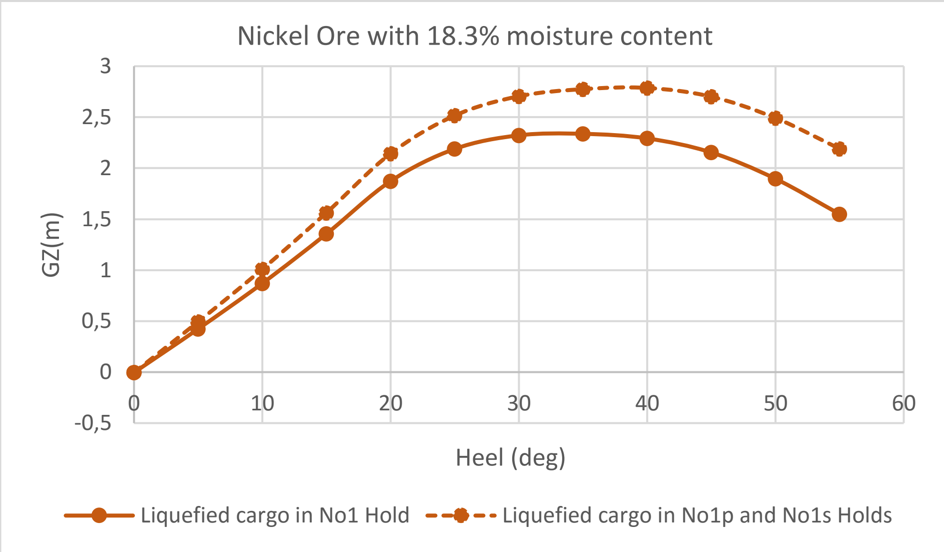


Figure 79 Comparison of the stability curves of the vessel with and without the longitudinal bulkhead. The vessel is loaded with Nickel Ore with 18.3% moisture content when one hold (or one port and one starboard hold) contain liquefied cargo.

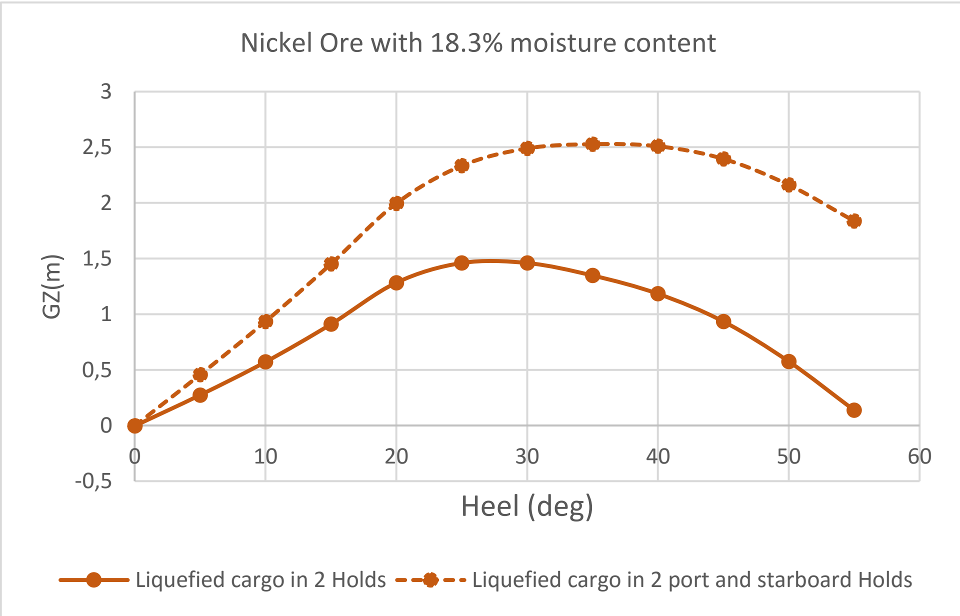


Figure 80 Comparison of the stability curves of the vessel with and without the longitudinal bulkhead. The vessel is loaded with Nickel Ore with 18.3% moisture content when two holds (or two port and starboard holds) contain liquefied cargo.

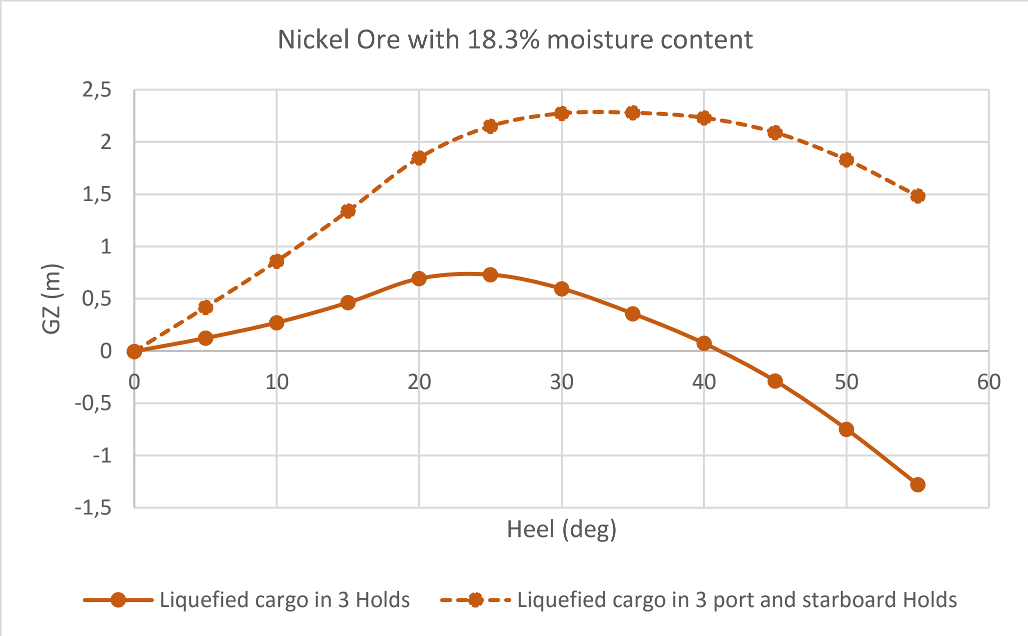


Figure 81 Comparison of the stability curves of the vessel with and without the longitudinal bulkhead. The vessel is loaded with Nickel Ore with 18.3% moisture content when three holds (or three port and starboard holds) contain liquefied cargo.

