The Problem of Cargo Liquefaction in the Maritime Industry

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Summary

This project presents an overview of the cargo liquefaction problem which affects bulk carrier vessels. In particular, gaining a clear understanding of the problem and proposing early solutions, is the main focus of this thesis. The project is divided into several chapters approaching the phenomenon from the point of view of operation and design. The understanding of the nature of liquefaction as well as microscopic and macroscopic behaviour of the material when liquefied, led us to identify the critical parameters that cause cargo liquefaction. The cargoes which are more susceptible to liquefaction are iron ore fines and nickel ore even though any granular cargo may liquefy. Ship safety is affected by those cargoes when their form is changed during the voyage and the consequences may be catastrophic both for the vessel and the crew.

Detailed accident statistics in the recent years indicate that small size ships, such as Handymax vessels are more at risk due to liquefaction than larger ships, where no accident has occurred so far. Progress in the Code of Safe Practice for Solid Bulk Cargoes (BC Code), which was adopted in the mid 60's due to a spate of losses, led to the adoption of the International Maritime Solid Bulk Cargo Code (IMSBC Code). However, serious shortcomings in regulations still prevail, thus forcing a revision of the code.
Developments in different disciplines of engineering, like soil mechanics, offshore engineering and mechanics of materials helped us enhance understanding in the marine field. Similarities of the problem in those areas allowed us to transfer valuable knowledge to our field. Liquefaction is a phenomenon that initially appeared in soil mechanics many decades ago due to high intensity earthquakes.

The project includes the experimental procedure that should be followed. The results of experiments will show precisely the transient or the steady nature of the phenomenon and thus the spectrum of excitation forces responsible for cargo liquefaction. As a consequence, our aim was to suggest remedial factors, which for instance, reduce the transport liquid mobility of the phenomenon, find methods and establish models that could solve the problem. A design solution that could be valuable for future research and its feasibility was studied through the AVEVA ship design software. This is air inflated devices. A Handysize bulk carrier was modelled to demonstrate the potential of these devices for improving the stability of the ship to any level required to resist capsize as a result of cargo liquefaction. Based on the aforementioned research, a number of conclusions and recommendations are offered for further research.

Acknowledgements

This project was carried out at Strathclyde University in Glasgow under the supervision of Professor Dracos Vassalos.

I would like to thank Professor Vassalos for his contribution into various aspects of my studies. First of all, for his valuable help during the period I was working in Glasgow. Additionally, I am grateful to him for his guidance and advice throughout my studies. However, the most important is the different way of thinking and point of view that I adopted due to his mentoring.

I would be ungrateful not to thank Mr Dimitris Konovessis not only for his kind assistance in Glasgow, where he was always available to answer to my questions and make various discussions, but also for his help offered for the completion of the required Erasmus procedures.

All the PHD students and members of SSRC and especially Przemek Zagorski who taught me the ship design software NAPA.

Moveover, I would like to thank Eleutheria ELiopoulou and George Papatzanakis for their willingness to help me accomplish the Ship Design Project, which was a huge part of my studies and apparently my thesis

Last but not least, I would like to thank my family, my friends and everyone who helped me mentally and substantially complete this project and further my studies.

Table Of Contents

Glossary Of Terms

IMSBC: International Maritime Solid Bulk Cargo

IMO: International Maritime Organisation

SOLAS: Safety of Life At Sea

MSC : Maritime Safety Committee

TML : Transportable Moisture Limit

FPM: Flow Moisture Point

MC: Moisture Content

SID: Safety Inflated Devices

g: Acceleration of gravity

FEM: Finite Element Method

DWT: Dead Weight

SPT: Standard Penetration Test

CPT: Cone Penetration Test

BPT: Becker Penetration Test

SAP: Superabsorbent Polymers

SCCS: Specially Constructed Cargo Ships

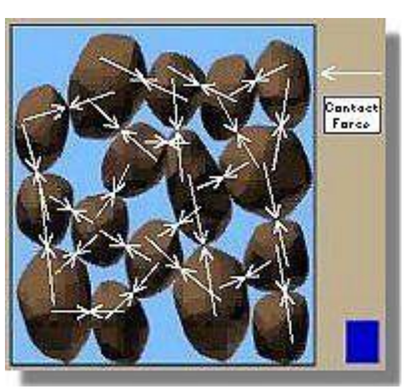
Chapter 1: Introduction

Liquefaction is a rapid transition of the particles that form the cargo from a stable solid state to a viscous fluid consistency [4]. Through this phenomenon, the contact forces between the individual solid particles are reduced, thereby softening and weakening the soil deposit. Therefore, the cargo will undergo a complete loss of strength and stiffness since there is no contact between particles. Liquefaction is produced by shaking forces or other rapid loading in cargoes and soils, which contain a sufficient amount of water.

This phenomenon requires considerable excess pore pressure. Pore pressure refers to the pressure of groundwater held within a soil or rock, in gaps between particles. Excess pore pressure is defined as the difference between the actual pore pressure and the hydrostatic pressure for still water level [36]. The contact forces are large when the void ratio i.e. the volume of voids per volume of solids, and subsequently the pore water pressure are low. Energy input leads to gradual settling and compaction of the cargo into its optimum packing density with the volume of the cargo decreasing and the bulk density increasing. Inevitably, the gaps between the particles become smaller, reducing the available volume for air and water.

As a consequence, both the bulk density and the pore water pressure are rising. If the volume of the water is higher than the volume of the gaps, the pore water pressure will increase suddenly to a value equal to the applied confining pressure, and the particles will be pressed away from each other. In such cases, the cargo loses its strength owing to the particle's loss of contact and behaves more like a liquid than a solid – hence, the name liquefaction.

Figure 1.1.a [36] shows the large contact forces, when the pore water pressure is low. The length of the arrows indicates the size of the contact forces between individual soil grains. *Figure 1.1.b* depicts the result of the increase of the pore water pressure. Notably, the contact forces become smaller because of the high water pressure.



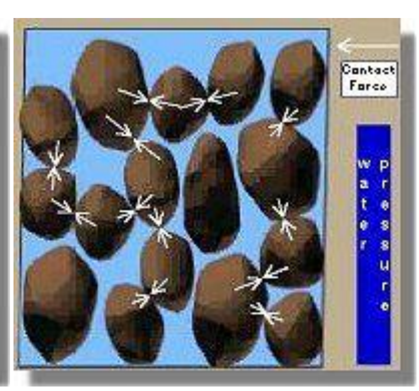


Figure 1.1.a ***Figure 1.1.b***

With regard to the shipping industry this transition happens in cargoes with high moisture content constituted of heterogeneous fine particles [39]. It is worth mentioning that heterogeneous and gap graded materials are more susceptible to liquefaction. Unprocessed ores are very heterogeneous, consisting of a mixture of fine-grained ores, clay-like materials and pebble sized stones. The ores that frequently "suffer" liquefaction are iron ore fines and nickel ore. Those are transported unpackaged by bulk carrier vessels, which often face serious safety problems when the cargo placed in the cargo holds is liquefied. A spate of losses in recent years and incomplete knowledge of the phenomenon in the maritime industry reinforces the need to examine the cargo liquefaction problem more in depth.

Figure 1.2: **Cargo hold with wet iron ore fines**

Figure 1.3: **Cargo hold with wet nickel ore cargo**

Liquefaction was first appeared as a subject in soil mechanics. It occurred through earthquake shaking of saturated soils and its effects are commonly observed in areas near rivers, lakes and oceans [36]. Liquefaction of subsurface sediment may lead to ground deformations and modification of seismic waves propagating through the liquefying layer. The latter modifications could affect bridges, buildings, pipelines and other constructed works.

Figure 1.4: Soil liquefaction occurred after the earthquake in Christchurch in 2011

Offshore structures are founded on potentially liquefiable soil. Hence, both earthquakes and wave loads can cause ground failure and put in danger the strength and the safety of those structures [5].

With regard to mechanics of granular materials, a single shift in conditions can drastically change the properties of a bulk material. For instance, quicksand which is a mixture of granular material such as sand and silt, clay and water, forms in saturated loose sand when the sand is suddenly agitated.

Liquefaction phenomenon as defined above leads to a serious problem akin not only to the shipping industry, i.e. cargo liquefaction, but also multiple areas of science. As a result, there is an imperative need to address this problem, by using the latest developments in theoretical and experimental research applicable to the problem at hand.

These developments emanate predominantly from the progress made in soil mechanics, where there is congruence of various numerical and experimental models concerning the parameters that cause liquefaction. In particular, these relate to experimental tests, results from shaking table tests as well as the Standard Penetration Test (SPT) or the Cone Penetration Test (CPT) correlate the intensity of the excitation forces, e.g. number and amplitude of cyclic loads, with the initial properties of the soils that lead to soil liquefaction [8]. On the other hand, theoretical models based on FEM and the "Simplified Procedure" by Seed and Idriss offer sufficient tools to study the liquefaction problem.

Thus, by analysing recent outcomes of these models and preparing our own experimental procedure, we will try to determine under which circumstances cargo liquefaction takes place.

More specifically, the objectives of this Thesis are as follows:

- To undertake a critical review of the cargo liquefaction problem, including accidents, legislation framework, theoretical and experimental research and practical implications spanning not only the shipping industry but also other areas of engineering.

- To develop an experimental programme aiming to identify and quantify the physical properties of cargo liquefaction concerning controlling parameters for the onset of the phenomenon and subsequent behaviour.

- To propose potential solutions concerning the stability of the cargo (liquefaction) as well as the ensuing ship stability problem and offer suitable recommendations.

Chapter 2: Bulk Carriers Market

2.1 Introduction

As regards the number of active vessels, bulk carriers are the most significant category of larger vessels and due to the number of casualties it seems more important than ever before to understand the connection between quality and the structure of the industry as it exists today.

According to the Benchmarking of INTERCARGO [38], 2011 saw 1061 new deliveries. This apparently had market implications, although the detrimental effects have been partially counterbalanced by unprecedented levels of scrapping. On the other hand, due to the fragmented nature of the sector it may well have other consequences for quality.

During 2011, the average age of the fleet decreased to 10.4 years. The remarkable amount of new deliveries in 2011 essentially renewed the total fleet. In effect, more than half the fleet is now less than 10 years old and with an average DPI rating (Deficiencies Per Inspection) of just 1.54. Vessels over 25 years still account for almost 15% of the total fleet and have an average DPI score of 6.63.

Every year, the vessels taken into account in calculating global fleet numbers are only those able to fulfil two crucial conditions. First of all, they have to trade internationally. Thus, some vessels that are deemed to be trading domestically have been excluded, and secondly, their DWT should be above 10,000 DWT.

2011 saw an astonishing growth of 1061 new deliveries, resulting in 8141 vessels. This represents a 7.8% increase on the previous year's total number of vessels. With respect to the actual net growth, i.e. excluding all those vessels that were scrapped in 2011, this is translated to 673 new vessels. A closer look at the new deliveries of 2011 reveals the following [38]:

- The average size of bulk carriers delivered was 85,810 DWT.
- In terms of ownership, more than 50% of the newly delivered vessels belong to Asia-based companies, with Japan receiving the highest number.
- Almost 28% fly the Panamanian Flag, followed by Hong Kong (14.7%) and Liberia (12.4%)
- Apart from nine vessels, all are classed at least with one IACS Member, with ABS leading the way (135), followed closely by Lloyds Register (12.3%), BV (12.2%) and DNV (10.1%).
- As for P&I market share, the North of England dominates with 14.6%, followed by the UK P&I with 11.6% and Gard with 11%.

As mentioned above, the average age of the fleet has now dropped to 10.4 years compared with 2010, where the average age of the fleet was 13.1 years.
It should be noted that for calculation of the data shown, the number of vessels that actually entered into service in 2011 are used.

Ship type	2012 No.	Tonnage (DWT)	2011 No.	Tonnage (DWT)
Bulk Carriers	7,019	502,790,766	6,798	455,198,842
Cement Carriers	48	1,046,054	52	1,183,290
Combi Carriers	30	2,838,233	62	5,923,424
Container/Bulk Carriers	62	2,146,105	75	2,527,804
General Cargo/Open Hatch	453	16,115,496	34	766,724
Gypsum Carriers	4	115,487	4	115,471
Limestone Carriers	5	105,793	5	105,794
Log/Lumber Carriers	167	4,683,167	195	5,459,310
Ore Carriers	168	42,216,262	138	32,127,341
Pipe Carriers	0	0	2	67,031
Refined Sugar Carriers	2	75,182	2	75,182
Stone Carriers	0	0	2	39,454
Trans-shipment Vessel	1	284,480	0	0
Urea Carriers	1	11,181	1	11,181
Woodships Carriers	181	9,208,219	183	9,348,006
Total	**8,141**	**581,636,425**	**7,553**	**512,948,854**

Table 2.1: It shows the numbers, types and tonnage of vessels.

According to new derived data from March 2013 [76], the dry bulk market has maintained its rising momentum, on the back of increased cargo availability. The market of Capesizes remained unchanged as the relative Capesize Baltic Dry Index (BDI) was invariable. On the other hand, the Panamax segment has experienced a good period lately thanks to the grain season in west Australia soaking up vessels from both the Pacific and Atlantic.

2.2 Casualties

Unfortunately, 2011 was a bad year for bulk carrier casualties with thirteen vessels lost, resulting in the loss of 38 seafarers' lives. One casualty alone (Vinalines Queen) was responsible for the loss of 22 seafarers' lives due to cargo liquefaction. Recently, there is a trend of more and more accidents. As a result, the goal of zero losses seems now more elusive than ever [38].

As given in the following tables, the ten year average for loss of life still shows some improvement between the 1993-2002 figures and the most recent 2002-2011 figures. During the period between 2002 and 2011, on average 24 lives were lost per year compared to 60 a decade ago - but clearly more still needs to be done.

While great improvements have been made in bulk carrier safety, there appears to be a tenacious element that keeps coming to the fore relating to smaller, older, vessels operating on intra-Asian trades. Three such losses were reported in 2011, which accounted for all 38 lives lost. All cases were due to cargo liquefaction.

Tables 2 to 7 reveal that smaller and older vessels account for the majority of casualties, not only during 2011, but in the ten-year period average as well. With regard to the cause of the incidents and although casualty information is not always easy to obtain, it is identified that groundings appear to be a major reason for casualties, with 61 grounding incidents reported in 2011 compared with 35 in 2010.

In terms of flag administrations, the Tables [38] show that Panama-flagged vessels had the greatest number of casualties in 2011. On the other hand, the number of bulk carriers which fly the Panamanian flag globally, has reached almost 2500 ships.