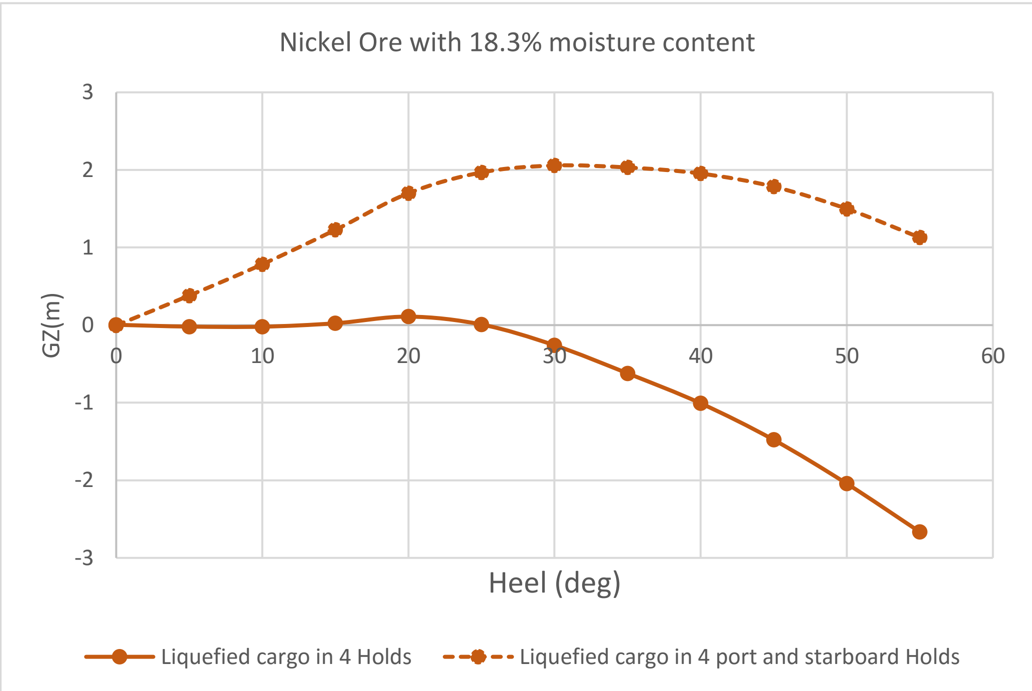


Figure 82 Comparison of the stability curves of the vessel with and without the longitudinal bulkhead. The vessel is loaded with Nickel Ore with 18.3% moisture content when four holds (or four port and starboard holds) contain liquefied cargo.

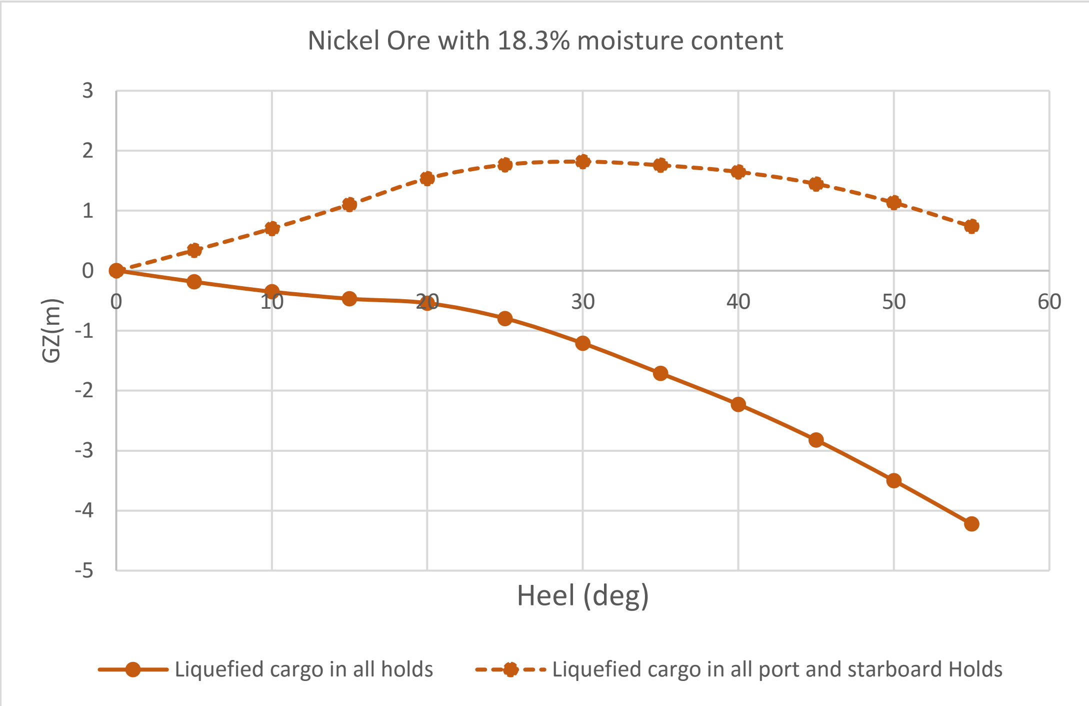


Figure 83 Comparison of the stability curves of the vessel with and without the longitudinal bulkhead. The vessel is loaded with Nickel Ore with 18.3% moisture content when all holds (or all port and starboard holds) contain liquefied cargo.

As it can be seen in the diagrams above, the righting lever curve of the vessel is a lot higher when the vessel is constructed with a longitudinal bulkhead. At the same time, it is important to mention that in all these loading conditions the draught of the vessel in the longitudinal center of flotation was approximately the same (from 17.6m to 17.88m). From Figure 80, it is obvious that the difference between the two righting levers curves is increasing. The liquefaction of the cargo does not seem to affect the stability of the vessel so much since the volume of each hold is smaller and consequently, the effect of the sloshing is diminished. In Figure 81, when two holds contain liquefied cargo, the condition of the vessel, that does not contain a longitudinal bulkhead, does not comply with the regulations of the IMO anymore.

On the other hand, the vessel with the longitudinal bulkhead still appears to be acceptable and comply with the criteria in Figures 81, 82 and 83, even when most of its holds contain liquefied cargo. Only after the liquefaction of the cargo in all the holds, the vessel with the longitudinal bulkhead does not comply with the criteria anymore, since its maximum metacentric height (GM) is not obtained in an angle larger than 30 degrees. Even in this loading condition though the stability of the vessel is a lot higher than the stability of the vessel without the bulkhead, that has been capsized.

In order to verify these results, the same calculations were executed for the vessel carrying Nickel Ore from Kastoria with 29.7% moisture content. Like it was expected, the results were similar, proving that indeed the use of a longitudinal bulkhead could be a solution for reducing the risk of ore's liquefaction. In Figures 84-87, the comparison of the righting lever is being illustrated for the vessel with and without the longitudinal bulkhead when it is transporting Nickel Ore from Kastoria.

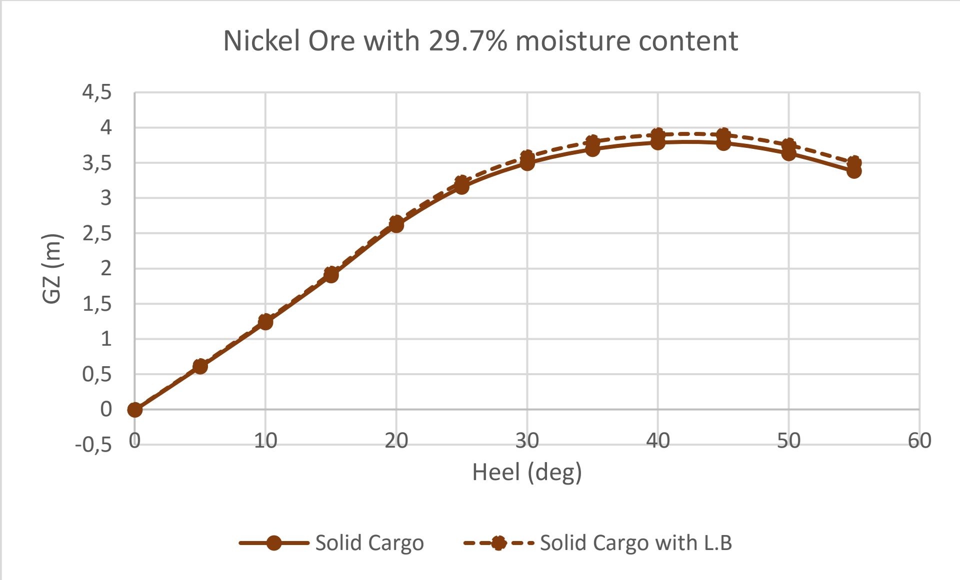


Figure 84 Comparison of the stability curves of the vessel with and without the longitudinal bulkhead. The vessel is loaded with Nickel Ore from Kastoria with 29.7% moisture content when the sample is still dry.

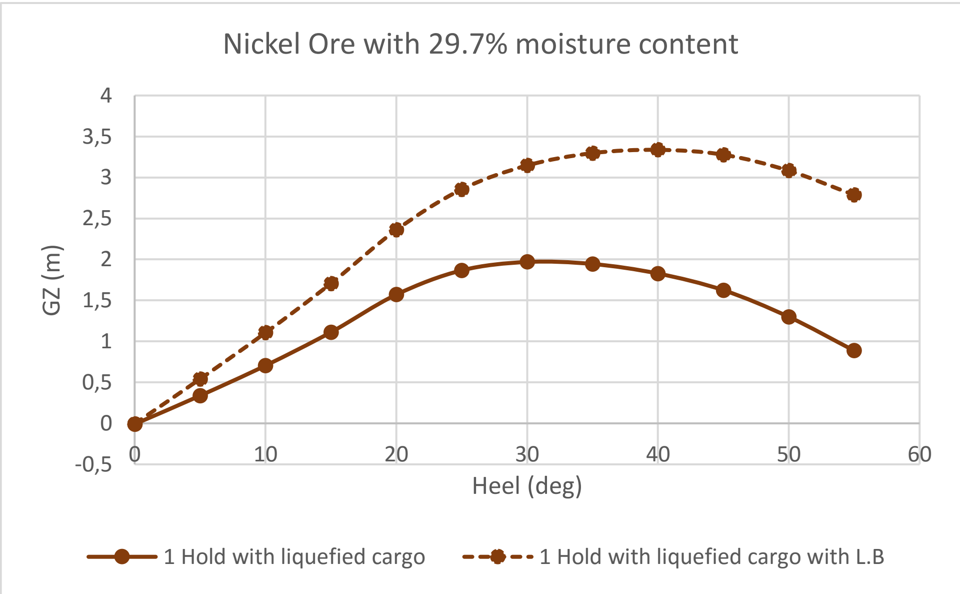


Figure 85 Comparison of the stability curves of the vessel with and without the longitudinal bulkhead. The vessel is loaded with Nickel Ore from Kastoria with 29.7% moisture content when one hold (or one port and one starboard hold) contains liquefied cargo.

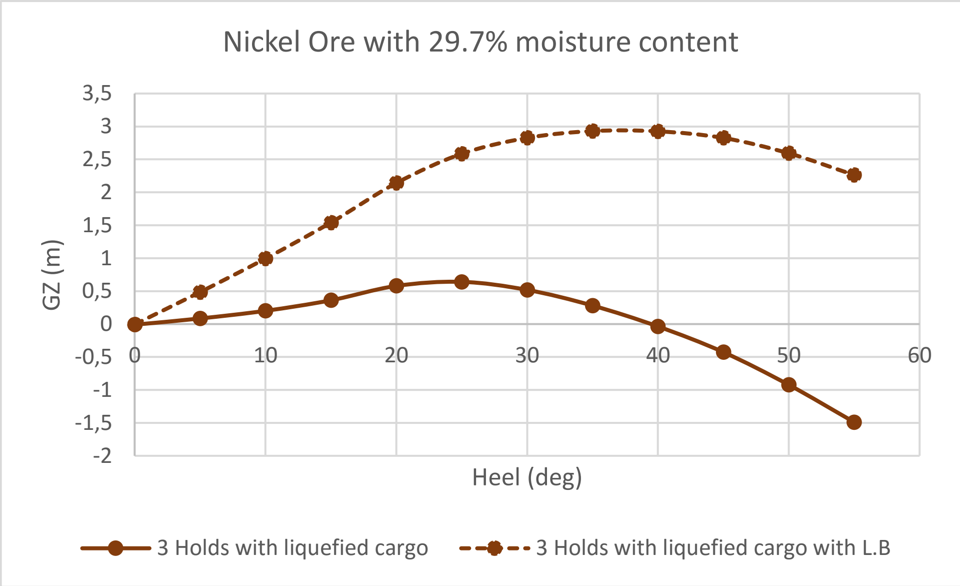


Figure 86 Comparison of the stability curves of the vessel with and without the longitudinal bulkhead. The vessel is loaded with Nickel Ore from Kastoria with 29.7% moisture content when three holds contain liquefied cargo (or three port and three starboard holds).

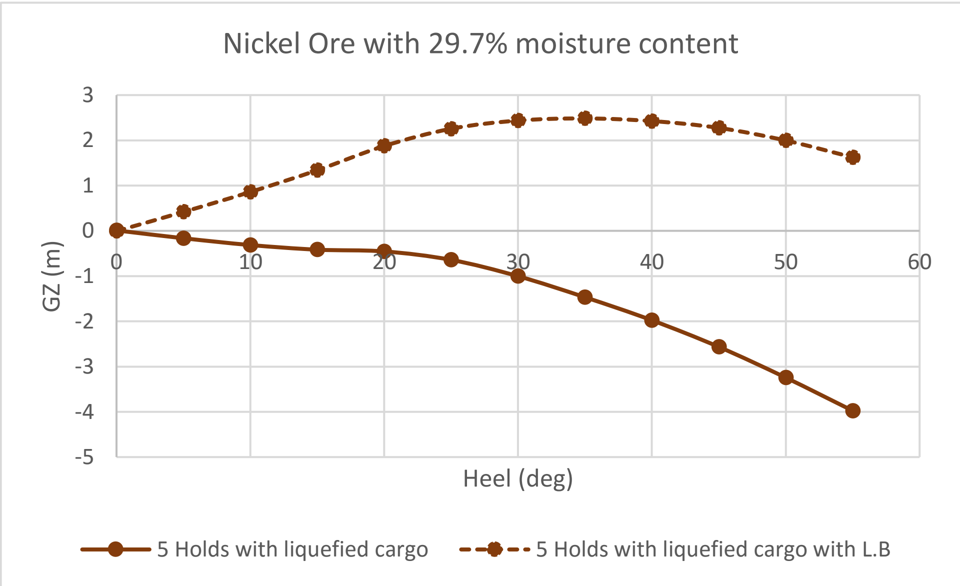


Figure 87 Comparison of the stability curves of the vessel with and without the longitudinal bulkhead. The vessel is loaded with Nickel Ore from Kastoria with 29.7% moisture content when all holds contain liquefied cargo.

CHAPTER 10: CONCLUSIONS

This chapter presents the general conclusions from the analysis of the previous chapters as well as the future steps required for a better understanding of the liquefaction of cargoes, like Nickel and Iron Ores.

10.1 General Conclusions

Through the execution of the experiments and the stability analysis on a vessel carrying nickel ore, information was obtained on how the phenomenon of liquefaction appears in cargoes like nickel ore as well as how this phenomenon influence the stability of the vessel.

As mentioned before, two different samples of nickel ore were used in the experiments. Even though the material was the same, as it was proved, the different density and chemical composition of the samples lead to non-identical behaviors. In order to be able to compare the two samples, the experiments were performed under the same (or similar) conditions. The basic conclusions about the liquefactions of nickel ore are listed below.

[1] The same material can appear to have totally different behavior when its density varies.

[2] The sample of nickel ore from Euboea which is the heaviest was the one that in a lower range of moisture content appeared a lot more like liquid when with the same moisture content the sample from Kastoria appeared to be a lot drier. A typical example is when the sample from Euboea contained around 28% moisture content and was behaving like water, shifting inside the tank from side to side when at the same moisture content the sample from Kastoria was barely moving inside the tank with only localized liquefaction to occur.

[3] The liquefaction of the sample from Euboea occurs when its moisture content is 18.3%, unlike the nickel ore from Kastoria that appears to change behavior when its moisture content is approximately 29.7%. This conclusion makes understandable that each sample (even from the same material) may liquefy containing a different amount of water.