	2011	2002-2011
Lives	38	237
Ship losses	13	68

***Table 2.2*: Analysis of total losses 2011**

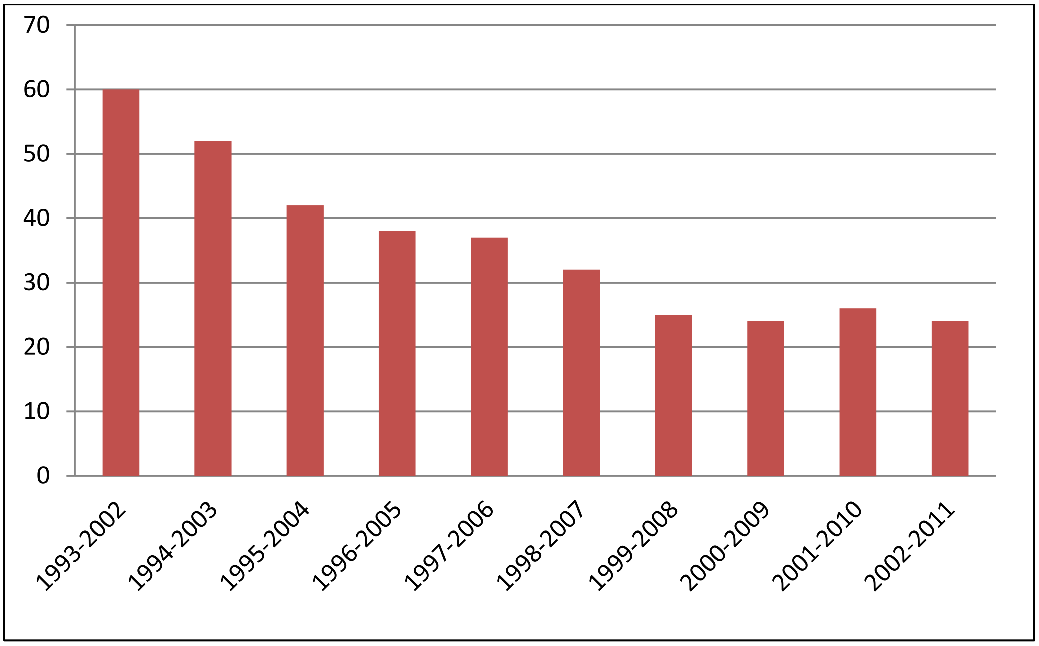


***Table 2.3*: Annual average number of lives lost 1993-2011**

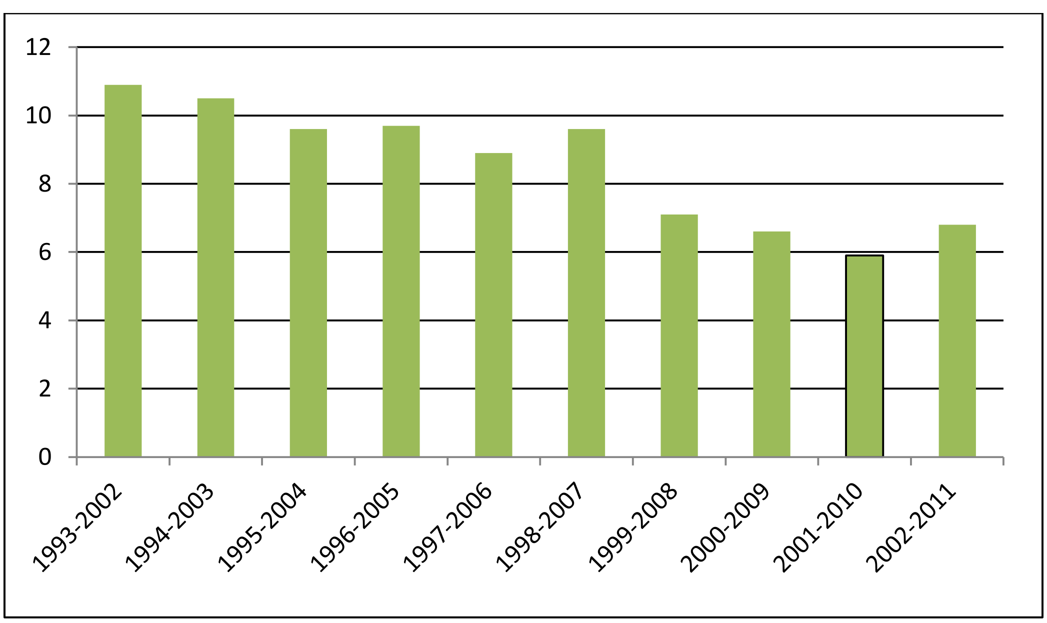


***Table 2.4*: Annual average number of ships lost 1993-2011**

	2011	2010	2002-2011
Cargo	1	3	7
Collision	2	1	11
Fire/Explosion	0	0	2
Flooding	0	0	11
Grounding	7	1	25
Machinery failure	0	0	1
Structural	1	0	5
Unknown	2	1	6

***Table 2.5*: Cause of Loss**

	2011	2010	2002-2011
Handysize	7	2	38
Hamdymax	1	3	12
Panamax	4	1	13
Capesize	1	1	5
Total	**13**	**7**	**68**

Table 2.6: Size of vessels lost

	2011	2010	2002-2011
0 to 4 years	2	1	4
5 to 9 years	0	1	5
10 to 14 years	0	1	3
15 to 19 years	0	0	4
20 to 24 years	3	0	18
25+ years	8	4	34

***Table 2.7*: Age of Casualty**

Chapter 3: Critical Review of Cargo Liquefaction

3.1 Introduction

Today, bulk carriers make up 40% of the world's merchant fleet and range in size from the single-hold mini bulker to very large ore carriers capable of carrying 400,000 tonnes, like Valemax ore ships. As mentioned above, the total number of internationally trading bulk carriers is 8,141 vessels, following the astonishing 1061 new deliveries in 2011. This represents a 7.8% increase on last year's total number [38]. Till September 2012 633 new bulk carrier ships were already delivered, with an average size of 85,810 DWT. During 2011, the average age of the fleet decreased to 10.4 years and more than half the fleet is now less than 10 years old. The vessels over 25 years account for almost 15%.

The most serious accident that occurred in 2011 was MV Vinalines Queen [62], a bulk carrier of the Vietnam National Shipping Lines. Vinalines Queen shipwreck led to the loss of 22 seafarers highlighting a serious problem that strikes the industry of bulk carriers for almost half a century and is related to the cargo. This problem refers to cargo liquefaction - a transition of the cargo from a solid state to a viscous fluid consistency in which all or a part of the cargo can flatten out to form a fluid surface. This subsequently puts in danger the ship's safety inducing undesirable events associated mainly with the loss of stability and secondarily with structural failure.

In terms of stability, the liquid cargo may shift transversely to one side with a roll and not return to the initial position with a roll on the other way. That will gradually cause a list to the ship with a subsequent capsize [29]. Vessels have capsized in the past in less than two minutes.

Turning to the hull strength, the immense forces generated by a potential slap of the liquefied cargo may have detrimental effects to the yield and buckling strength of the vessel. Both in stability and hull strength, free surface effects should be taken into consideration because the cargo is treated as liquid.

The Japanese Classification Society NK has published a guideline including rules to be followed when the cargo of a bulk carrier vessel which transfers nickel ore is liquefied.

3.1.1 Stability Requirements for Behaviour as Liquid

According to NK [30] when the cargo is liquefied, it is assumed as liquid, the free surface effect of cargo is to be considered, and the initial metacentric height (GM) and stability curve is to be assessed in accordance with the calculations below.

1) The initial GM is to be corrected by the transverse moment of inertia of cargo at 0^o angle of heel.
2) The stability curve can be corrected by any of the following method.
    - Correction based on the actual moment of fluid transfer for each angle of heel calculated
    - Correction based on the moment of inertia, calculated at 0^0 angle of heel, modified at each angle of heel calculated.

The initial metacentric height and stability curve corrected in accordance with the above mentioned requirements are to comply as well with the following requirements in **Figures 5 and 6**.

1) *General stability requirements*.

a) A_1 (area under stability curve between 0^0 and 30^0) is to be not less than *0.055* m*rad.
b) A_2 (area under stability curve between 30^0 and θ_m) is to be not less than *0.03* m*rad.
c) (A_1+A_2) is to be not less than *0.09* m*rad.
d) GZ is to be at least *0.20* m at an angle of heel equal or greater than 30^o.
e) θ_{max} is to be not less than 25^o.
f) G_0M (initial metacentric height corrected by the free surface effect) is to be not less than *0.15* m.

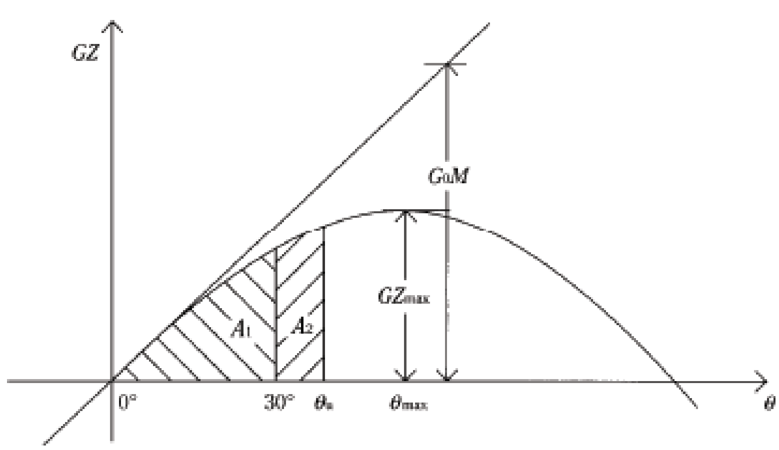


***Figure 3.1.1*: Stability Curve (General Stability Requirements)**

2) Stability requirements in wind and waves.

a) θ_0 is to be less than *16^0* or an angle corresponding to *80%* of immersing angle of deck edge, whichever is lesser.

b) Area b is to be not less than area a.

Where,

L_{wl} : Heeling moment lever caused by steady wind (m) given the following Formula: *0.0514* AZ/W' (m)

A: Projected lateral area of hull and cargoes on deck above the waterline (m^2)

Z: Vertical distance between the centre of ''A'' and the centre of under water projected lateral area of hull (m)

W': Displacement (t)

a : Area encircled by stability curve, L_{w2} and θ_r (m*rad).

b : Area encircled by stability curve, L_{w2} and θ_2 (m*rad).

θ_r: Angle at rolling stop motion

θ_c: Heeling angle at the second intersection between heeling moment lever L_{w2} and stability curve.

θ_2: Heeling angle to be taken of whichever is least, downflooding angle, θ_c or *50^0*.

θ_0: Angle of heel under action of steady wind

θ_1: Angle of roll to windward due to wave action given by the following formula: $109 x_1 x_2 k\sqrt{rs}$

x_1, x_2: Values obtained from tables according to the ration of the moulded breadth of the ship (B) to the mean moulded draught of the ship (d').

k: Value determined according to the type of the bilge of the ship.

A_k: Total area of bilge keels, projected lateral area of bar keels or sum of those areas.

r: Values obtained from the following formula: 0.73 + 0.6(OG/d')

OG: Distance between the centre of gravity and waterline (m), and is taken as positive when the centre of gravity is above waterline.

s: Value obtained from Tables and depends on the value of rolling period of the vessel (T)

T: Rolling period (seconds) obtained from the following formula:
$2B/\sqrt{G0M}$ (0.373 + 0.023 B/d' – 0.043 L'/100)

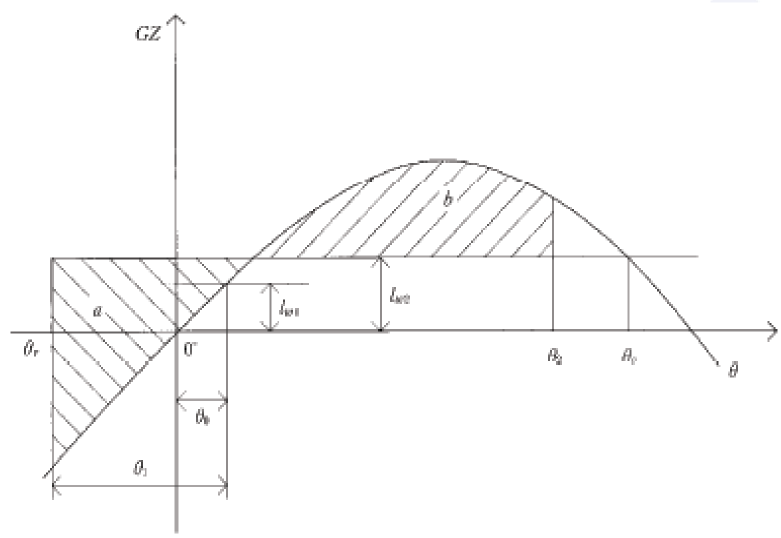


***Figure 3.1.2*: Stability and Wind-heeling Moment Lever Curve**

3.1.2 Hull Structural Strength Requirements

The structural strength of each cargo hold of a ship carrying nickel ore having a moisture content in excess of the transportable moisture limit is to comply with the below quoted requirements [30]:

1. Loads for local strength assessment are to take into account the liquefaction of the cargo.

2. Liquefaction of cargoes under severe loading conditions affecting yield and buckling strength from the loading conditions of nickel ore having a moisture content in excess of the transportable moisture limit are to be considered for loads during the yield strength and buckling strength assessment.

Applicable Members

Strength assessment of the structural members which are shown below should be performed in according to the following assessment procedure.

1. Longitudinal bulkhead plating and stiffeners attached to longitudinal bulkhead plating in ships of double-side skin construction.
2. Side shell plating, bilge hopper slant plating, and stiffeners attached to bilge hopper slant plating in ships of single-side skin construction.
3. Transverse bulkheads in holds.
4. Primary supporting members.
5. Members for which evaluation is deemed necessary by the Society.

Assessment Procedure

I. The structural members mentioned in 1. to 3. are to be decided based on the results of local strength assessment.
II. The structural members mentioned in 4. are to be decided based on the results if yield strength assessment and buckling strength assessment after performing direct strength calculations.
III. The structural members mentioned in 5. are to be decided by assessment methods deemed appropriate by the NK Society.

3.2 Accident Reports

3.2.1 Introduction

An important contribution in this project is to present an overview of the problem pertaining to some of the numerous accidents that are connected with cargo liquefaction and quoting the legislative framework for the carriage of unprocessed ores. Accidents reflect the impact to the society and unfortunately there are observed some legislative gaps, which will be mentioned. Additionally, it will be examined which ships are affected, why are they affected, and which were the prevailing conditions before and during the casualties.

In this chapter the most significant accidents and incidents related to cargo liquefaction are presented. These accidents occurred predominantly by liquefaction of iron ore fines and nickel ore. Nevertheless, a variety of materials such as bauxite and fluorspar led to serious accidents. Unfortunately, till now there is not available any sufficient technical information which provides detailed description of incidents or casualties resulting from liquefaction.

3.2.2 Casualties

Vinalines Queen

In December 2011, Vinalines Queen sank while carrying 54,000 MT of nickel ore from Indonesia to China. It is believed that bad weather, which subsequently subjected the ship to shaking, liquefaction of nickel ore cargo and the captain's wrong judgement are possibly the main reasons for this shipwreck [41]. Only one of the 23 crew members was rescued [62]. Both the investigator and the sole survivor claimed that the ship sank very quickly.

The Incident

The ship lost contact on December 25 when it was northeast of the Philippines's Luzon Island. It was on its way from Morowali, which is a non-traditional port in a primitive area of Indonesia, to Ningde in China [60]. *Vinalines said before disappearing, the ship had tilted 18 degrees.* About an hour earlier, the vessel also reported that it had tilted 20 degrees due to unknown reasons, and that it was being striken by strong winds.

The ore was loaded at the Morowali port in Indonesia by local workers who used cranes to dump it into the hold. But, to ensure that the ore is placed in the hold in a way that it does not move around during the voyage, loaders also need to use a conveyor, the investigators said. When the ship was losing its balance, the captain had ordered the crew to pump water to balance it [61]. The latter mitigation measure was not efficient and caused more disadvantages. He also made a wrong judgment when changing the ship's direction, because the change allowed waves to induce further instability. According to the investigators, the captain also failed to estimate the danger and make correct decisions like sending S.O.S signals and organizing a timely evacuation.