[4] The sample from Kastoria, even though it appeared to be dry before the experiments, when its moisture content was 27.9% and 29.7%, it started behaving like mud during the test, shifting inside the tank. This proves that even though a cargo may appear dry, it is not always safe for carriage. More tests should always be contacted.

[5] The frequency and the amplitude of the experiments also appeared to affect the results. As it was noticed, when the experiment was executed on a higher frequency and lower amplitude the amount of water that appeared in the surface was slightly more than when the experiment was executed in a lower frequency, and its amplitude was bigger.

[6] After the experiments when the sample was being stored inside the tank, and its moisture content was low the phenomenon of 'ship's sweat' was appearing and water drops could be seen in the walls of the tank.
[7] On the other hand when the moisture content of the sample was higher, and it was being stored inside the tank, then another phenomenon was noticed. The sample was separated into layers. The grains remained at the bottom of the tank, while the water that was contained inside the sample remained on the top, creating a layer of liquid.
[8] Before the samples liquefy entirely, water appeared in their surface causing localized liquefaction by creating small 'lakes' of water.
[9] However, when this localized liquefaction was observed, it resulted in the whole liquefaction of the sample and the behavior of the material did not change.
[10] In the sample from Euboea, when its moisture content was low, only the upper part of the sample was shifting during the experiments. The higher the moisture content, the more the amount of sample that started shifting in the tank. On the other hand, for the sample from Kastoria the sample did not move inside the tank until its moisture content reached the 29.7%, when all of the sample started shifting.

Regarding the effect of vessel stability, which is loaded with materials which may liquefy, the conclusions drawn are listed below:

[1] The transfer of heavier loads into the hull of the ship implies a more stable ship where the righting lever curve is higher since the center of gravity of the vessel is decreasing.
[2] For dry cargoes the homogenous loading results into a more stable vessel but this changes when the cargo is liquid. The homogenous loading leads to the capsizing of the vessel when its cargo is liquid since the effect of the free surface moment is destructive.
[3] The vessel carrying liquefied cargo in only one of its holds, still comply with the criteria of the IMO, even though its righting lever curve decreases considerably.
[4] The vessel carrying liquefied cargo in two or more of its holds, does not comply with the criteria of the IMO, since its maximum GM appears in an angle smaller than 30 degrees.
[5] The vessel carrying liquefied cargo in all of its holds will be capsized.
[6] The effect of the longitudinal bulkhead in a bulk carrier when the cargo is dry is insignificant.
[7] The effect of the longitudinal bulkhead in a bulk carrier when the cargo is liquid (even in one of the holds) is noteworthy. The phenomenon of cargo liquefaction appears to affect the stability of the vessel a lot less. The condition of the vessel complies with the criteria of IMO even when four port and four starboard holds contain liquefied cargo.
[8] When all of the vessels' holds contain liquefied cargo, the vessel does not comply with the criteria anymore since its maximum GM appears in an angle smaller than 30 degrees.

[9] The use of the longitudinal bulkhead can reduce the risk of liquefaction in vessels, but at the same time reduces the DWT of the vessel. (Appendix C)

10.2 Future Research

In order to determine the accuracy of the above calculations and to supplement the simplified model, the following steps are considered as a follow-up to the present study:

1. Continue to examine the behavior of the two samples minutely on a controlled moisture content and to systematically record critical parameters that lead to a change in the behavior of the material (e.g. moisture content, frequency and amplitude, time of the experiment)

2. Examination of the behavior of both samples in tanks of different dimensions (or also geometry) to determine the dependence of the behavior of the material on them.

3. Performing experiments for more samples of nickel ore, with different density and chemical composition, to identify a possible critical reason for varying material behavior.

4. Performing experiments with different materials dangerous to maritime transport, such as iron ore, that is supposed to have the same behavior as nickel ore.

5. Examination of the behavior of materials in larger roll movements, as it is claimed to be the most dangerous for the liquefaction of cargoes.

6. Examination of the behavior of materials in the case of combined moves of the shaking table (e.g. roll and sway) and the case of non-harmonic stimulation (e.g. realistic scenarios of sea waves).

7. Further research on the design of bulk carriers with longitudinal bulkhead (cost of the bulkhead, if it will be permanent or removable, material that should be used).

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APPENDIX A

In Appendix A some more information about the Ore Carriers is being presented. Due to the high density of Ores their transportation many times is being executed with special bulk carriers that started being used around 1920 and are called "Ore Carriers". This type of vessels has a slightly different midship from the typical bulk carriers as it can be seen in Figure 88. They have smaller cargo holds, with two longitudinal bulkheads, two wing tanks and a double bottom throughout the cargo region. (E. Lehmann, M. Bockenhauer, W. Fricke, 1997)
They carry ores in the middle hold only, and their stability is higher than the stability of the typical bulk carriers. With the more narrow holds, they eliminate the shifting of the cargo and thus the free surface effect that could lead even to the capsizing of the vessels. Another difference from the typical bulk carriers is the increased height of double-bottom.
These vessels though are not usually preferred from the typical bulk carriers as they can be loaded only on the one route and usually will return empty.

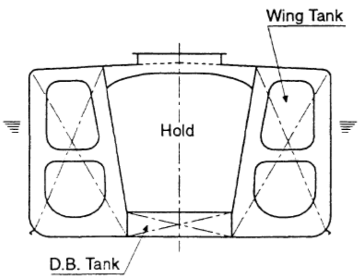

Figure 88 Midship of Ore Carrier.

Later, to face this problem, vessels that could carry both Oil and Ores (not at the same time though) were designed and their midship looks like in the figure below.

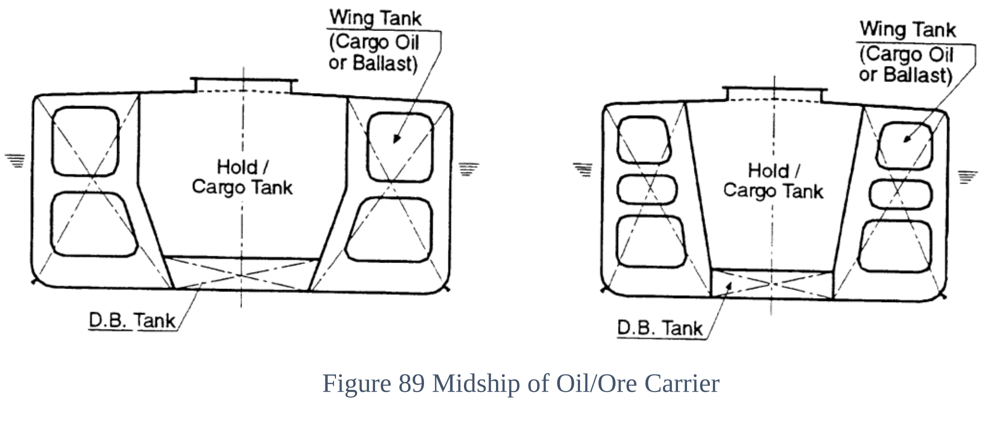

Figure 89 Midship of Oil/Ore Carrier

APPENDIX B

In Appendix B, the general criteria that should be applied for all conditions of loading in a bulk carrier are being mentioned (IMO, 2008).

- The area under the righting lever curve (GZ curve) shall not be less than 0.055 metre-radians up to the angle of 30 degrees.
- The area under the righting lever curve (GZ curve) shall not be less than 0.03 metre-radians from the angle of 30 degrees to the angle of 40 degrees.
- The area under the righting lever curve (GZ curve) shall not be less than 0.09 metre-radians up to the angle of 40 degrees.
- The initial GM should be bigger than 0.15 meters.
- The righting lever GZ should be at least 0.2 m at an angle of heel equal to or greater than 30°.
- The maximum righting lever should occur at an angle bigger or equal to 30 degrees.
- Severe wind and rolling criterion (weather criterion) (More information about weather criterion can be found in the IMO report 'ADOPTION OF THE INTERNATIONAL CODE ON INTACT STABILITY, 2008', pages 12-16).

APPENDIX C

Appendix C presents the results that were extracted from the AVEVA Marine program, having loaded the ship with dry Nickel Ore from Kastoria and Euboea. The same results are extracted using the bulk carrier with the longitudinal bulkhead.

- **Loading condition for Nickel Ore with density 1.589t/m3**

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	SM
HEAVY FUEL OIL TANKS										
HFOT01P	31-46	HFO	98.0	0.980	872.6	29.22	-14.98	22.96	2145.0	
HFOT01S	31-46	HFO	98.0	0.980	872.6	29.22	14.98	22.96	2145.0	
HFOT02P	27-31	HFO	98.0	0.980	122.9	20.00	-13.00	22.95	133.8	
HFOT02S	27-31	HFO	98.0	0.980	122.9	20.00	13.00	22.95	133.8	
HFOT03P	24-27	HFO	98.0	0.980	92.2	17.20	-13.00	22.95	100.4	
HFOT03S	24-27	HFO	98.0	0.980	92.2	17.20	13.00	22.95	100.4	
HFOT04S	18-24	HFO	98.0	0.980	138.3	13.60	12.00	22.95	84.7	
HFOWTP	46-58	HFO	98.0	0.980	1561.8	51.20	-19.27	22.99	6474.2	
HFOWTS	46-58	HFO	98.0	0.980	1551.5	51.20	19.28	22.97	6474.5	
Total HEAVY FUEL OIL TANKS					**5427.1**	**40.61**	**0.27**	**22.97**	**17791.7**	
LUBE OIL TANKS										
LO SUMP1	32-45	LO	98.0	0.900	57.2	27.60	0.00	1.18	13.7	
LOT02STORE	24-46	LO	98.0	0.900	183.5	26.40	8.00	22.95	12.5	
Total LUBE OIL TANKS					**240.7**	**26.69**	**6.10**	**17.77**	**26.2**	

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	SM
DIESEL OIL TANKS										
DOTP	18-24	DO	98.0	0.900	127.0	13.60	-12.00	22.95	77.8	
Total DIESEL OIL TANKS					**127.0**	**13.60**	**-12.00**	**22.95**	**77.8**	
FRESH WATER TANKS										
FWTP	9-18	FW	100.0	1.000	184.1	8.58	-12.36	23.14	210.3	
FWTS	9-18	FW	100.0	1.000	184.1	8.58	12.36	23.14	210.3	
Total FRESH WATER TANKS					**368.2**	**8.58**	**0.00**	**23.14**	**420.6**	
PAYLOAD										
C.HOLD01	225-268	PL	95.0	1.589	32348.4	256.22	0.02	13.57	0.0	
C.HOLD03	140-184	PL	95.0	1.589	37626.9	205.79	0.00	13.06	0.0	
C.HOLD05	86-100	PL	95.0	1.589	37693.3	154.88	0.00	13.04	0.0	
C.HOLD07	67-77	PL	95.0	1.589	37693.3	103.95	0.00	13.04	0.0	
C.HOLD09	46-58	PL	95.0	1.589	39161.8	51.76	0.00	13.69	0.0	
Total PAYLOAD					**184523.6**	**150.74**	**0.00**	**13.27**	**0.0**	
Fixed										
FIXED WEIGHT					213.4	115.31	0.00	21.65	0.0	
Total Fixed					**213.4**	**115.31**	**0.00**	**21.65**	**0.0**	
Lightweight					**26559.3**	**131.94**	**0.00**	**13.53**	**0.0**	
Deadweight					**190900.0**	**147.04**	**0.01**	**13.59**	**18316.2**	
Total Displacement					**217459.3**	**145.20**	**0.01**	**13.58**	**18316.2**	
Buoyancy					**217459.3**	**145.18**	**0.02**	**9.21**	**2369482.8**	

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	S M
Total Buoyancy					**217459.3**	**145.18**	**0.02**	**9.21**	**2369482.8**	

Drafts at equilibrium angle

Draft at LCF	17.881	metres
Draft aft at marks	18.461	metres
Draft fwd at marks	17.294	metres
Draft at AP	18.461	metres
Draft at FP	17.294	metres
Mean draft at midships	17.877	metres

Hydrostatics at equilibrium angle

Density of water	1.0300	tonnes/cu.m
Heel to starboard	0.08	degrees
Trim by the stern	1.167	metres
KG	13.583	metres
FSC	0.084	metres
KGf	13.668	metres
GMt	6.438	metres
BMt	10.896	metres
BMl	342.339	metres
Waterplane area	12639.34	sq.metres
LCF	138.996	metres
TCF	0.027	metres
TPC	130.185	tonnes/cm
MTC	2658.745	tonnes-m/cm
Shell thickness	0.000	mm

Righting Lever (GZ) Curve

Heel to Stbd (deg)	GZ (m)	GM (m)	Trim (m)	WLrad (m)	Freeboard (m)	Wind (m)
0.00	-0.0092	6.4384	-1.167	17.877	7.01[25]	0.0117
5.00	0.5556	6.5410	-1.131	17.807	5.06[6]	0.0117
10.00	1.1379	6.8561	-1.028	17.594	2.90[6]	0.0117
15.00	1.7569	7.4018	-0.866	17.240	0.75[6]	0.0117
20.00	2.3803	5.9305	-0.692	16.778	-1.43[6]	0.0117
25.00	2.7783	3.4176	-0.520	16.388	-3.80[6]	0.0117
30.00	2.9997	1.8133	-0.313	16.065	-6.33[2]	0.0117
35.00	3.1091	0.9669	-0.087	15.776	-8.97[2]	0.0117
40.00	3.1754	0.3269	0.109	15.437	-11.68[0]	0.0117
45.00	3.1414	-1.0935	0.302	15.035	-14.41[0]	0.0117
50.00	2.9876	-2.3405	0.501	14.543	-17.05[0]	0.0117
55.00	2.7392	-3.2786	0.699	13.953	-19.57[165]	0.0117

IMO Wind heeling

Property	Value	Units
Area to leeward (Area b)	1.96100	m-radians
Area to windward (Area a)	0.00003	m-radians
Gust angle	0.186	degrees
Rollback angle	19.974	degrees
Steady state angle	0.151	degrees
Max. angle to leeward	50.000	degrees

IMO 749 Intact Stabilty Criteria non - passenger

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.885	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.542	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	1.426	0.090
4	Initial GM to be at least 0.15 metres	Not Appl..	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	3.179	0.200
6	Max GZ to be at an angle > 30 degrees	41.131	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	0.151	16.000
8	IMO Weather Criterion (Areas)	Indeterm.	1.000

Condition complies with the regulations

Note

Term	**Meaning**
Not Appl..	The criterion cannot be applied, because some condition is not met, e.g. the criterion might only apply when the ship is upright, but in the condition, the ship has an angle of heel.
Indeterm.	The value cannot be determined, although the ship passes the test. The reason may be that the value has some very large value. Another reason may be that no profile has been defined, and thus the wind moment cannot be calculated.