Moreover, another possible detrimental factor was the correlation between the cargo quantity and vessel capacity, which negatively reflects the Captain's and his Chief Mate's perception of the liquefying rate of nickel ore. With 54,000 tonnes of nickel shipped on a 56,040 DWT, it was not obviously safe when the liquefaction of the cargo led in an increase in weight that the vessel had to carry.

Technical Report

As stated in the technical report [61] following the accident, the condition of the vessel was at a quite satisfactory level, as the ship was built in 2005 and there are specific reports, referring that the necessary maintenance dry dockings were successfully completed. Hence, there was unlikely a possibility of sinking resulted from technical problems based on her age. In addition, the 31-year-old sole survivor of the deadly accident, told inspectors that he was in charge of checking the hold and closing them. They were in a normal condition before the sinking, he said.

Asian Forest

Asian Forest [63] sank on 17 July 2009 off the coast of Mangalore carrying 13000 MT of iron ore from India to China. The cargo ship had earlier berthed at New Mangalore Port to embark *Iron Ore*. The ship sailed out on 17 July 2009 for Zhavgiagang in China. On leaving harbour, the ship encountered rough seas due to which its cargo shifted to one side thereby causing a list of approximately 30 degree to the right side. The master of the ship, alarmed by this occurrence, made distress call after due hours of its departure to New Mangalore Port Trust. Luckily, the entire crew of the vessel was rescued.

The recent findings have brought to light that the transportation and loading of iron ore fines onto the vessel at New Mangalore port on the West coast of India was undertaken when the area was experiencing heavy monsoon. This caused liquefaction of the iron ore fines to take place resulting in the separation of moisture content and some kind of separated water-fines mixing.

Shortly after leaving port probably due to poor ballasting system in terms of integrity / pumping out, the vessel initiated de-ballasting during the voyage. The vessel commanded by a Chinese captain postponed dealing with hold bilges due to de-ballasting. Hence, there was upward migration resulting in scattered puddles of cargo during de-ballasting. The combined effects of liquefaction and unsatisfactory de-ballasting resulted in dangerous listing. The vessel listed initially 3^0 starboard later reaching to 10^0starboard in one hour. Vessel was then beached at 17^0 starboard list off Old Mangalore waters to avoid capsizing.

According to witnesses earlier a Greek captain had refused the cargo. The Chinese captain of *Asian Forest* accepted the cargo after being given the survey certificate, which is considered fraudulent as the survey was undertaken several days earlier when the cargo was in much better condition. Hence, the report observed that had the captain insisted on a revised survey report seeing the condition of the cargo, the incident would not have occurred

Figure 3.2.2.1**: MV Asian Forest**

Padang Hawk

Padang Hawk [64], [40] was a Handymax 46 635 tonne deadweight 'geared' bulk carrier, carrying in its five cargo holds nickel ore from the Philippines, Indonesia and New Caledonia.
Between 17 and 23 July 1999, the Singapore flag bulk carrier Padang Hawk loaded a full cargo of nickel ore from barges at Kouaoua, New Caledonia. Late on 23 July, the ship sailed for Townsville, Australia. During the passage, Padang Hawk was subjected to rough seas and rolled heavily. On 26 July, the ship developed a 15° list to port.

A quick examination in the holds showed that the cargo in four of the five holds had liquefied. The cargo in the forward holds appeared to be 'flowing' with the movement of the ship. The master reduced speed and altered course to put the wind and seas on the ship's port quarter. Ballast was then pumped to correct the list. The ship's course was maintained so that it entered the inner route of the Great Barrier Reef by Grafton Passage rather than the more southerly Palm Passage.

The ship finally arrived safely in Townsville at 2000 on the evening of 28 July.

***Figure 3.2.2.2*: Padang Hawk**

The Incident

Padang Hawk [64] sailed from Townsville on the evening of 13 July and arrived at the anchorage at Kouaoua, New Caledonia on 17 July. The loading of iron ore started from shore barges early in the evening. The ship's cranes were manned by shore labour and loading from the barges was carried out from about 0500 each morning until about 2030 in the evenings. With the exception of one morning, when there were a few hours of light drizzle, the weather was fine throughout the loading operation. Soundings of the cargo holds for water were taken each day and no bilge water was recorded. During the loading operation, the ship's crew noticed that some 'grabs' of cargo had water running from them as they were lifted out of the barges and into the ship's holds.

The cargo loading was completed on 23 July and the ship sailed from Kouaoua before midnight. The following days the ship faced rough seas, which compelled it to roll and pitch heavily. The bilges in all holds were pumped several times, as the vessel continued to roll. On 27 July Padang Hawk suddenly developed a 15° list to port. It is worth mentioning that the crew checked and found the cargo hatches and the small hold access hatches secured. They opened an access hatch to each of the holds in turn. They found that the cargo in all but number 5 hold had settled and shifted to port. The cargo in the first 3 holds appeared to be semi-liquid.

As a potential measure of averting capsize the master decided to ballast starboard side tanks to correct the list. Numbers 3 and 5 starboard topside tanks were filled. He used as well the double bottom tanks to correct the list. Thus, the ship's list had been reduced to about 5° after several hours. In the afternoon of 28 July, Padang Hawk anchored off Townsville and final adjustments were made to the ballast to minimise the list and reduce the ship's draught. The ship arrived safely alongside in Townsville on 28 July.

Initial Inspection

When Padang Hawk arrived at Townsville in the evening of 28 July 1999, investigators inspected the ship's cargo holds. Cargo in holds 1, 2, 3 and 4 had settled and shifted [64]. In each hold, the surface of the ore showed that a portion of the ore had apparently liquefied leading to a mud like material. In number 1 hold, water was created on the surface of the ore and the whole cargo in this hold had settled to be almost level. The cargo in holds 2, 3, and 4 showed varying amounts of liquefaction with a central mound of unaffected cargo surrounded by cargo that had liquefied.

In number 5 hold, the cargo retained the form in which it was loaded, with cargo forming a flattened pyramid which reached to the level of the bottom of the topside hopper tank, 3.5 m below the deck level. The disposition of the cargo in number 5 indicated the way in which the cargo had been trimmed and what the cargo must have looked like in holds 1, 2, 3, and 4 after the completion of loading. Examination of the hatch covers, coamings and other openings into the cargo holds, showed no obvious sign of any ingress of water.

***Figure* 3.2.2.3: Cargo hold number 1**

***Figure* 3.2.2.4: Cargo hold number 3**

Investigators took samples of the nickel ore from just beneath the top layer and between 20–30 cm below the cargo surface in number 1 and number 5 holds. The ore was a red sand or dust with larger pieces of solid greenish rock interspersed throughout. These larger pieces were generally less than 5 mm in size. To ascertain whether the cargo had been contaminated by seawater they used two different tests. Specifically, the Mohr's Method Chlorine test and the High Temperature Chlorine test. Both tests showed that there was not any amount of seawater within the holds. Tests of the actual moisture contained in the samples resulted that the surface sample from number 1 hold was 41 %, whereas the sub-surface sample in the same hold was 36.5 %. In addition, the sub-surface sample number in hold five was 38.9 %. To obtain the flow moisture point of the nickel ore sample it was used the Flow Table method resulting in a TML of 29.2 %. All of the ore samples represented had moisture contents that significantly exceeded the TML determined using the IMO standard flow table test.

To sum up, the factors contributing to the shift of Padang Hawk's nickel ore cargo and the consequent port list include the facts that the cargo was loaded with excessive moisture content, the vessel was subjected to heavy seas, which led to the cargo changing state from a solid to a viscous liquid in 4 of the 5 holds and the mined nickel ore was stockpiled in areas open to the ingress of rainwater.

Black Rose

A Mongolian ship transporting iron ore to China from Paradip [65] port on the east coast of India, sank off Paradip port on the 9th September 2009, killing one of the 27 crew members while the others 26 were rescued. MV Black Rose had loaded 23,847 MT of iron ore while at anchor it developed a list of 20 degrees to starboard and which eventually increased to 30 degrees to starboard. The ship began to list six miles off the loading port.

According to a surveyor the ship was loaded with iron ore fines having excess moisture content. The official cause of sinking was the loss of stability due to high moisture iron ore fines cargo shifting. Initially, the captain of the ship objected to load the cargo, because of the high excess moisture content. However, his complaint was not taken into consideration by the vessel's agent in India. After loading of about 24,000 metric tonnes of iron ore files, the ship tilted to the right and finally sank when 7,000 tonnes more were left to be loaded. Investigations found out that the vessel had developed a hole.

Intercargo notes that the *Black Rose* and also the *Asian Forest* were both lost while carrying a cargo of iron ore, both incidents occurred to vessels which had loaded cargoes in India during the monsoon season.

Jian Fu Star, Nasco Diamond, Hong Wei

There is a strong correlation between those three accidents, because all vessels sank in a period of 39 days having loaded the same nickel ore cargo from Indonesia. 44 crew members were lost.

Jian Fu Star

It was the first of the three bulk carrier that shipped nickel ore from Indonesia and sank on the 27th October 78nm south of Oluanpi, Taiwan when on route from Indonesia for Qingdao China with 43000 MT. The prevailing weather conditions were heavy seas and the official cause of capsizing was due to a cargo shift.

Nasco Diamond

The Chinese cargo vessel Nasco Diamond [49] sank on the 10th November 2010 off Japan's southern islands killing 21 out of 25 crewmen. Nasco Diamond was transporting 50000 tonnes of nickel ore from Indonesia to China. According to the Japanese Coast Guard the exact cause of ship's disappearance could not be established. Officials claimed that weather could not have played a possible role in the sinking of the ship, since the area was calm with good visibility, moderate wind and without rain. One of the rescued crewmembers said that he was in the engine room when water suddenly came in, forcing him to jump into the sea with a life jacket. However, the accident is attributed to cargo liquefaction because apart from its extensive hull damage Nasco Diamond suffered a cargo shift and foundered.

Hong Wei

The ship sank off Taiwan [55] while carrying 40000 tonnes of nickel ore from the same Indonesian port to Dalian port in northeastern China. The vessel encountered rough monsoon weather, its cargo liquefied, and therefore sank midway through its voyage. 14 crew members were rescued but 10 were lost.

MV Maria VG

The vessel [59] developed a list 20^0 at sea due to liquefaction of its cargo which was ilmenite sand in September 2003. The cargo was too wet, almost saturated and the measured moisture contents varied between 39%-46%. This clearly exceeded the assumed average moisture status of about 28%. The estimate was based on post production reviews and it did not include the moisture increase caused by rain in the open storage field.

In addition, the water content of the cargo clearly exceeded the Transportable Moisture Limit (TML) value of 22.7%, determined for this investigation. The TML value was not determined by the shipper, although one transport had been aborted due to excess moisture. As can be easily concluded, the procedures that were followed before the loading of the cargo did not correspond to the normal practices of the Code of Safe Practice for Solid Bulk Cargoes (BC Code) issued by IMO.

As a consequence, the cargo condensed due to the high moisture content and the ship vibrations during transportation. This caused the water to be pushed upwards in the cargo leading reasonably to liquefaction of the top part of the cargo. The density of the waste concentrate contributed to the condensation process and the liquefied pressurized slurry was shifting in the hold almost like a liquid.

Finn Baltic

Liquefaction is not a new problem. More than 20 years ago, on 27 December 1990 [17], pusher Finn capsized along with the barge Baltic outside Hanko. The pusher-barge combination Finn-Baltic was en route from Raahe to Koverhar with 13,398 tons of iron ore concentrate when the cargo shifted in heavy weather, resulting in the loss of stability and the vessel capsizing in 10–15 seconds. Seven crew members and a pilot lost their lives in the accident, but the chief engineer and first officer survived.

The Finn-Baltic left the port of Raahe carrying a cargo of 13,398 tons of iron ore concentrates bound for a steel factory of Finland, on 25 December 1990. The vessel had been loaded in Lulea of Sweden, on 21 December and brought to Raahe by the pusher Rautaruukki on the following day to wait for transit to the south. During its stay in Raahe, the barge developed a list of 1–2 degrees to port and the workers noted that the cargo seemed to be wet and some of the ore heaps had collapsed.

As the weather was severe, both main engines were operating to improve the manoeuvrability of the vessel, increasing its speed to around six knots. However, this also increased the amount of water entering the cargo hold every time the bow slammed to a wave and the watch officer, who used search lights to monitor the state of the cargo, noticed that more ore heaps had collapsed. Later in the evening the combination passed the lighthouse and pilot station of Tankar, and the wind seemed to calm down.

On 26 December, the Finn-Baltic continued its journey while maintaining an average speed of 6–7 knots in heavy head seas. In daylight the chief officer noticed that in the forward part of the cargo compartment three or four ore piles had collapsed to half of their original height and the others appeared to be wet. Sea water flowed continuously to the hold and washed ore to the sea through the storm shutters on the sides. However, during the last watch of the day the weather seemed to calm down again.

The incident

According to the chief engineer, who was in the engine control room at the time of the accident, the vessel suddenly heeled at the portside and could not return at its upright position itself. Within the next 10–15 seconds, the list increased to 4–5 degrees and, after briefly stopping at 10 degrees, the Finn-Baltic capsized. At the same time, the chief officer noticed that the ship had developed a permanent list to port, realized that something was wrong and decided to head to the bridge.

After capsizing the main engines of the Finn-Baltic immediately went out and the emergency diesel generator started automatically. However, it ran only for a short time and after a while even battery-operated lights dimmed and died out. The chief engineer heard someone yelling in the darkness and found the chief officer from the corridor outside the control room in a shock-like state. After getting dry clothes for the chief officer they waited several hours in the switchboard room, until the rising water forced them to move to the aft most part of the engine room next to the propeller shaft. Even before the accident the chief engineer had planned to find his way to this location in case the vessel capsized because there was no double bottom and, once free of its cargo, the combination would stay afloat upside-down. After 20 minutes they heard someone banging the hull outside the ship.

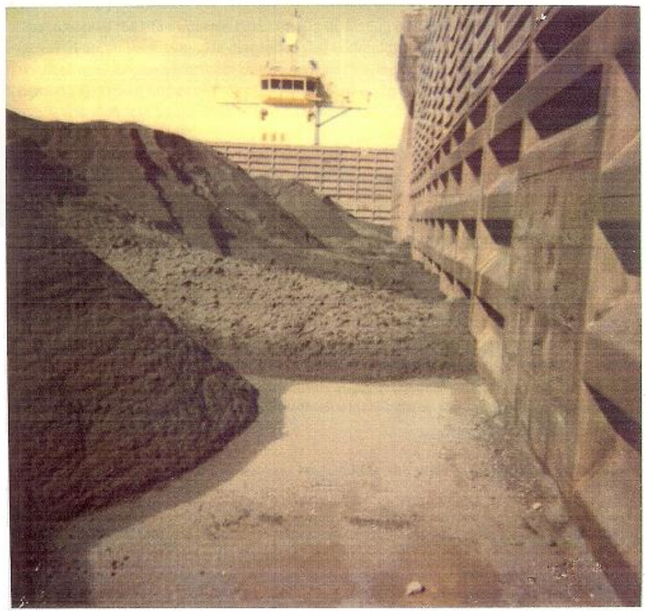


Figure 3.2.2.5**: The slopes of cargo sliding on board the barge TASKU of the Finn-Baltic**

Hui Holg [15]

On 18 May 2005, the Hong Kong registered ship Hui Long [15] was sailing from Sungei Pakning of Indonesia to India. The vessel was loaded with 11,245 tonnes of mixed general cargoes including 5,185 tonnes of fluorspar mineral in bulk. Whilst the vessel was 173 nautical miles from Sri Lanka it suddenly developed a list of 15 degrees to port. The list continued to be worsening and the Master abandoned the vessel after the port weather deck has been immersed into water at a list of 40 degrees. All 23 crew were rescued by a passing container vessel 'P&O Nedlloyd Asia'. A salvage tug was called in the following day trying to rescue the vessel without success and the Vessel finally sank on 20 May 2005.