Immersion Particulars

State of Openings = X-ray: Normal condition

Intact

Type	Point #	X position (m)	Y position (m)	Z position (m)	Ht. above WL (m)	Flood Angle (deg)	Downflood Compartment
Deck Edge	6	42.000	24.450	25.490	7.171	16.754	

- **Loading condition for Nickel Ore with density 1.896t/m3**

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	SM
HEAVY FUEL OIL TANKS										
HFOT01P	31-46	HFO	98.0	0.980	872.6	29.22	-14.98	22.96	2145.0	
HFOT01S	31-46	HFO	98.0	0.980	872.6	29.22	14.98	22.96	2145.0	
HFOT02P	27-31	HFO	98.0	0.980	122.9	20.00	-13.00	22.95	133.8	
HFOT02S	27-31	HFO	98.0	0.980	122.9	20.00	13.00	22.95	133.8	
HFOT03P	24-27	HFO	98.0	0.980	92.2	17.20	-13.00	22.95	100.4	
HFOT03S	24-27	HFO	98.0	0.980	92.2	17.20	13.00	22.95	100.4	
HFOT04S	18-24	HFO	98.0	0.980	138.3	13.60	12.00	22.95	84.7	
HFOWTP	46-58	HFO	98.0	0.980	1561.8	51.20	-19.27	22.99	6474.2	
HFOWTS	46-58	HFO	98.0	0.980	1551.5	51.20	19.28	22.97	6474.5	
Total HEAVY FUEL OIL TANKS					**5427.1**	**40.61**	**0.27**	**22.97**	**17791.7**	
LUBE OIL TANKS										
LO SUMP1	32-45	LO	98.0	0.900	57.2	27.60	0.00	1.18	13.7	
LOT02STORE	24-46	LO	98.0	0.900	183.5	26.40	8.00	22.95	12.5	
Total LUBE OIL TANKS					**240.7**	**26.69**	**6.10**	**17.77**	**26.2**	
DIESEL OIL TANKS										
DOTP	18-24	DO	98.0	0.900	127.0	13.60	-12.00	22.95	77.8	

Title	Frames	Cargo	% full	SG	Weight	LCG	TCG	VCG	FSM	S
				(t/m3)	(t)	(m)	(m)	(m)	(t-m)	M
Total DIESEL OIL TANKS					**127.0**	**13.60**	**-12.00**	**22.95**	**77.8**	
FRESH WATER TANKS										
FWTP	9-18	FW	100.0	1.000	184.1	8.58	-12.36	23.14	210.3	
FWTS	9-18	FW	100.0	1.000	184.1	8.58	12.36	23.14	210.3	
Total FRESH WATER TANKS					**368.2**	**8.58**	**0.00**	**23.14**	**420.6**	
PAYLOAD										
C.HOLD01	225-268	PL	100.0	1.896	40629.7	256.26	0.01	14.18	0.0	
C.HOLD03	140-184	PL	100.0	1.896	47259.6	205.79	-0.01	13.69	0.0	
C.HOLD07	67-77	PL	100.0	1.896	47342.9	103.95	-0.01	13.68	0.0	
C.HOLD09	46-58	PL	100.0	1.896	49187.3	51.72	-0.01	14.29	0.0	
Total PAYLOAD					**184419.5**	**149.67**	**-0.00**	**13.95**	**0.0**	
Fixed										
FIXED WEIGHT					213.4	115.31	0.00	21.65	0.0	
Total Fixed					**213.4**	**115.31**	**0.00**	**21.65**	**0.0**	
Lightweight					**26559.3**	**131.94**	**0.00**	**13.53**	**0.0**	
Deadweight					**190795.9**	**146.01**	**0.01**	**14.25**	**18316.2**	
Total Displacement					**217355.1**	**144.29**	**0.00**	**14.16**	**18316.2**	
Buoyancy					**217347.1**	**144.26**	**0.01**	**9.21**	**2375701.7**	
Total Buoyancy					**217347.1**	**144.26**	**0.01**	**9.21**	**2375701.7**	

Drafts at equilibrium angle

Draft at LCF	17.873	metres
Draft aft at marks	18.826	metres
Draft fwd at marks	16.907	metres
Draft at AP	18.826	metres
Draft at FP	16.907	metres
Mean draft at midships	17.866	metres

Hydrostatics at equilibrium angle

Density of water	1.0300	tonnes/cu.m
Heel to starboard	0.04	degrees
Trim by the stern	1.919	metres
KG	14.160	metres
FSC	0.084	metres
KGf	14.244	metres
GMt	5.896	metres
BMt	10.930	metres
BMl	345.119	metres
Waterplane area	12671.80	sq.metres
LCF	138.910	metres
TCF	0.015	metres
TPC	130.520	tonnes/cm
MTC	2678.953	tonnes-m/cm
Shell thickness	0.000	mm

Righting Lever (GZ) Curve

Heel to Stbd (deg)	GZ (m)	GM (m)	Trim (m)	WLrad (m)	Freeboard (m)	Wind (m)
0.00	-0.0046	5.8964	-1.919	17.866	6.63[25]	0.0117
5.00	0.5127	5.9996	-1.880	17.796	4.81[6]	0.0117
10.00	1.0477	6.3169	-1.768	17.585	2.65[6]	0.0117
15.00	1.6196	6.8703	-1.591	17.231	0.50[6]	0.0117
20.00	2.1932	5.4044	-1.429	16.774	-1.68[6]	0.0117
25.00	2.5469	2.9108	-1.313	16.385	-4.08[6]	0.0117
30.00	2.7255	1.3181	-1.165	16.063	-6.62[6]	0.0117
35.00	2.7933	0.4636	-0.988	15.776	-9.27[6]	0.0117
40.00	2.8177	-0.1208	-0.828	15.441	-11.92[6]	0.0117
45.00	2.7467	-1.5108	-0.697	15.039	-14.55[2]	0.0117
50.00	2.5584	-2.7259	-0.561	14.548	-17.10[2]	0.0117
55.00	2.2787	-3.6253	-0.421	13.958	-19.53[2]	0.0117

IMO Wind heeling

Property	Value	Units
Area to leeward (Area b)	1.76506	m-radians
Area to windward (Area a)	0.00002	m-radians
Gust angle	0.158	degrees
Rollback angle	19.794	degrees
Steady state angle	0.121	degrees
Max. angle to leeward	50.000	degrees

IMO 749 Intact Stabilty Criteria non - passenger

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.813	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.487	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	1.299	0.090
4	Initial GM to be at least 0.15 metres	5.896	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	2.818	0.200
6	Max GZ to be at an angle > 30 degrees	39.482	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	0.121	16.000
8	IMO Weather Criterion (Areas)	Indeterm.	1.000

Condition complies with the regulations

Note

Term	**Meaning**
Indeterm.	The value cannot be determined, although the ship passes the test. The reason may be that the value has some very large value. Another reason may be that no profile has been defined, and thus the wind moment cannot be calculated.