Hui Long was a general cargo carrier with four cargo holds. The vessel was fitted with cranes and tween decks at No. 2, 3 and 4 holds. When the accident took place, the vessel was carrying mixed general cargoes including 5,000 tonnes of fluorspar in bulk in No. 3 lowerand No. 1 holds. According to previous surveys done by its classification society, it was judged that the vessel had no major structural problem before the accident.

***Figure 3.2.2.6*: Hui long after the initial listing**

The vessel was loaded with a cargo of acid grade fluorspar in bulk to ship's No. 3 lower and No. 1 holds in Hong Kong. Loading was carried out by grabs from the barges that were moored alongside the ship. When the loading was completed, a pile of about 4 meters height of bulk fluorspar was stowed inside the No. 3 lower hold. It is worth mentioning that there was not any trimming procedure after loading. The vessel sailed to Singapore on the next day.

According to the weather report there had been slight showers on the day of loading. The crew stated that showers did not impair the loading of the cargo. Cargo surveyors took samples and examined the moisture content of the cargo to so that to issue a moisture content certificate. According to the certificate, the moisture content of the fluorspar cargo was at 9.8%. However, the certificate did not provide the details of the Transportable Moisture Limit (TML) of the fluorspar.

On 18 May 2005 the vessel suddenly developed a 15º list to port. The bridge navigating officer stated that the vessel was navigating in normal order and rolled moderately at about 10 degrees to both sides in seaway before the list. There was not noticed something strange such as collision with other object during the watch and in the voyage. The sudden listing was immediately reported to the Master. When the Master realized what had happened he informed the engineers to upright Hui Long by filling the starboard double bottom tanks. However, due to severe listing, this measure was not effective. Thus, the crew was not able to upright the vessel with ballasting. The listing continued to be worsening to about 40º list to port. The port deck edge was immersed into the sea. Due to the dangerous situation, the Master decided to abandon the vessel. According to the weather report of the sea area there was no adverse weather condition prevailing in the area.

Condition of Vessel

The vessel was operating in good condition before the accident. According to the ship management company, the maintenance record of the ship was in good condition. The survey record from its classification society has also indicated that the vessel had no major structural problem. In addition, the ship's safety and trading certificates were inspected to be in order. During interview, the crews stated that the vessel had been operating in good condition.

Cause of accident-Fluorspar Liquefaction

Nobody on the vessel was sure of what had caused the sudden listing. The second officer who was on duty at time of listing said that the vessel all of a sudden listed to port side and could not return to upright position. The only possible cause of the capsizing is attributed to cargo liquefaction. The vessel was carrying 4685 tonnes of fluorspar at No. 3 lower hold and 450 tonnes at No. 1 hold. After the accident it was estimated that due to the large width of No. 3 lower hold, a transverse shift of approximate 800 tonnes of liquefied fluorspar cargo could cause an initial heel of 21º to the vessel.
Fluorspar, which was carried on board the vessel, is a raw material used for fluor-chemicals industry. When the accident took place the procedures, regarding sampling, testing loading and transporting were under the Code of Safe Practice for Solid Bulk Cargoes, 2004 (BC Code) published by the International Maritime Organization. Thus, fluorspar was categorized as Group A and B cargo. It is a material that may liquefy if shipped at moisture content in excess of the Transportable Moisture Limit (TML). The fluorspar cargo on board the vessel was originated from a nearby port in Pearl River Delta. The cargo was shipped to Hong Kong by coastal barges for loading to the vessel. After loading on board, cargo sample was taken by a cargo surveyor for testing of the moisture content. A moisture content was tested to be 9.8% by the surveyors and a certificate was issued to this effect. However there was no certification regarding the TML of the fluorspar cargo from the shipper or the cargo survey firm.

Moreover, there was no laboratory test certificate or documentary proof in verifying the actual TML of fluorspar loaded in Hong Kong. In the absence of the TML of the fluorspar cargo, there is a possibility that the moisture content of 9.8% could have already exceeded the TML and the cargo would be liable to liquefy. Finally, the amount of sample taken by the survey firm would not be sufficient for a proper determination of moisture content as far as the BC Code is concerned.

Some other minor cargo liquefaction accidents [58], [56] and incidents which occurred few years ago due to iron ore liquefaction affecting very small size ships are roughly mentioned below:

Sun Spirit

The Panamanian - registered cargo ship [71] sank off the Philippines eastern seaboard on the 15th January 2012. The cargo vessel was carrying iron ore bound for China after leaving the central Philippine province of Leyte. The ship suddenly created a list and capsized, due to cargo liquefaction. The area where the ship sank had extreme turbulent waters. All crew members were rescued.

Wen Qiao

The Chinese cargo vessel capsized off Bohai Sea on the 17th September 2007. It loaded 4500 t of iron ore at a port of India bound for China. One crew member was lost.

Chang Le Men

The vessel loaded iron ore from Mangalore port in India on 5/9/2007 and after a few hours it beached with 35^{0} list near port.

Discovery II

The vessel loaded iron ore cargo at Haldia and after three hours it developed a severe list and entered port of Vizag for discharge.

Vien Dong 2

The 7500 DWT Vietnamese registered cargo ship beached with 20^{0} list off Nicobar Island in Caribbean on 30/9/2007. The vessel was transporting iron ore fines, which were loaded at Haldia port four days before the accident.

Heng Tai

The ship capsized and sank west of Bangkok on 02/10/2007 after loading iron ore fines from Haldia Port like the two previous above mentioned cargo vessels. It was carrying 5500 tonnes of iron ore fines and due to the capsizing two lives were lost.

Hodasco 15

The Vietnamese registered vessel sank off Malaysia after creating a severe list. It had loaded approximately 6500 tonnes of iron ore fines at Calcutta port.

Vinalines Mighty

The 22625 DWT bulk carrier vessel loaded iron ore from Paradip port on 10/9/2009 and she created a list shortly after sailing and returned to load port.

Liquefaction accidents of lateritic nickel ore

Lateritic nickel ore is also known to liquefy. In 1988 the Mega Taurus [57] was carrying ore from the Philippines when it capsized with the loss of all 20 crewmen. In 1988 the Sea Prospect was shipping ore from Indonesia when it capsized during its voyage to Japan with the loss of 10 lives. Other vessels carrying the same cargo have been fortunately luckier. In 1990 the Oriental Angel developed a list after loading cargo in New Caledonia. A similar incident was repeated in 1999 with the Padang Hawk. Jag Rahul in 2005 was another victim of liquefaction, when carrying ore from Indonesia.

***Figure 3.2.2.7*: Liquefied lateritic nickel ore**

3.2.3 New accidents – incidents

Unfortunately, liquefaction remains a problem that not only is not ameliorated in the recent years, but also on the other hand new valuable indications come up, which reveal that any material can liquefy and the spate of losses in the previous years was not a coincidence. Thus, on dawn of 2013 a serious accident took place, with a bulk carrier vessel carrying nickel ore. Additionally, there are some important incidents regarding bulk carriers which transport bauxite. This kind of material is recently responsible for various incidents that luckily are not catastrophic till now.

It is well known that several vessels have recently experienced cargo liquefaction problems after loading bauxite in the Amazon region in northern Brazil, apparently from terminals in Trombetas [68]. The exact causes of the incidents have not been reported so far, but it has been suggested that heavy rain in the region has led to an unusually high moisture content of the loaded bauxite.

Bauxite is a cargo which normally consists of lumps [69], with relatively low moisture content. Due to these typical characteristics of the cargo, it is listed in the IMSBC Code as a Group C cargo: a cargo not liable to liquefy. Appendix 1 of the IMSBC Code describes bauxite as a cargo with moisture content between 0% and 10% consisting of 70%-90% lumps varying in size between 2.5 and 500 mm and 10%-30% powder.

Furthermore, according to P&I Clubs there are difficulties encountered by vessels that have loaded sinter feed at Ponta da Madeira in Brazil [70]. After loading sinter feed at Ponta da Madeira, at least two ships have experienced cargo liquefaction problems on passage. Although both vessels managed to reach port without the situation becoming critical, significant amounts of free water were found to have accumulated in the corners of each hold, and in certain holds the cargo was completely submerged. Vessels due to load "Sinter Feed" at Ponta da Madeira are advised to treat the product as being a Group A cargo, irrespective of what may be stated on the cargo declaration.

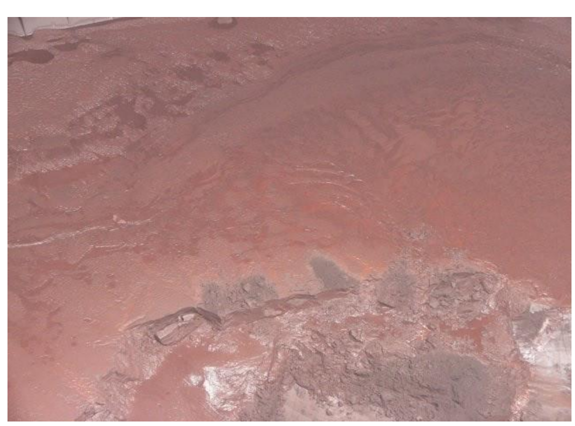


***Figure 3.2.3.1*: Sinter feed loaded at Ponta da Madeira after liquefaction onboard**

MV Harita

The Panamanian registered [74] bulk carrier vessel sank on the evening 17th of January off Cape Bolinao while carrying 47450 mt nickel ore from Indonesia bound for China. Officially, the vessel sank after suffering engine failure, and heavy rolling in rough weather, as its nickel ore cargo was liquefied, shifted and consequently the vessel capsized. Although ten crew members were rescued, 15 lives were lost.

3.2.4 Accidents Analysis

- Cargo liquefaction impacts small size ships, notably Handymax and Handysize vessels.
- Presumably the necessary energy that should be imparted on a vessel leading to liquefaction is less in small size ships than in larger vessels. In contrast, large size ships like Capesizes cannot berth in many ports of Indonesia due to constraints in draught.
- 3 casualties attributed to this phenomenon two years ago **within 39 days** were Handymax vessels. All ships were carrying nickel ore from Indonesia. 44 lives were lost. Approximately 140,000 MT of nickel ore were poured into the sea. Limited sea pollution due to oil spills.
- Apart from one accident (Nasco Diamond), the prevailing weather conditions were severe, i.e. rough seas.
- A detailed report of the Padang Hawk shipwreck showed that cargo liquefaction was severe in the forward cargo holds. However, in number 5 hold, the cargo retained the form in which it was loaded.
- The majority of the ships capsized after facing stability problems, rather than structural failure.

3.2.5 First specially constructed vessel

In October 2012 the Japanese classification society NK announced [67] that the world's first specialized vessel for the transport of nickel ore has been built. The vessel, named the Jules Garnier II, was built by Naikai Zosen Corporation and delivered to Japanese shipping major JX Shipping Co. Ltd, and is the first vessel in the world to be recognized as a Specially Constructed Cargo Ship for the carriage of Nickel Ore in accordance with the IMO's IMSBC Code.

Based on extensive research, ClassNK developed the world's first hull structure and stability requirements for building such "Specially Constructed Cargo Vessels" in 2011, and released them for use by the maritime industry as part of its Guidelines for the Safe Carriage of Nickel Ore in March 2012. These requirements have since been approved by the government of Panama and Japan for use in vessels flagged with their administrations. They have further earned the recognition of INTERCARGO as well as the wider maritime industry, and ClassNK was presented with the "Safety Award" at the Lloyd's List Global Awards in September 2012 for its contribution to the safe transportation of nickel ore.

***Figure 3.2.5.1*: The first specially constructed bulk carrier vessel Jules Garnier II**

The 27,200 dwt Jules Garnier II is the first vessel in the world to apply ClassNK's new requirements in its construction and makes use longitudinal bulkheads in its cargo holds to ensure stability and structural strength even when liquefied nickel ore cargoes are loaded. The ship's design earned the approval of the Panamanian government in September 2012, and with its completion in the same month, is the first and currently only vessel to be certified as safe to carry liquefied nickel ore cargoes in line with the IMSBC code. The vessel is also the first to earn ClassNK's new SCCS notation for safe carriage of nickel ore in recognition of its special construction.

3.3 Legislative Scheme

3.3.1 Introduction

Bulk carriers were developed in the 1950s to carry large quantities of non-packed commodities such as grains, coal and iron ore. Since mid-60s, IMO and Class have established several regulations and rules because during this period the maritime profession realised the significance of the cargo liquefaction problem. Initially, regulations were non-mandatory, including recommendations to ship operators, flag authorities and shipmasters on various procedures that should be adopted for the shipment of different types of bulk cargoes. The aim was to bring to the attention of those concerned an internationally-accepted method of dealing with the hazards to safety which may be encountered when carrying cargo in bulk. These regulations constituted the International Code of Safe Practice for Solid Bulk Cargoes (BC Code) and were the core of the subsequent International Maritime Solid Bulk Cargo Code (IMSBC Code) that was adopted by the Maritime Safety Committee (MSC), 85th session in 2008 [54].

IMSBC Code came into force on 1st January 2011 and in contrast to its predecessor BC Code it is mandatory. The reason is that in recent years a rise in accidents has taken place due to lack of awareness in the transport of some unprocessed cargoes such as nickel ore and iron ore fines that may liquefy. Its purpose was to provide information to Governments, shippers, masters, etc., on the dangers associated with the shipment of certain types of cargo and instructions on the appropriate procedures to be adopted.

Some decades ago mineral concentrates were seen as the most likely to liquefy, but because of the establishment of testing, sampling procedures and certification requirements these accidents have been substantially reduced.

3.3.2 Legislative History

A spate of losses in the 1960s led to the adoption of the Code of Safe Practice for Solid Bulk Cargoes Code (BC Code) in 1965 [54]. The regulations were *recommendatory* and have been updated at regular intervals since then, e.g. Resolution MSC.193(79).

The Code highlights the dangers associated with the shipment of certain types of bulk cargoes. Additionally, it gives guidance on various procedures that should be adopted. It lists typical products, which are shipped in bulk, giving at the same time valuable advice on their properties and how they should be handled. Finally, as the nature of the materials is known, it describes various test procedures which should be employed to determine the characteristic cargo properties.

A number of general precautions are included in the IMSBC. The Code is putting emphasis on the fact that the bulk cargoes should be properly stowed and distributed during voyage with the aim of safeguarding against loss of stability and structural strength.

3.3.2.1 BLU Code

BLU Code [54] is the outcome of the continuing loss of ships carrying solid bulk cargoes during the 90s. At times, these ships were lost without leaving any trace, and obviously killing many crew members. IMO recognised that a number of accidents have occurred as a result of improper loading and unloading of bulk carriers and as a result the Sub-Committee on Dangerous Goods, Solid Cargoes and Containers (DSC) at its first session (February 1996) developed a draft code of practice for the safe loading and unloading of bulk carriers, with the aim of preventing such accidents.
The resulting Code of Practice for the Safe Loading and Unloading of Bulk Carriers (BLU Code) was approved by the MSC at its 68th session (June 1997) and adopted by the Assembly at its 20th session (November 1997) by resolution A.862(20).
The BLU Code, which provides guidance to masters of bulk carriers, terminal operators and other parties concerned with the safe handling, loading and unloading of solid bulk cargoes, is also linked to regulation VI/7 of the 1974 SOLAS Convention, as amended by resolution MSC.47(66)

3.3.2.2 Chapter XII-Additional Safety Measures for Bulk Carriers

In November 1997 IMO adopted new regulations in SOLAS containing specific safety requirements for bulk carriers, Chapter XII - *Additional Safety Measures for Bulk Carriers,* which came into force on 1 July 1999 [54].

The regulations state that all new bulk carriers 150 metres or more in length, which were built after 1 July 1999 and carrying cargoes with a density of 1,000 kg/m^3 and above should have sufficient strength to withstand flooding of any one cargo hold, taking into account dynamic effects resulting from the presence of water in the hold and taking into account the recommendations adopted by IMO.

For existing ships carrying bulk cargoes with a density of 1,780 kg/m^3 and above, the transverse watertight bulkhead between the two foremost cargo holds and the double bottom of the foremost cargo hold should have sufficient strength to withstand flooding and the related dynamic effects in the foremost cargo hold.

Heavy cargoes, i.e. with a density of 1,780 kg/m^3 and above, include iron ore, pig iron, steel, bauxite and cement [45]. Lighter cargoes, but with a density of more than 1,000 kg/m^3, include grains such as wheat and rice, and timber.

Following the 1998 publication of the report into the sinking of the bulk carrier Derbyshire, the Maritime Safety Committee (MSC) initiated a further review of bulk carrier safety, involving the use of Formal Safety Assessment (FSA) studies to help assess what further changes in regulations might be needed.

In December 2002, at its 76th session, the MSC adopted amendments to SOLAS chapter XII and the 1988 Load Lines Protocol and also agreed to a number of recommendations to further improve bulk carrier safety. Those established the fitting of high level alarms and level monitoring systems on all bulk carriers, in order to detect water ingress.

The MSC at its 79th session in December 2004 adopted a new text for SOLAS chapter XII (Additional safety measures for bulk carriers), incorporating revisions to some regulations and new requirements relating to double-side skin bulk carriers. The amendments entered into force on 1 July 2006.

The amendments include the addition of a new regulation on restrictions from sailing with any hold empty and requirements for double-side skin construction as an optional alternative to single-side skin construction. The option of double-side skin construction will apply to new bulk carriers of 150 m in length and over, carrying solid bulk cargoes having a density of 1,000 kg/m^3 and above.

The MSC also adopted mandatory standards and criteria for side structures of bulk carriers of single-side skin construction and standards for owners' inspections and maintenance of bulk carrier hatch covers.

3.3.2.3 International Solid Bulk Cargo Code (IMSBC Code)

A factor that exacerbates the cargo liquefaction problem is that in a few underdeveloped countries, which export unprocessed ores, no infrastructure and sophisticated test methods are implemented. These countries are for example Philippines and Indonesia the humid climate of which makes the moisture content (MC) of the cargo high. More worrying is the fact that his happens also with developing countries, for example in Brazil. The moisture content is verified from previous test methods that as regards the cargo properties are the most important factor of causing liquefaction. As the MC increases the possibility of liquefaction is high whilst below a certain level no liquefaction will occur.

IMO has adopted three laboratory test methods for determining the lowest moisture content at which liquefaction can occur and this is defined as the Flow Moisture Point (FMP). These methods are the Flow Table Test, which is the most widely used method, the Penetration Test and the Proctor/Fagerberg Test. The latter is rarely used up to now. The MC of a transported cargo should be 90% of FMP and this corresponds to the Transportable Moisture Limit (TML). It is noteworthy that the basic principle and intention of these methods is to simulate the energy input of a cargo during ocean carriage by creating shockwaves.

According to their properties the IMSBC Code lists the bulk cargoes in three large groups:

- **Group A:** consists of cargoes, which may liquefy if shipped at moisture content in excess of their transportable moisture limit.

- **Group B:** consists of cargoes which possess a chemical hazard, which could give rise to a dangerous situation on a ship.

- **Group C:** consists of cargoes which are neither liable to liquefy (Group A) nor possess a chemical hazard (Group B).

Cargoes that may liquefy include cargoes, which contain a certain proportion of fine particles and a certain amount of moisture. They may liquefy if shipped with moisture content in excess of their transportable moisture limit (TML). Those cargoes are classified into Group A and Group A and B cargoes. The present research is focused on the Group A cargoes, particularly on nickel ore and iron ore fines, which are more susceptible to liquefaction.

Every material should have a specific Bulk Cargo Shipping Name (BCSN) according to which it is categorised into one or more of the three groups mentioned above. A BCSN identifies a bulk cargo during transport by sea. When a cargo is listed in the IMSBC Code, the Bulk Cargo Shipping Name of the cargo is identified by capital letters in the individual schedules or in the index. When the cargo is dangerous goods, as defined in the International Maritime Dangerous Goods (IMDG) Code, as defined in the regulation VII/1.1 of the SOLAS Convention, the Proper Shipping Name of the cargo is the Bulk Cargo Shipping Name.

The shipper should provide the master or his representative with appropriate information on the BCSN in advance of loading to enable precautions, which may be necessary for proper stowage and safe carriage of the cargo to be put into effect. Cargo information should be confirmed in writing and by appropriate shipping documents prior to loading. The cargo information shall include additional information in the form of a certificate on the moisture content of the cargo and its transportable moisture limit in the case of a concentrate or other cargo, which may liquefy.

A test to determine the TML of a solid bulk cargo shall be conducted within six months to the date of loading the cargo. Notwithstanding this provision, where the composition

or characteristics of the cargo are variable for any reason, a test to determine the TML shall be conducted again after it is reasonably assumed that such variation has taken place. TML is equal to 90% of Flow Moisture Point (FMP). FMP is the lowest moisture content at which liquefaction can occur.
Sampling and testing for moisture content shall be conducted as near as practicable to the time of loading [46]. If there has been significant rain or snow between the time of testing and loading, check tests shall be conducted to ensure that the moisture content of the cargo is still less than its TML. *The interval between sampling/testing and loading should never be more than seven days.*

Test Methods [39]

Flow Table Test

This test method is the most widely used to date. It is appropriate for mineral concentrates or other fine material with a maximum grain size of 1 mm. It is applied to cargo materials, which hold a maximum grain size of 7 mm. In addition, it cannot give representative measurements for cargoes more that the above mentioned diameter, or with a coarser form. However, due to lack of a new established test method it is normally used for testing iron ore and nickel ore samples.

The necessary apparatus is described below:

Apparatus

- Standard Flow Table of 700 mm base diameter (ASTM Designation 230-68)
- Flow Table Mounting
- Mould of 100 mm base diameter
- Tamper
- Scale
- Suitable sample container
- Mixing bowl approximately 30 cm diameter
- Drying oven with controlled temperature up to 110 °C

***Figure 3.3.1*: Flow Table Testing of nickel ore. Filling the mould and tamping procedure**

Preparation of the test samples

With a view to carrying out the Flow table test, as a first step we have to prepare three different samples. Those samples named (A), (B) and (C) are removed from the mixing bowl according to a specific procedure, as follows. About one fifth of the sample (A) should be weighed and placed in the drying oven to determine the moisture content of the sample as received. Two further samples, each of about two fifths of the gross weight, should then be taken, one (B) for the preliminary FMP test and the other (C) for the main FMP determination.

Procedure

The quantity of material required for a flow moisture test varies according to the specific gravity of the material to be tested. It ranges from approximately 2 kg for coal to 3 kg for mineral concentrates. It should be collected as a representative sample of the cargo being shipped. Experience has shown that more accurate test results will be obtained by ensuring that the moisture content of the test sample is increased rather than decreased towards the FMP.

Consequently, it is recommended that a preliminary flow moisture test should be conducted, to indicate the condition of the test sample, i.e., the quantity of water and the rate at which it is to be added or whether the sample should be air-dried to reduce its moisture content before commencing the main flow moisture test.

Immediately after removing the mould, the flow table is raised and dropped up to 50 times through a height of 12.5 mm at a rate of 25 times per minute. If the material is below the FMP, it usually crumbles.

At this stage, the flow table is stopped and the material returned to the mixing bowl, where 5-10 m*l* of water, or possibly more, is sprinkled over the surface and thoroughly mixed into the material. Then, the mould is filled again and the flow table is operated for up to 50 drops. If a flow state is not developed, the process is repeated with further additions of water until a flow state has been reached.

The impacting action of the flow table causes the grains to rearrange themselves through a process called compaction. As a result, the fixed volume of moisture contained in the material at any given level, increases as a percentage of the total volume. A flow state is considered to have been reached when the moisture content and compaction of the sample produce a level of saturation such that plastic deformation occurs. At this stage, the moulded sides of the sample may start deforming.

With repeated action of the flow table, the sample continues to slump and to flow outwards. In certain materials, cracks may also develop on the top surface. However, cracking with the appearance of free moisture is not a safe indication of development of a flow state. In most cases, measurement of the deformation is helpful in deciding whether or not plastic flow has occurred. A template which, for example, will indicate an increase in diameter of up to 3 mm in any part of the cone is a useful guide for this purpose. Some additional observations may be useful. For example, when the increasing moisture content is approaching the FMP, the sample cone begins to show a tendency to stick to the mould. Further, when the sample is pushed off the table, the sample may leave tracks of moisture on the table. If such stripes are seen, the moisture content may be above the FMP. On the other hand, the absence of tracks is not necessarily an indication of being below the FMP.

A useful step that should be taken for judging the FMP is to measure the diameter of the cone, at the base or at half height. By addition of water at a portion of 0.4% to 0.5% and applying 25 drops of the flow table, the first diameter will increase between 1 and 5 mm and after an additional increment of water the base diameter will have expanded by between 5 and 10 mm.

As the preliminary FMP test is done, the sample (C) which is for the main test is adjusted to a moisture content of about 1% to 2% below the flow moisture point.

Main Flow moisture test

When a flow state has been reached in the preliminary test, the moisture content of sample (C) is adjusted to about 1% to 2% less than the last value, which did not cause flow in the preliminary test. The reason for this is to avoid starting the main test too close to the FMP and then having to waste time air-drying it and starting again.

The final test is then carried out on this adjusted sample in the same manner as for the preliminary test, but in this case with the addition of water in increments of no more than 0.5% of the mass of the test material. After each stage, the whole moulded sample should be placed in a container, weighed immediately and retained for moisture determination if required. This will be necessary if the sample flowed or if the next, slightly wetter, sample flows. If not required it may be returned to the mixing bowl.

When a flow state has been reached, the moisture content should be determined on two samples, one with moisture content just above the FMP and the other with moisture content just below the FMP. The difference between the two values should then be 0.5% or less, and the FMP is taken as the mean of these two values.

Penetration Test

The penetration test constitutes a procedure whereby a material in a cylindrical vessel is vibrated. An indication that the calculated moisture content represents the FMP relies on the basis of the penetration depth of an indicator. Compared with the Flow table test, its predominant advantage is that it is appropriate for materials more than 7mm and up to 25 mm. Therefore, this method is broadly used for mineral concentrates, similar materials, and coals up to a top size of 25 mm.

The sample placed in a cylindrical vessel, is subjected to a six minute vertical vibration of 2*g rms* + 10%, where g is the acceleration of gravity. *When the penetration depth of a bit put on the surface exceeds 50 mm,* it is judged that the sample contains moisture greater than the flow moisture point.

Apparatus

- A vibrating table
- A cylindrical box
- A penetration bit
- A bit holder
- A tamper
- A mixing bowl

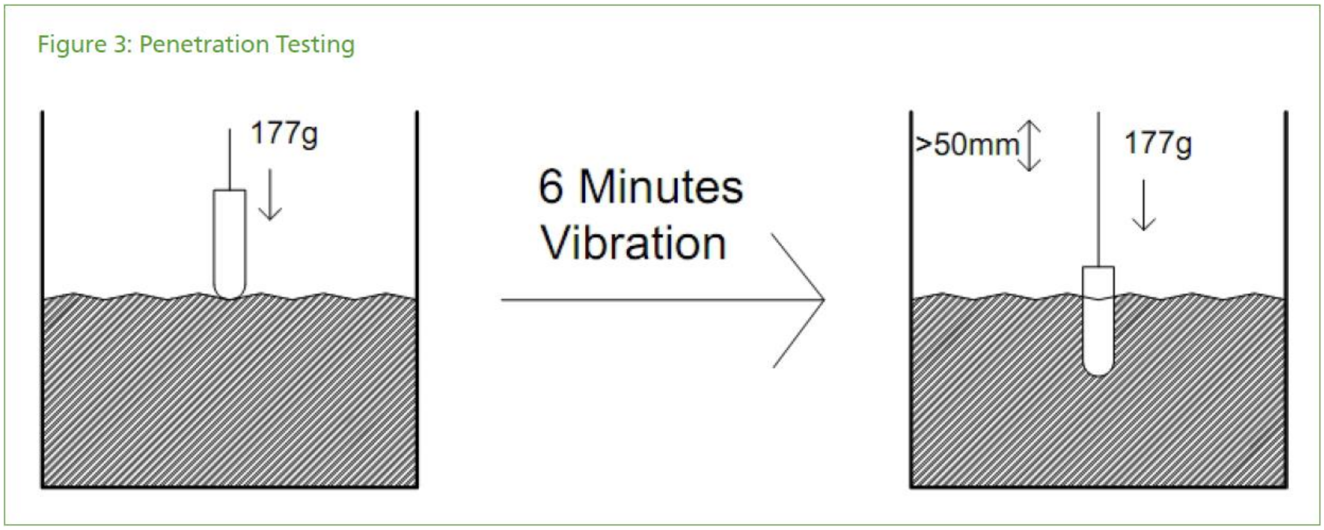


***Figure 3.3.2 [4]*: Penetration Testing**

Preparation of the test sample

As in the Flow table test, three samples are prepared for the purpose of conducting a preliminary and a main penetration test. The amount of the sample required is approximately six times or more the capacity of the selected cylindrical vessel. There are two sizes of vessels. The small size is used for a maximum particle size of 10 mm and the large size that can test materials of a grain size up to 25 mm. The inner diameters of the containers are 146 mm and 194 mm, respectively. The amount of representative test sample with which each container is filled should be approximately 1,700 cm^3 for the small container, and 4,700 cm^3 for the large container.

The sample is mixed well and divided into three approximately equal parts, namely (A), (B) and (C). Sample (A) should be weighed and placed in the drying oven to determine the moisture content of the sample as received. Samples (B) and (C) are used for the preliminary test and the main test, respectively.

The preliminary flow moisture test

Regarding the particles size, a suitable box is filled with sample (B) in four different intervals and tamped after the addition of each layer using a specified tamper. The latter applies evenly the pressure over the whole surface area of the material until a uniformly flat surface is obtained. The penetration bit is placed on the surface of the material through the holder. Then, the vibrator operates at a frequency of 50 Hz or 60 Hz with an acceleration of 2*g* rms + 10% for 6 minutes. After this period the depth of the bit is checked. If it is less than 50 mm, it is judged that liquefaction did not take place. As a consequence, the material is sprinkled with an increment of water of not more than 1% of the mass of the material in the bowl and mixed well. The procedure is repeated till the depth of the penetration in the first attempt exceeds 50 mm.

The main flow moisture test

On the basis of the preliminary test, the main test should be carried out to determine the flow moisture point more accurately. The moisture content of the sub-sample (C) is adjusted to the last value of the preliminary test, which did not lead to flow. The procedure followed is similar to Flow table method and thus the addition of water in increments should not be more than 0.5% of the mass of the test material. When a flow state has been reached, the moisture content should be determined on two samples, one with moisture content just above the FMP and the other with moisture content just below the FMP. The difference between the two values should then be 0.5% or less, and the FMP is taken as the mean of these two values.