Immersion Particulars

State of Openings = X-ray: Normal condition

Intact

Type	Point #	X position (m)	Y position (m)	Z position (m)	Ht. above WL (m)	Flood Angle (deg)	Downflood Compartment
Deck Edge	6	42.000	24.450	25.490	6.933	16.180	

- **Loading condition for Nickel Ore with density 1.589t/m3 in vessel with longitudinal bulkhead.**

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	S M
HEAVY FUEL OIL TANKS										
DOTP: HEAVY FUEL OIL TANK 03 PORT	18-24	HFO	98.0	0.980	138.3	13.60	-12.00	22.95	84.7	
HFOT01P: HEAVY FUEL OIL TANK 01 PORT	31-46	HFO	98.0	0.980	872.6	29.22	-14.98	22.96	2145.0	
HFOT01S: HEAVY FUEL OIL TANK 01 STARBOARD	31-46	HFO	98.0	0.980	872.6	29.22	14.98	22.96	2145.0	
HFOT02P: HEAVY FUEL OIL TANK 02 PORT	27-31	HFO	98.0	0.980	122.9	20.00	-13.00	22.95	133.8	
HFOT02S: HEAVY FUEL OIL TANK 02 STARBOARD	27-31	HFO	98.0	0.980	122.9	20.00	13.00	22.95	133.8	
HFOT03P: HEAVY FUEL OIL TANK 03 PORT	24-27	HFO	98.0	0.980	92.2	17.20	-13.00	22.95	100.4	
HFOT03S: HEAVY FUEL OIL TANK 03 STARBOARD	24-27	HFO	98.0	0.980	92.2	17.20	13.00	22.95	100.4	
HFOT04S: HEAVY FUEL OIL TANK 04 STARBOARD	18-24	HFO	98.0	0.980	138.3	13.60	12.00	22.95	84.7	
HFOWTP: HEAVY FUEL WING TANK PORT	46-58	HFO	98.0	0.980	1403.3	51.09	-18.87	23.37	6474.3	

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	S M
HFOWTS: HEAVY FUEL WING TANK STARBOARD	46-58	HFO	98.0	0.980	1393.0	51.09	18.88	23.36	6474.7	
Total HEAVY FUEL OIL TANKS					**5248.5**	**39.20**	**-0.03**	**23.17**	**17876.7**	
LUBE OIL TANKS										
LO SUMP1: LUB OIL TANK 02 STORE	32-45	LO	98.0	0.900	57.2	27.60	0.00	1.18	13.7	
LOT02STORE: LUB OIL TANK 02 STORE	24-46	LO	98.0	0.900	183.5	26.40	8.00	22.95	12.5	
Total LUBE OIL TANKS					**240.7**	**26.69**	**6.10**	**17.77**	**26.2**	
FRESH WATER TANKS										
FWTP: FRESH WATER TANK PORT	9-18	FW	100.0	1.000	163.0	8.45	-11.92	23.05	100.8	
FWTS: FRESH WATER TANK STARBOARD	9-18	FW	100.0	1.000	163.0	8.45	11.92	23.05	100.8	
Total FRESH WATER TANKS					**326.0**	**8.45**	**0.00**	**23.05**	**201.6**	
PAYLOAD										
C.HOLD01: CARGO HOLD NO01p	225-268	PL	95.0	1.589	16183.3	256.23	9.48	13.55	0.0	
C.HOLD03: CARGO HOLD NO03s	140-184	PL	95.0	1.589	18802.5	205.79	11.30	13.05	0.0	
C.HOLD05: CARGO HOLD NO05s	86-100	PL	90.0	1.589	17844.2	154.87	11.57	12.47	0.0	

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	SM
C.HOLD07: CARGO HOLD NO07s	67-77	PL	95.0	1.589	18835.7	103.95	11.32	13.04	0.0	
C.HOLD09: CARGO HOLD NO09s	46-58	PL	95.0	1.589	19569.9	51.76	10.38	13.68	0.0	
CARGO HOLD NO01p: CARGO HOLD NO01p	225-268	PL	95.0	1.589	16165.1	256.21	-9.46	13.58	0.0	
CARGO HOLD NO03p: CARGO HOLD NO03p	140-184	PL	95.0	1.589	18824.4	205.79	-11.29	13.06	0.0	
CARGO HOLD NO05p: CARGO HOLD NO05p	86-100	PL	90.0	1.589	17865.0	154.87	-11.57	12.48	0.0	
CARGO HOLD NO07p: CARGO HOLD NO07p	67-77	PL	95.0	1.589	18857.6	103.95	-11.31	13.05	0.0	
CARGO HOLD NO09p: CARGO HOLD NO09p	46-58	PL	95.0	1.589	19591.9	51.76	-10.37	13.69	0.0	
Total PAYLOAD					**182539.6**	**150.69**	**-0.00**	**13.17**	**0.0**	
Fixed Subset 0										
FIXED WEIGHT					213.4	115.31	0.00	21.65	0.0	
Total Fixed Subset 0					**213.4**	**115.31**	**0.00**	**21.65**	**0.0**	
Lightweight					**26559.3**	**131.94**	**0.00**	**13.53**	**0.0**	
Deadweight					**188568.2**	**147.14**	**0.01**	**13.48**	**18104.5**	
Total Displacement					**215127.5**	**145.27**	**0.01**	**13.48**	**18104.5**	
Buoyancy					**215119.3**	**145.25**	**0.01**	**9.16**	**2356791.4**	
Total Buoyancy					**215119.3**	**145.25**	**0.01**	**9.16**	**2356791.4**	

Drafts at equilibrium angle

Draft at LCF	17.782	metres
Draft aft at marks	18.349	metres
Draft fwd at marks	17.208	metres
Draft at AP	18.349	metres
Draft at FP	17.208	metres
Mean draft at midships	17.778	metres

Hydrostatics at equilibrium angle

Density of water	1.0250	tonnes/cu.m
Heel to starboard	0.05	degrees
Trim by the stern	1.141	metres
KG	13.484	metres
FSC	0.084	metres
KGf	13.568	metres
GMt	6.546	metres
BMt	10.956	metres
BMl	344.160	metres
Waterplane area	12636.00	sq.metres
LCF	139.094	metres
TCF	0.016	metres
TPC	129.519	tonnes/cm
MTC	2644.122	tonnes-m/cm
Shell thickness	0.000	mm

Righting Lever (GZ) Curve

Heel to Stbd (deg)	GZ (m)	GM (m)	Trim (m)	WLrad (m)	Freeboard (m)	Wind (m)
0.00	-0.0056	6.5457	-1.141	17.779	7.12[25]	0.0119
5.00	0.5685	6.6476	-1.105	17.709	5.17[6]	0.0119
10.00	1.1602	6.9620	-1.001	17.498	3.01[6]	0.0119
15.00	1.7884	7.5079	-0.837	17.145	0.86[6]	0.0119
20.00	2.4295	6.2161	-0.657	16.680	-1.32[6]	0.0119
25.00	2.8499	3.6520	-0.480	16.281	-3.68[6]	0.0119
30.00	3.0900	2.0100	-0.267	15.951	-6.21[2]	0.0119
35.00	3.2135	1.0605	-0.034	15.658	-8.84[2]	0.0119
40.00	3.2873	0.4301	0.169	15.315	-11.58[0]	0.0119
45.00	3.2596	-1.0494	0.367	14.905	-14.29[0]	0.0119
50.00	3.1086	-2.3173	0.571	14.404	-16.93[165]	0.0119
55.00	2.8613	-3.2729	0.772	13.805	-19.44[165]	0.0119

IMO Wind heeling

Property	Value	Units
Area to leeward (Area b)	2.01968	m-radians
Area to windward (Area a)	0.00002	m-radians
Gust angle	0.153	degrees
Rollback angle	19.980	degrees
Steady state angle	0.119	degrees
Max. angle to leeward	50.000	degrees

IMO 749 Intact Stabilty Criteria non - passenger

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.905	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.560	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	1.465	0.090
4	Initial GM to be at least 0.15 metres	6.546	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	3.293	0.200
6	Max GZ to be at an angle > 30 degrees	41.422	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	0.119	16.000
8	IMO Weather Criterion (Areas)	Indeterm.	1.000

Condition complies with the regulations

- **Loading condition for Nickel Ore with density 1.896t/m3 in vessel with longitudinal bulkhead.**