Proctor/Fagerberg Test

This test method is rarely used to date. It is suitable for fine as well as relatively coarse-grained ore concentrates or similar materials up to a top size of 5 mm. This method should not be used for coal or other porous materials. The transportable moisture limit (TML) of a cargo is taken as equal to the critical moisture content at 70% degree of saturation according to the Proctor/Fagerberg method test.

Apparatus

1. A cylindrical iron mould with a compaction cylinder and a compaction tool, i.e. the compaction hammer guided by a pipe open at its lower end.
2. Scales and weights and suitable sample containers.
3. A drying oven with a controlled temperature interval from 100 ^{0}C to maximum 105 ^{0}C. This oven should be without air circulation.
4. A suitable mixer. Care should be taken to ensure that the use of the mixer does not reduce the particle size or consistency of the test material.
5. Equipment to determine the density of the solid material.

Figure 3.3.3: **Proctor/Fagerberg test apparatus**

Procedure

It is based on a completely different principle from the other two test methods in that testing does not involve inducing actual liquefaction in a test sample and then determining the moisture content at which occurs. Instead, it involves first oven-drying the entire sample to zero moisture, and then adding water again to produce separate samples with each of between five and ten-predetermined target moisture contents. At each of these moisture contents, the sample is compacted with a standardized tamping procedure in a one litre cylindrical vessel, and the bulk density of the compacted samples is then measured.

From the moisture content and the bulk density, it is possible to calculate the degree of saturation of the sample, i.e. the percentage of the void spaces between the solid particles occupied by water as opposed to air. The TML is then interpolated from these results as the moisture content at which a degree of saturation of 70% is reached, i.e. 70% of the gaps between the solid mineral particles are occupied by water.

The method was developed originally in Sweden, and until recently was rarely used by shippers outside Scandinavia. Within the past year, some shippers of sinter feed elsewhere have started offering declarations based on Proctor/Fagerberg testing.

A complementary test procedure for determining the possibility of liquefaction

The Master should be able to carry out the CAN test if the cargo’s MC is ambiguous. The procedure is given below:

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

Main points of current legislation

- Cargoes of Group A may liquefy if transported in moisture content in excess of the Transportable Moisture Limit (TML).
- Cargoes which may liquefy, i.e. MC>TML, can be transferred in specially constructed or in specially fitted cargo ships.
- The Shipper must provide the Master the Bulk Cargo Shipping Name (BCSN) of the cargo according to which the cargo is included in one of the three Groups. If the cargo is classed in Group A or in Group A and B the Master should also provide the TML of the cargo.
- Flow Table Test is the most widespread method. Penetration Testing uses more complex equipment, but there is an objective verification of TML.
- The TML obtained by the Proctor/Fagerberg Test is larger than the TML for the penetration test
- TML is equal to 90% of Flow Moisture Point (FMP).
- FMP is the lowest moisture content at which liquefaction can occur.
- The number of sub-samples and sample size are given by the competent authority or determined, in accordance with the weight of the consignment.
- The interval between sampling, testing and loading the unprocessed ores shall never be more than seven days.
- Trimming procedures are required for reducing the likelihood of cargo shifting and minimizing the air entering the cargo.

3.3.3 Lack of Legislation

Although cargo liquefaction remains a serious problem that strikes the shipping industry and accidents continue to take place frequently, affecting actually bulk carrier vessels that transport various sorts of cargoes, there are still many legislative gaps. The latter derive both from poor knowledge of the properties of some materials and from bureaucracy problems. Specifically, many regulations come into force and become mandatory after many years of their adoption [2]. For instance, draft amendments (02-13) to the IMSBC Code, prepared by the Editorial and Technical Group 18 (E&T 18), will be submitted directly to MSC 92, with a view to adoption for coming into effect on a voluntary basis from 1 January 2014 and on a mandatory basis from 1 January 2015.

Notably, last September the Sub-Committee agreed to the draft amendment 02-13 [54] to the International Maritime Solid Bulk Cargoes (IMSBC) Code, including a nickel ore schedule, and relevant draft guidelines. However, the draft texts will be firstly considered by the (E&T), with a view to be finalized and submitted to the Maritime Safety Committee MSC. If every procedure goes in line with the schedule the draft amendment will be adopted in June 2013.

With regard to iron ore fines, the Sub-Committee discussed the report of a correspondence group, providing a new individual schedule for iron ore fines. However, it was felt that it was important to await the outcome of significant research being carried out in Australia and Brazil on carriage of iron fines and for this research to provide input into the final schedule.

The correspondence group was therefore instructed to finalize the draft schedule and test methods for iron ore fines, for discussion at the next DSC session, **with a view to incorporating the iron ore fines schedule in the next set of amendments (03-15) to the IMSBC Code** [54].

As can be noted above, amendments to the IMSBC Code containing provisions on measures on cargo liquefaction will not enter into force until 1 January 2015, giving thus enough time for more accidents to take place!

Notwithstanding the numerous revisions made by IMO regarding the old BC Code, it has not established until now a specific BCSN for all cargoes that are shipped. Thus, there are some ambiguities in categorizing those cargoes and consequently handling them for safe transportation. Nickel ore and iron ore fines do not hold a specific BCSN and they are not listed in the IMSBC Code. However, a tri-party agreement between the competent authorities of the ports of loading and unloading and the Flag State is compulsory for the transportation of those cargoes. In the absence of such agreement they should be transported as Group A cargoes.

Moreover, some iron ore products are classified either into Group A, i.e. they can liquefy if shipped at moisture content in excess of TML, or into Group C where there is zero possibility of liquefaction according to IMSBC Code.

Material	Group	References
IRON CONCENTRATE	A	See Mineral Concentrates schedule
IRON CONCENTRATE (pellet feed)	A	See Mineral Concentrates schedule
IRON CONCENTRATE (sinter feed)	A	See Mineral Concentrates schedule
Iron disulphide	C	See PYRITE
IRON ORE	C	
Iron ore (concentrate, pellet feed, sinter feed)	A	see IRON CONCENTRATE (pellet feed or sinter feed)
IRON ORE PELLETS	C	
Mineral Concentrates	A	

***Figure 3.3.4*: Iron ore is addressed in Appendix 1 as Group A and in Appendix 4 as Group C**

Furthermore, some cargoes are listed as Group C, but are sometimes shipped with much finer size distributions than specified in the Code, so that samples show flow behaviour on laboratory testing. This includes pyrites, chrome concentrate and bauxite. The latter as mentioned before, is recently responsible for various incidents.

Evidence has shown that chrome ore cargoes can undergo liquefaction and pose a serious hazard to bulker vessels and their crew [46]. Scientists are warning that chromite or chrome ore also poses a threat of liquefaction, and want IMO to reclassify it as a group A cargo – a cargo prone to liquefaction – under the International Maritime Solid Bulk Cargoes (IMSBC) Code.

Under the IMSBC Code, chromite and chrome ore are listed as a Group C cargo, i.e. one that is neither liable to liquefy (Group A) nor to possess chemical hazards (Group B). Therefore, shippers take advantage of this legislation gap and do not carry out any testing procedure regarding the moisture content of chrome ore cargoes. At the same time they do not provide the master with appropriate information on moisture content or TML, which are required for all Group A cargoes.

Although not as widespread as some minerals, chrome ore is regularly shipped from India and Turkey, and large volumes of chrome concentrate with very fine average particle sizes are shipped from open stockpiles in South Africa. Problems are unlikely to arise when chrome is shipped in lump ore form or large particle sizes. However, some grades of chrome concentrate are shipped as very fine sand, with average particle sizes of around 0.3mm, and these are likely to exhibit flow properties unless shipped dry.

ANGLE OF REPOSE	BULK DENSITY (kg/m^3)	STOWAGE FACTOR (m^3/t)
Not applicable	1667	0.6
SIZE	**CLASS**	**GROUP**
8 to 25 mm	Not applicable	C

Figure 3.3.5: **Chrome pellets are classified into Group C**

In 2007, a serious chrome-ore-related shipping disaster was narrowly averted off the coast of India when chrome concentrate in a bulker liquefied and smashed through a wooden bulkhead at the forward end of the cargo hold, causing the vessel to lurch forward.

Additionally, titanomagnetite [75], a material that is at risk of liquefaction, has not entered IMSBC Code because in the last two sessions DSC 16 & DSC 17 there was lack of consensus among the members in which group to categorize the cargo. Other cargoes such as coal tar pitch, sludge as raw material for cement, chemical gypsum, coarse iron and steel slag, used casting sand, scale generated in steel making, etc., are characterized liquefiable and at the same time classified as Group A cargoes.

Operational hazards

A variety of objective operational hazards are also reported due to lack of legislation. The shippers take advantage of legislative gaps and try all means to load the cargo. For instance, sometimes cargoes are described to avoid application of the Code provisions. The most repeated misinformation, including obvious intent, is the wrong BCSN of the cargo, which categorises the material into Group C rather than into Group A [3]. As is also mentioned above, in this way, the shipper is not obliged to provide a certificate including sampling and testing procedures to verify that the moisture content of the cargo is under the TML.

On the other hand, although some cargoes might be addressed as Group-A cargo, the certificates and the declarations are not provided by the shippers. This is due to commercial pressure put on masters so as not to delay shipment and to carry cargoes without the provision of accurate certificates [2]. This pressure is generated also from restrictive clauses between the charter parties in the contract of carriage.

Albeit the cargo could be collected from different stockpiles, only one certificate is required while there is more than one distinct source of cargo.

Exposure of stockpiles and barges

Remote mining areas, stockpiles in open areas, local weather seasons, lack of independent laboratories and equipment, are all part of the problem which ultimately comes down to attaining a reliable FMP and TML.

Once mined, the material is often stored outside in the open air rather than in warehouses and is exposed to the elements unless large scale covers are employed [60]. The risk of rain and ensuing water contamination of the raw material can be high and the tolerances of such materials before they change states are low. The margin of safety is thin.

***Figure* 3.3.6 [12]: Iron ore mine**

Most mines are situated in remote locations and as a result loading and port facilities are therefore non-existent or very limited and loading equipment and methods rudimentary. Cargo is stock-piled, uncovered, on the beach and accordingly totally exposed to the prevailing weather conditions.

For instance, the traditional practice has been to ship nickel ore cargoes in the dry season, between February and May/June, when rainfall in the past years was negligible. However, in recent years anecdotal evidence suggests that the distinction between the wet and dry seasons has been substantially eroded, and heavy rainfall is now experienced during the dry season.

The mines are not easily accessible due to their remoteness, and it is therefore difficult for independent surveyors acting for the vessel to attend the mines and take samples of the cargo to be loaded.

Moreover, there are few and sometimes no independent laboratories in Indonesia and the Philippines where a great amount of raw ore products are mined [60]. The mines usually have their own obsolete laboratories and it is often not possible to determine whether the correct testing equipment is available and in a satisfactory condition or whether they are following the procedures laid down under the IMSBC Code when testing cargo samples. Such audits, which took place in the past indicated that both the testing procedures and the followed processes are not appropriate.

Cargo is often loaded on to the ship from barges, where the cargo is unprotected from any precipitation and water ingress due to the waves. In this way, the moisture content of the cargo may have changed dramatically from the last time that was checked.

Figure 3.3.7 [12]**: A barge transporting nickel ore slammed by waves**

Shortcomings of current testing methods

The adequacy of the current test methods for determining the TML is dubious. Each of the currently available methods has inherent limitations when applied to iron ore products. The Flow Table is generally suitable for mineral concentrates or other fine material with a maximum grain size of 1 mm [43]. However, more than 70% of seaborne traded Brazilian iron ores have top size greater than 7 mm.

In addition, as regards the penetration test, when the depth of the penetration bit is greater than 50 mm, it is judged that liquefaction took place. On the other hand, there is no theoretical or experimental information to justify the value adopted for this figure. A new vibration penetration test is proposed to IMO and its capacity will be thoroughly described in the following pages.

Moreover, the Proctor/Fagerberg test is a method for fine and relatively coarse-grained ore concentrates or similar materials up to a top size of 5 mm. In contrast, more than 70% of seaborne traded Brazilian iron ores have top size greater than 7 mm [2]. There is also a particular concern about using the Proctor/Fagerberg method for cargoes that contain clay-like constituents or that otherwise interact or react with water in anything other than a purely physical form, e.g. by forming hydrates. This is because it is a part of this test that the samples must be oven-dried prior to the start of the testing and new water is then added during the test itself. In this way, because of the likelihood of incomplete rehydration, the test is unsuitable for all nickel ore, and for many nickel ore fines.

We should also highlight the fact that moisture certification is too old to be representative, as the most recent period of sampling and testing is seven days. During this interval, due to the rain, the exposure of the material as placed in the stockpiles and the open transportation in barges the moisture content will have possibly increased. The Master is able to carry out the CAN test if he doubts the TML of the cargo that is shipped, but this test does not take into account the 10% margin of TML.

Wet base formation

Another characteristic of liquefaction, which requires a careful examination is the wet base formation [20]. Some cargoes are subject to downwards water migration during the voyage, by a process of natural drainage, which may lead to the formation of a dangerous wet base even if the average moisture content at the time of loading is less than the TML. As a result, liquefaction occurs and the safety of the ship is uncertain. Specifically, wet base cargo means that even if the cargo has a low inherent moisture content at the time of loading, moisture can gradually settle downwards over the course of a voyage, forming a dangerous wet base on which the drier surface cargo may slide, with the risk of causing a ship to list. Wet base layers are a greater risk if the cargo has not been trimmed in the hold properly, with the result that moisture settles unevenly. IMO has not established yet any test method to check the propensity of the cargo to forming a wet base.

3.3.4 Specially Constructed or Fitted Cargo Ships

According to IMSBC Code, cargoes having moisture content in excess of the TML can be carried in specially constructed cargo ships (SCCS) or in specially fitted cargo ships. Specially constructed cargo ships should have permanent structural boundaries, so arranged as to confine any shift of cargo to an acceptable limit. They satisfy the stability and the hull strength criteria. The ship concerned should carry evidence of approval by the Administration.

Specially fitted cargo ships should be fitted with specially designed portable divisions to confine any shift of cargo to an acceptable limit. The design and positioning of such special arrangements should adequately provide not only the restraint of the immense forces generated by the flow movement of high-density bulk cargoes, but also for the need to reduce to an acceptable safe level the potential heeling movements arising out of a transverse cargo flow across the cargo space. Divisions provided to meet these requirements shall not be constructed of wood.

According to the Code [39], cargo sampling and testing is not necessary for specially designed vessels as safe transportation is ensured with cargo liquefied inside the cargo holds. However, IMO has not established up to now any precise design criteria on how a specially constructed of fitted bulk carrier should be built.

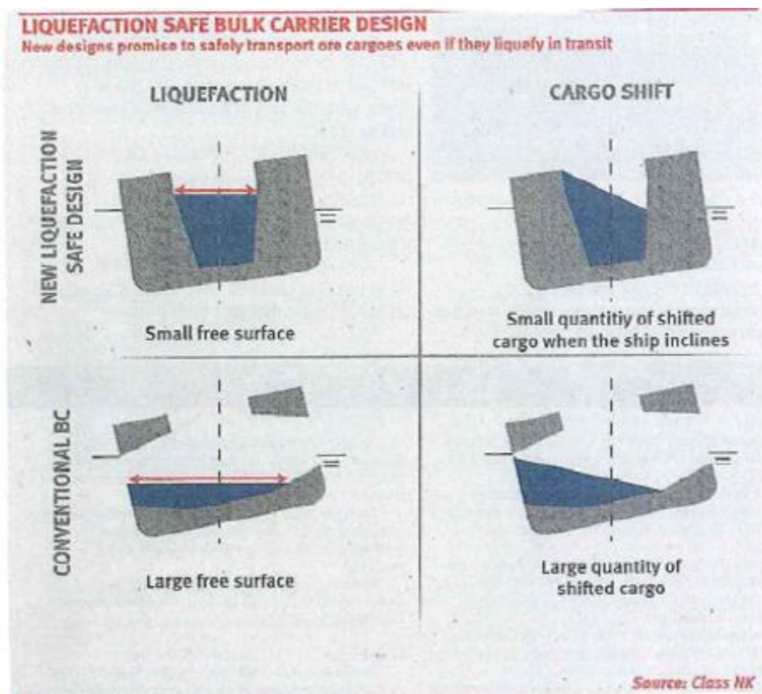


Figure 3.3.8: **[12] Midship sections of an average bulk carrier and a SCCS**

3.3.5 Recent Developments

The Sub-Committee at its seventeenth session last September [73], submitted that the competent authority should operate independently from the shipper. The shipper should provide certificate to ship, issued by an entity recognised by the Competent Authority of the port of loading. The most significant difference from the previous legislative scheme is that procedures for sampling, testing and controlling moisture content being established by shipper, need the competent authority's approval and their implementation should be checked by that authority at the port of loading. The Competent Authority at the port of loading is to approve and check the implementation of the shipper's procedures for ensuring that the moisture content of the cargo is less than the Transportable Moisture Limit (TML). Additionally, notwithstanding this provision, now the shipper should allow the vessel's nominated representative to inspect, sample and test the cargo stockpiles.

As referred above cargoes are shipped on from barges. Fortunately, in the last IMO sessions it was defined that if the cargo is to be loaded from barges, the shipper's procedures should include measures to protect the material from precipitation and water ingress.

After extensive discussion on the above submissions and notwithstanding the comprehensive research undertaken by Brazil [73], the Sub-Committee decided not to finalise a draft schedule for iron ore fines at this session in order to await the outcome of the associated Australian research, which is expected to be completed prior to DSC 18, and other related research, with a view to finalising the draft schedule and appropriate test methods at the next session, for incorporation in the next set of amendments (03-15) to the IMSBC Code.

Moreover, the Sub-Committee invited all members and international organisations to make available to the Organization detailed technical information on incidents or casualties resulting from liquefaction.

It should also be mentioned that IMO examines the capacity of the existing test methods for determining the TML. Thus, new amendments may be included in Appendix 2 by the end of May.

An alternative to the recommended testing procedures given in Appendix 2 of the IMSBC Code, the Vibration Table with Penetration Bit test (VTPB test) [58] has also been presented to the IMO DSC for approval. The VTPB Test is reportedly suitable for nickel ores including large elements of less than or equal to 30 mm in diameter, and is particularly relevant to nickel ore cargoes extracted from mines in New Caledonia. However, the new test has been developed for the New Caledonia nickel ores and their specific granulometry and may not be appropriate for other nickel ores.

It is also notable that the dynamic requirements applied during this VTPB test are compatible with the situations usually encountered on very rough seas. They can be compared with those observed in the ship's bow and close to maximum ship design requirements.

Brazilian research on iron ore fines [47]

Brazil carries out a research programme to assess safe carriage condition of Brazilian iron ore fines in bulk. The research includes on board monitoring, model scale testing and laboratory analysis. The objectives of the research are as follows:

- Provide a greater understanding of the liquefaction problem.
- Assess the suitability and applicability of the existing three test methodologies to determine TML.
- Develop a new approach in order to provide more comprehensive determination of the liquefaction potential of iron ore fines.

It is important to emphasize that the Brazilian research showed that all samples of Brazilian iron ore fines tested could be safely transported, having a level of risk not greater than other cargoes categorized as Group C.

Additionally, although moisture content is noted as a very important parameter of liquefaction, it is not the sole parameter. Variables such as permeability, degree of saturation, bulk density and particle size distribution play an important role.

On-board cargo monitoring

The on-board cargo monitoring was implemented to provide both a visual and numerical record of the material behaviour in relation to potential deformation, density variations and relative movement during loading, seaborne voyages and discharge operations [47].

Two sister ship Capesize bulk carriers were selected to undertake the cargo monitoring activities. This is because Capesizes represent the majority of vessels that are utilised to transport iron ore fines globally and according to the researchers potentially represent the optimum case with regard to vessel stability within the context of the research programme.

Comparing vessel motions and relative wave height during the voyages, it is determined that commencement pore water pressure increases within the cargo material coinciding with the deteriorating sea state. The pressure dissipates over the remainder of the voyage with a calmer sea state. No further increases in pore water pressure were observed.

Model scale testing

The model scale tests uses data from the full-scale cargo monitoring programme and form a key linkage between the laboratory analysis and the full-scale behaviour of the iron ore fines material. The model accurately replicates the vessels used for the full-scale cargo monitoring research. The test programme comprises pure ship motions, combined ship motions and ship motions derived from sea spectra.

Numerical analysis

Numerical analysis, including finite element modelling, was undertaken to determine the response of iron ore fines cargo in a hold of a bulk carrier subjected to roll motions.

The analysis considered the potential liquefaction of iron ore fines below an assumed saturated zone using a modified version of the fully coupled dynamic effective stress finite element software UWLC.

Considering the constitutive model for the liquefiable iron ore is an elasto-plastic model then the unsaturated ore above the water table is modelled as an elastic material. The stability of the elastic element is evaluated by a local safety factor based on the rigid plastic criteria.

3.3.6 Conclusions & Recommendations

- The laboratory testing has established firm relationships between the moisture content, degree of saturation and void ratio. In turn, the dynamic behaviour of the materials under these conditions has been determined to allow the estimation of safety factors.
- Considering the results of the various testing regimes detailed previously, it is concluded that a more suitable and sufficient test methodology for determining a safe transportable limit for Brazilian iron ore fines can be proposed within the annex to this document.
- Bilge well pumping data was recorded throughout the voyage and confirms a decrease in pore water pressure in the areas adjacent to the bilge wells immediately upon commencement of pumping operations.

3.4 Liquefaction in other engineering disciplines

3.4.1 Introduction

Progress in liquefaction has been pursued in different disciplines of engineering, notably in soil mechanics, offshore engineering and mechanics of materials. The knowledge of these sectors of engineering, where liquefaction problems appeared decades ago, will help us understand and address the "maritime" problem as the phenomenon seems similar in many aspects.

Thereafter, a brief report is introduced on other sections of engineering that face problems attributed to liquefaction. Thus, the main purpose of this review is to correlate cargo liquefaction with liquefaction events in other disciplines and use this information to help us solve the maritime problem. As a result, the importance of the numerical and experimental modelling that has been used up to now will be critically reviewed.

As regards the numerical approach, Finite Element Method is the most widely used method both in soil mechanics and in offshore engineering. As mentioned in the previous chapter, FEM is already used for cargo liquefaction for the purpose of determining the response of iron ore fines cargo in a hold of a bulk carrier subjected to roll motions.

With respect to experimental models, predominantly the Standard Penetration Test and secondarily the Cone Penetration Test are performed to assess the possibility of liquefaction in granular soils. Cyclic mobility plays an important role in liquefaction and this is the main reason why those test methods are used.

In the next few sections a complete overview of the nature of liquefaction is described in these areas.

3.4.2 Soil Mechanics

Soil liquefaction describes a phenomenon whereby a saturated soil loses strength and stiffness in response to an applied stress, usually earthquake shaking or other sudden change in stress condition, causing it to behave as a liquid. The drastic difference between liquefied and non-liquefied soils can be attributed to the loss of grain contacts of the soil.

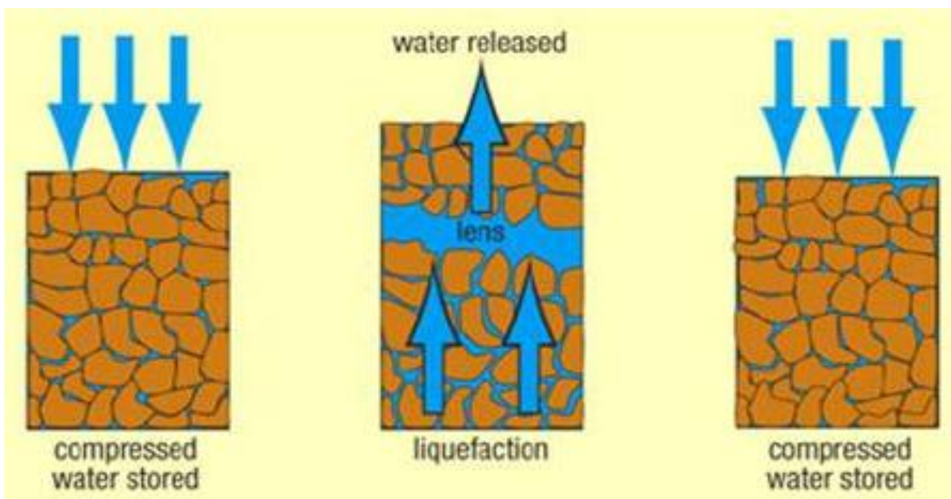


Figure 3.4.1: **Grain contacts are lost due to liquefaction**

During wave loading, e.g. seismic loading, saturated soils tend to decrease in volume, which produces an increase in their pore water pressures and consequently a decrease in shear strength, i.e. reduction in effective stress. Buoyancy causes the total collapse of the soil structure resulting in a "liquefied mass" which does not possess any shear strength or load carrying capacity.

According to Seed [18] four crucial parameters dominate soil liquefaction. These are the soil type, the intensity of ground pressure, the initial confining pressure and the duration of shaking.

Accidents attributed to soil liquefaction

Soil liquefaction is a major cause of damage during earthquakes. Modern engineering treatment of liquefaction related issues evolved initially in the wake of the two devastating earthquakes of 1964. Those took place in 1964 in Niigata of Japan and in Great Alaska. The first has been cited symbolically as the first event in the world where all kinds of modern infrastructure were destroyed by what came to be well known later as soil liquefaction. Seismically-induced soil liquefaction produced spectacular and devastating effects in both of these events, thrusting the issue forcefully to the attention of engineers and researchers.

Figure 3.4.2: **Effects of soil liquefaction after the 2004 Chūetsu earthquake**

Niigata 1964

The Niigata Earthquake [50] resulted in dramatic damage due to liquefaction of the sand deposits in the low-lying areas of Niigata City. It had an intensity of M=7.5. In and around this city, the soils consist of recently reclaimed land and young sedimentary deposits having low density and shallow ground water table. It should be noted that the damaged concrete buildings were built on very shallow foundations or friction piles in loose soil.

Civil engineering structures, which were damaged by the Niigata Earthquake, included port and harbour facilities, water supply systems, railroads, roads, bridges, airport, power facilities and agricultural facilities. The main reason for these failures was ground failure, particularly the liquefaction of the ground in Niigata City which was below sea level as a result of ground subsidence.

Figure 3.4.3: **Buildings sloping during the 1964 Niigata earthquake**

Alaska 1964

The Alaskan earthquake [50] had an intensity of M=8.6. It resulted in approximately 130 deaths and property damage estimated in 300 million dollars. The greatest damage caused by the earthquake resulted from soil slides and from waves generated by those slides that occurred under water. The most spectacular landslide involving about 9.6 million cubic meters of soil took place at the Turnagain Height area of Anchorage, Alaska. The slide extended approximately 1,600 meters and extended inland an average of 280 meters. The Turnagain Height slide was a laterally spreading landslide caused by the combination of dynamic stresses and induced high pore water pressure in layers of soft clay and sands underlying the sliding mass. Within the slide area the original ground surface was completely devastated by displacements that broke up the ground into a complex system of ridges and depression.

Figure 3.4.3: **Displacement and tilting of houses due to soil liquefaction in the Turnagain Height area of Anchorage during the 1964 Alaska Earthquake**

Caucete 1977

On 23 November 1977 [50] another earthquake took place resulting in extensive soil liquefaction. The Caucete earthquake in Argentina had an intensity of M=7.4. It is worth mentioning that no surface faulting was detected and the most notable effect of this earthquake was the thousands of square kilometres area of liquefaction.

Nihonkai-Chubu 1963

The high acceleration levels of Nihonkai-Chubu [50], Japan earthquake which occurred in May 1963 seemed to be responsible for extensive damage of structures caused by liquefaction. Although, the epicentre of this earthquake was located approximately 100 kilometres offshore from Akita City, the seismic disturbance and the tsunami of this earthquake resulted in significant damage to coastal areas along the Japan Sea. The maximum ground acceleration recorded was 0.20g (200 gals) and it has been estimated that in one area the acceleration exceeded 0.30g (300 gals). However, the duration was about 60 seconds, about twice as long as those recorded previously.

Loma Prieta 1989

The Loma Prieta earthquake [51] occurred on October 17, 1989. It had a maximum magnitude of 6.9 and a surface wave magnitude of 7.1. The duration was 15 to 20 seconds. Some homes and buildings in San Francisco's Marina district suffered severe damage. These structures were built on loose, sandy soil, permeated with water. As a result, liquefaction occurred. Much of the displacement was vertical motion typical of reverse or thrust faults.

Luzon 1990

The Luzon earthquake of 1990 caused soil liquefaction in a widespread area that in turn caused crucial damage to various structures. It had an intensity of M=7.8. Almost 2,000 people were killed. The buildings that suffered large settlement and tilting are found to be located near rivers and abandoned river channels.

Kobe 1995

The 1995 Kobe earthquake was one of the most devastating earthquakes ever to hit Japan. It had an intensity of M=6.9 and more than 5,500 were killed. The strong ground motions that led to collapse of the Hanshin Express way also caused severe liquefaction damage to port and wharf facilities as can be seen in the following figure.

Figure 3.4.5: **Extensive damage caused to Hanshin Express way due to soil liquefaction**

Christchurch 2011

The Christchurch earthquake [52] occurred in February 2011 in New Zealand. It had an intensity of M=6.8 and killed almost 200 peoples. Liquefaction has been a feature of this earthquake, seen as tonnes of silt on the roads and sand volcanoes or sand boils on people's lawns. A characteristic that deteriorated the liquefaction effects was that much of Christchurch is built on sandy soil.

Figure 3.4.6: **Soil liquefaction after the Christchurch earthquake**

There are more earthquakes that have given rise to soil liquefaction during the last fifty years. Two significant are the 1995 Hyogoken-Nambu and the recent 2011 Tokyo Bay earthquake.

It is notable that all the above reported earthquakes had a great magnitude and some of them lasted for a long time interval. Thus, those two characteristics may be the key for identifying the parameters of the liquefaction phenomenon.

Assessment of susceptibility

One of the parameters, which trigger soil liquefaction, is the properties of the soil. Some soils are potentially liquefiable, while others are not. As a general rule, soils with 50% or more of their grain size in the range of 0.02mm to 0.2mm are potentially liquefiable when saturated [6].

Sandy soils with few fines are characterized as vulnerable to liquefaction when they are intensively induced by earthquake or other shaking loads. A detailed research on that field shows that for soils with sufficient fines (particles finer than 0.074 mm) to separate the coarser (larger than 0.074 mm) particles, the characteristics of the fines control the potential for cyclically induced liquefaction. This separation of the coarser particles typically occurs as the fines content exceeds about 15% to 35%, with the precise fines content required being dependent principally on the overall soil gradation and the character of the fines [18]. Well-graded soils have lesser void ratios than uniformly-graded or gap-graded soils, and so require lesser fines contents to fill the remaining available void space and thus separate (or “float”) the coarser particles in a matrix of the fines. Similarly, clay fines carry higher void ratios than silty particles and so are more rapidly effective at over-filling the void space available between the coarser (larger than 0.074mm) particles; a lesser weight (or percentage) of clay fines is required than would be required if the fines were lower plasticity silty particles.