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	S M
HEAVY FUEL OIL TANKS										
DOTP: HEAVY FUEL OIL TANK 03 PORT	18-24	HFO	98.0	0.980	138.3	13.60	-12.00	22.95	84.7	
HFOT01P: HEAVY FUEL OIL TANK 01 PORT	31-46	HFO	98.0	0.980	872.6	29.22	-14.98	22.96	2145.0	
HFOT01S: HEAVY FUEL OIL TANK 01 STARBOARD	31-46	HFO	98.0	0.980	872.6	29.22	14.98	22.96	2145.0	
HFOT02P: HEAVY FUEL OIL TANK 02 PORT	27-31	HFO	98.0	0.980	122.9	20.00	-13.00	22.95	133.8	

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	SM
HFOT02S: HEAVY FUEL OIL TANK 02 STARBOARD	27-31	HFO	98.0	0.980	122.9	20.00	13.00	22.95	133.8	
HFOT03P: HEAVY FUEL OIL TANK 03 PORT	24-27	HFO	98.0	0.980	92.2	17.20	-13.00	22.95	100.4	
HFOT03S: HEAVY FUEL OIL TANK 03 STARBOARD	24-27	HFO	98.0	0.980	92.2	17.20	13.00	22.95	100.4	
HFOT04S: HEAVY FUEL OIL TANK 04 STARBOARD	18-24	HFO	98.0	0.980	138.3	13.60	12.00	22.95	84.7	
HFOWTP: HEAVY FUEL WING TANK PORT	46-58	HFO	98.0	0.980	1403.3	51.09	-18.87	23.37	6474.3	
HFOWTS: HEAVY FUEL WING TANK STARBOARD	46-58	HFO	98.0	0.980	1393.0	51.09	18.88	23.36	6474.7	
Total HEAVY FUEL OIL TANKS					**5248.5**	**39.20**	**-0.03**	**23.17**	**17876.7**	
LUBE OIL TANKS										
LO SUMP1: LUB OIL TANK 02 STORE	32-45	LO	98.0	0.900	57.2	27.60	0.00	1.18	13.7	
LOT02STORE: LUB OIL TANK 02 STORE	24-46	LO	98.0	0.900	183.5	26.40	8.00	22.95	12.5	
Total LUBE OIL TANKS					**240.7**	**26.69**	**6.10**	**17.77**	**26.2**	
FRESH WATER TANKS										
FWTP: FRESH WATER TANK PORT	9-18	FW	100.0	1.000	163.0	8.45	-11.92	23.05	100.8	

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	S M
FWTS: FRESH WATER TANK STARBOARD	9-18	FW	100.0	1.000	163.0	8.45	11.92	23.05	100.8	
Total FRESH WATER TANKS					**326.0**	**8.45**	**0.00**	**23.05**	**201.6**	
PAYLOAD										
C.HOLD01: CARGO HOLD NO01p	225-268	PL	80.0	1.896	16260.5	256.12	9.81	11.91	0.0	
C.HOLD03: CARGO HOLD NO03s	140-184	PL	80.0	1.896	18892.3	205.78	11.84	11.43	0.0	
C.HOLD05: CARGO HOLD NO05s	86-100	PL	70.0	1.896	16560.4	154.87	11.89	10.40	0.0	
C.HOLD07: CARGO HOLD NO07s	67-77	PL	80.0	1.896	18925.6	103.95	11.86	11.42	0.0	
C.HOLD09: CARGO HOLD NO09s	46-58	PL	80.0	1.896	19663.4	51.88	10.80	12.13	0.0	
CARGO HOLD NO01p: CARGO HOLD NO01p	225-268	PL	80.0	1.896	16242.1	256.09	-9.79	11.95	0.0	
CARGO HOLD NO03p: CARGO HOLD NO03p	140-184	PL	80.0	1.896	18914.3	205.78	-11.84	11.44	0.0	
CARGO HOLD NO05p: CARGO HOLD NO05p	86-100	PL	70.0	1.896	16579.7	154.87	-11.89	10.41	0.0	
CARGO HOLD NO07p: CARGO HOLD NO07p	67-77	PL	80.0	1.896	18947.6	103.95	-11.86	11.43	0.0	
CARGO HOLD NO09p: CARGO HOLD NO09p	46-58	PL	80.0	1.896	19685.4	51.87	-10.80	12.13	0.0	

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)	S M
Total PAYLOAD					**180671.1**	**150.63**	**-0.00**	**11.49**	**0.0**	
Fixed Subset 0										
FIXED WEIGHT					213.4	115.31	0.00	21.65	0.0	
Total Fixed Subset 0					**213.4**	**115.31**	**0.00**	**21.65**	**0.0**	
Lightweight					**26559.3**	**131.94**	**0.00**	**13.53**	**0.0**	
Deadweight					**186699.7**	**147.05**	**0.00**	**11.85**	**18104.5**	
Total Displacement					**213259.0**	**145.17**	**0.00**	**12.06**	**18104.5**	
Buoyancy					**213256.0**	**145.15**	**0.00**	**9.08**	**2356351.9**	
Total Buoyancy					**213256.0**	**145.15**	**0.00**	**9.08**	**2356351.9**	

Drafts at equilibrium angle

Draft at LCF	17.637	metres
Draft aft at marks	18.264	metres
Draft fwd at marks	17.004	metres
Draft at AP	18.264	metres
Draft at FP	17.004	metres
Mean draft at midships	17.634	metres

Hydrostatics at equilibrium angle

Density of water	1.0250	tonnes/cu.m
Heel to starboard	0.02	degrees
Trim by the stern	1.260	metres
KG	12.063	metres
FSC	0.085	metres
KGf	12.148	metres

Density of water	1.0250	tonnes/cu.m
GMt	7.985	metres
BMt	11.049	metres
BMl	347.475	metres
Waterplane area	12638.82	sq.metres
LCF	139.227	metres
TCF	0.008	metres
TPC	129.548	tonnes/cm
MTC	2646.469	tonnes-m/cm
Shell thickness	0.000	mm

Righting Lever (GZ) Curve

Heel to Stbd (deg)	GZ (m)	GM (m)	Trim (m)	WLrad (m)	Freeboard (m)	Wind (m)
0.00	-0.0035	7.9854	-1.259	17.634	7.20[25]	0.0122
5.00	0.6961	8.0817	-1.223	17.565	5.27[6]	0.0122
10.00	1.4124	8.3800	-1.116	17.355	3.11[6]	0.0122
15.00	2.1632	8.9015	-0.948	17.005	0.96[6]	0.0122
20.00	2.9348	7.8388	-0.761	16.537	-1.21[6]	0.0122
25.00	3.4918	5.1581	-0.588	16.127	-3.56[6]	0.0122
30.00	3.8585	3.4067	-0.380	15.786	-6.08[2]	0.0122
35.00	4.0975	2.2364	-0.150	15.486	-8.70[2]	0.0122
40.00	4.2696	1.5570	0.055	15.141	-11.37[1]	0.0122
45.00	4.3330	-0.0819	0.247	14.717	-14.08[0]	0.0122
50.00	4.2614	-1.4645	0.442	14.203	-16.69[0]	0.0122
55.00	4.0838	-2.5333	0.636	13.592	-19.19[165]	0.0122

IMO Wind heeling

Property	Value	Units
Area to leeward (Area b)	2.55974	m-radians
Area to windward (Area a)	0.00002	m-radians
Gust angle	0.113	degrees
Rollback angle	20.263	degrees
Steady state angle	0.083	degrees
Max. angle to leeward	50.000	degrees

IMO 749 Intact Stabilty Criteria non - passenger

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	1.105	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.713	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	1.818	0.090
4	Initial GM to be at least 0.15 metres	7.985	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	4.333	0.200
6	Max GZ to be at an angle > 30 degrees	44.740	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	0.083	16.000
8	IMO Weather Criterion (Areas)	Indeterm.	1.000

Condition complies with the regulations