Silty soils of very low plasticity, tend to experience “triggering” of cyclically induced soil liquefaction at relatively low shear strains (typically on the order of 3% to 6%), and the loss of strength can be severe [27]. Soils of higher plasticity, on the other hand, may also exhibit loss of strength and stiffness, accompanied by increased pore pressures, but the pore pressure ratios achieved may be somewhat lower than those associated with more “classically” liquefiable soils, and the loss of strength and stiffness becomes pronounced at somewhat larger shear strains.

Additionally, saturation plays an important role to liquefaction. The more saturated a soil is, the more potential for liquefaction to take place [18]. Saturation is a complex term depending on various main parameters such as pore spaces, void ratio, total porosity, permeability and relative density.

Pore space is the spaces within a granular body that are unoccupied by solid material. Saturation in turn, is the volume of water per volume of pore space. As the pore space increases, liquefaction potential increases too, if pore space is occupied by water, and thus the degree of saturation is higher [22].

A decrease in the saturation degree of a sandy soil leads to an important increase in their resistance to liquefaction. Consequently, a decrease in saturation degree leads to a decrease in the induced pore-water pressure. It can be thus claimed that soil saturation highly affects soil liquefaction. This is clearly noticed in the following graph [18], where it is shown that a reduction of saturation leads to a decrease in the induced pore-water pressure.

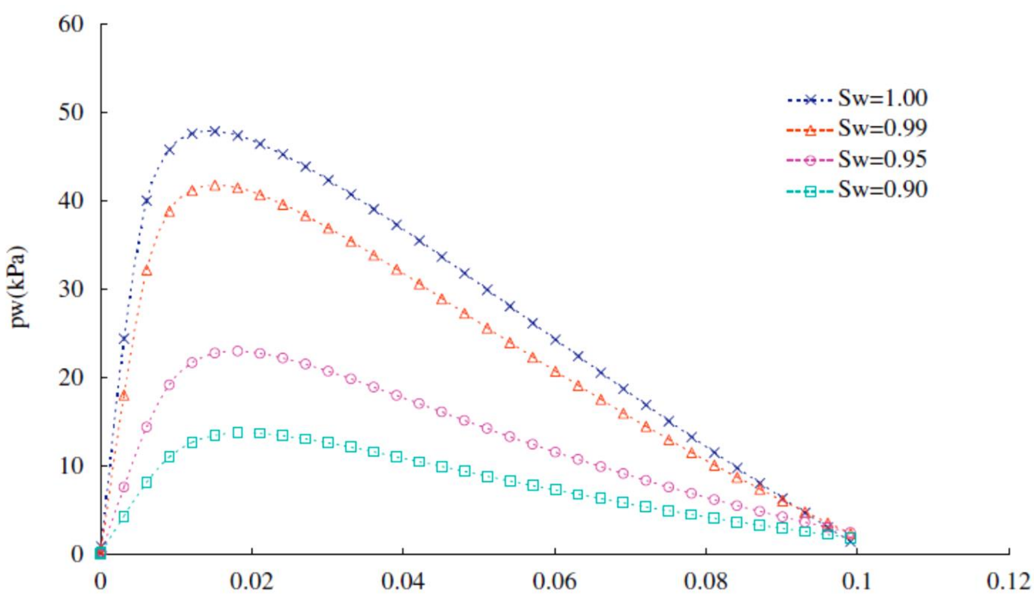


Figure 3.4.7: Saturation degree reduction leads to decrease of pore-water pressure

As regards the void ratio, i.e. the volume of voids per volume of solids, results show that the global void ratio does not reflect the real behaviour of the soil and the undrained shear strength at the phase transition state can be correlated to the inter-granular void ratio of the sand–silt mixtures up to 50% fines content. Indeed, it decreases linearly with further increase in the inter-granular void ratio [11].

The inter-granular void ratio increases hyperbolically with an increase of fines content. We notice in general that an increase in the amount of fines leads to a reduction in the confining effective pressure and consequently to a decrease of the peak resistance of the mixtures.

Turning to the relative density, i.e. how dense or tightly packed the soil is relative to the soil in its densest state void ratio increases as relative density diminishes. Soil consists of soil particles and those soil particles can be arranged either very densely, very loosely, or somewhere in between. A soil that is 80 to 85% relative density is pretty dense. That means generally that it is 80 to 85% of its most dense state. Void ratio is calculated relative to the relative density. Thus, as relative density increases the possibility of liquefaction decreases [18].

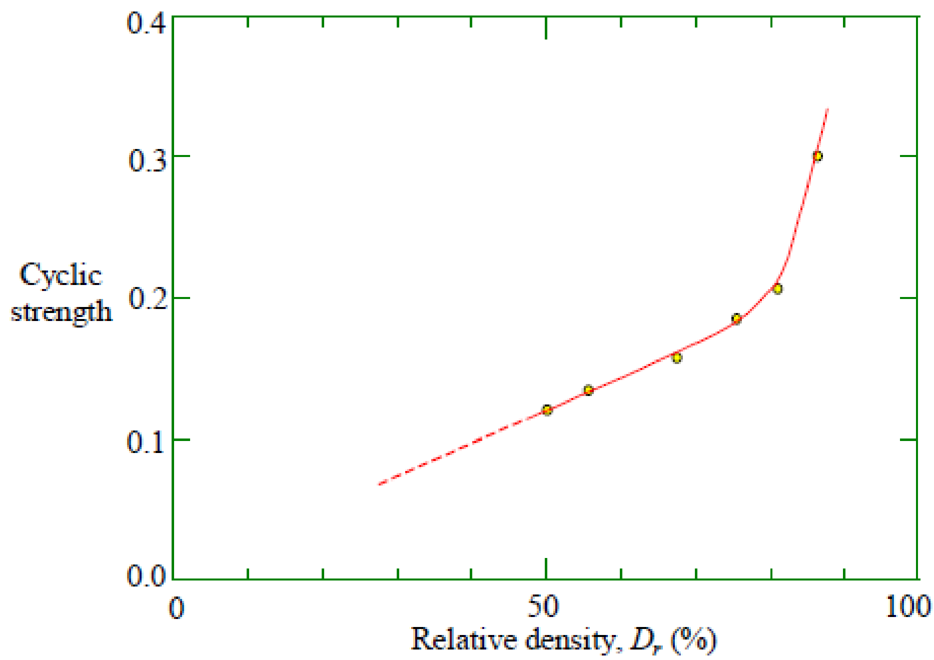


Figure 3.4.8: Cyclic strength versus relative density (Ishihara, 1996)

Soil permeability [1] is the property of the soil to transmit water and air. The more permeable a soil is, the greater the seepage. It is calculated in m/s, like the velocity. According to the soil consolidation theory soil permeability increases when, the void ratio decreases. The latter is given as well in the figure below. It can easily be rendered that a permeable soil is not susceptible to soil liquefaction.

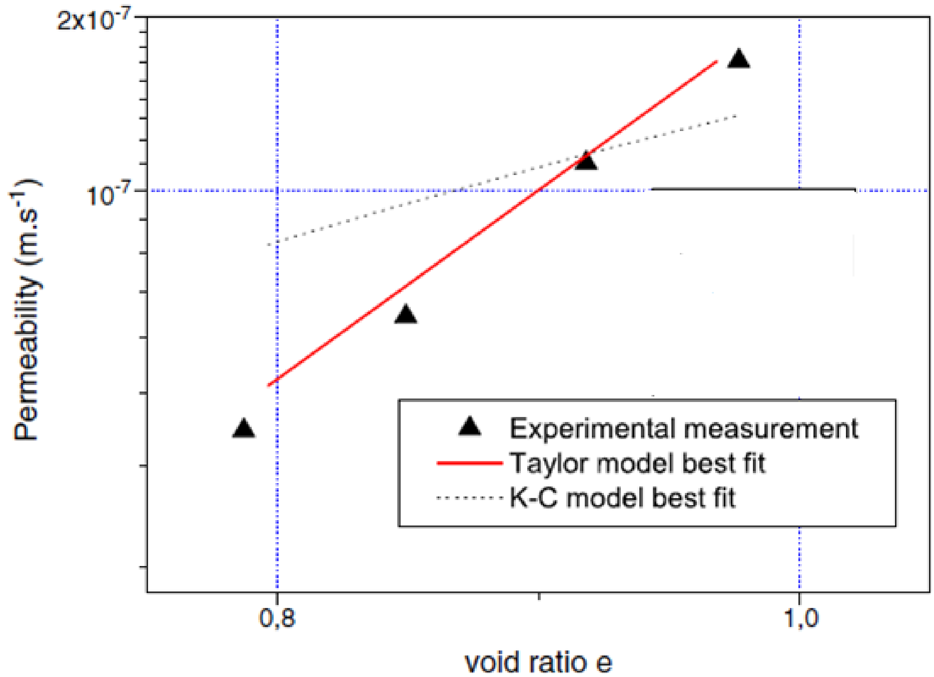


Figure 3.4.9: **Permeability decreases as void ratio increases**

To sum up, as can easily be concluded from the above analysis there are many major parameters which make a soil susceptible to soil liquefaction. An increase in predominantly fines content, saturation degree and void ratio involves a liquefiable soil. On the other hand, permeability and relative density, i.e. how dense is the soil, prevents the soil from liquefaction.

Assessment of triggering potential

As a first step for the complete understanding of liquefaction, researchers established numerical and experimental models so as to conduct a quantitative analysis of liquefaction. Experimental approach is complex because it is very expensive to perform high-quality cyclic simple shear testing, which truly represents the loading conditions for most seismic problems.

With respect to the numerical approach, three methods [8] are usually used:

1) **Empirical Correlations**: They are based essentially on comparison of grain size distribution of the site to the grain size envelope of sites that have liquefied in the past worldwide.

2) **Finite Element and Finite Difference Analyses:** There are an increasing number of finite element (FEM) and finite difference (FDM) programs available for analysis of liquefaction-related problems. Finite element analysis can be carried out to obtain the pore pressure distribution and ground displacement along the depth of the soil deposit

3) **The "Simplified Procedure" by Seed and Idriss'':** Analytical evaluation of liquefaction potential by calculating a factor of safety, FS, against liquefaction.

The latter method has been modified and improved by several researchers. The fundamental concept of the method is the calculation of a factor of safety, against liquefaction in terms of the cyclic stress ratio, CSR, and the cyclic resistance ratio, CRR [36]. CRR is the in-situ cyclic undrained shear strength of the soil mobilised for the equivalent number of stress cycles developed due to the earthquake, and CSR is the average shear stress level developed in the ground due to earthquake loading at the depth under consideration. In effect, CSR is the earthquake loading and CRR the liquefaction resistance.

A factor of safety greater than one indicates that the liquefaction resistance exceeds the earthquake loading, and therefore that liquefaction would not be expected. According to Seed and Idriss [6], the formula given below calculates the safety factor, FS.

$$FS = \left(\frac{CRR_{7.5}}{CSR}\right) MSF \cdot K_{\sigma} \cdot K_{\alpha}$$

Where, CRR7.5 is the cyclic resistance ratio for magnitude 7.5 earthquakes, MSF is the Magnitude scaling factor, Kσ is the overburden correction factor, and Kα is the correction factor for sloping ground.

CSR is, in turn, is estimated as shown below:

$$\mathrm{CSR} = 0.65 \frac{a_{\max}}{g} r_d \gamma_s z$$

Where, γ_s is the unit weight of soil, a_{max} is the peak horizontal acceleration at the ground surface, r_d is the stress reduction coefficient, z is the depth below ground surface in metres and g is the acceleration of gravity.

Liyanapathirana and Poulos [7] produced a similar numerical model. They used a parameter named liquefaction potential I_L. Thus, when comparing liquefaction potential I_L of different soil deposits, the factor of safety at various depths within the deposit should be compared, and this can be facilitated by using I_L, as it is the integrated value of several factor of safety values along the soil deposit as shown below:

$$I_L = \int_0^{20} FW(z)dz$$

Where, $F=1-F_L$ for $F_L \leq 1.0$ and $F=0$ for $F_L>1.0$. $W(z)=10-0.5z$ and z is the depth in meters. F_L is the factor of safety against liquefaction.

Experimental models

As mentioned above, liquefaction resistance is evaluated by determining the Cyclic Resistance Ratio (CRR). There are four experimental methods to calculate the CRR [18].

1) The Standard Penetration Test (SPT).

2) The Cone Penetration Test (CPT).

3) Measurement of in-situ shear velocity V_s.

4) Becker Penetration Test (BPT).

SPT is the oldest and most widely used method. The main purpose of this test is to provide an indication of the liquefaction resistance. Consequently, cyclic strength is measured, which is usually presented as the number of cycles of load that is required for liquefaction of the soil, *Nl* [19]. CPT adopts the same philosophy but follows a different procedure for estimating the critical N value as well using other equipment.

BPT characterizes the liquefaction resistance of coarse gravelly soils. The Becker Penetrometer is essentially a large-diameter steel pipe pile driven by a diesel pile hammer, while retrieving cuttings pneumatically up through the hollow pipe. The Becker Penetrometer Test resistance can be correlated with SPT to develop “equivalent” N-values (N_{BPT}) [18].

The last experimental method is based on correlations that can provide both a potentially rapid screening method, and a method for assessment of coarse, gravelly soils, which cannot be reliably penetrated or reliably characterised with small diameter penetrometers (SPT and CPT). The measurements of in-situ shear wave velocity (V_S-based correlations) are very attractive because firstly V_S can be measured with nonintrusive methods (e.g. Spectral Analysis of Surface Waves (SASW)), and secondarily V_S can be measured in coarse soils (gravelly soils and coarser) in which SPT and CPT can be obstructed by interference with coarse soils particles.

Outcomes of experimental and numerical analysis

Earthquakes, which caused liquefaction were compared with others which did not lead to the same results. The intensity, i.e. the magnitude, the frequency, the duration of the earthquake, as well the soil deposit was examined. The simulation of the earthquake loading was carried out by using both experimental methods, mostly SPT, and numerical models such as the Seed and Idriss equations [8]. It is worth mentioning that there is corellation between numerical and experimental approaches heading to some key findings which are given below:

- Field observations and measurements in shaking table tests showed that liquefaction occurred mostly after a first few seconds of ***sufficiently strong shocks***.
- Pore pressure is increasing after the first seconds where the acceleration takes a certain value of some g.
- As pore water pressure rises, a progressive loss of strength of the soil occurs as effective stress is reduced.
- Results show that there is a critical or limit value of pore pressure, above which all the samples, regardless of grading, suffered sudden collapse and liquefaction, and below which they dilated and gained some measure of stability.
- The increase of oscillation amplitude corresponds with the interval of most rapid rise of pore pressure.
- To initiate liquefaction local ground acceleration greater than 0.10 is required.
- It was observed in shaking table tests that liquefaction of sand specimens is more likely under a shaking of greater amplitude, lower frequency, longer duration, and/or multiple directions.
- It is necessary for the shaking to continue for some time (a characteristic of large earthquakes).
- It is verified that deformation during cyclic loading will depend on the soil's density, the magnitude, initial confining pressure and duration of the cyclic loading.

- Liquefaction is more likely to occur in loose to moderately-saturated granular soils with poor drainage.
- The fines content greatly influences the susceptibility to liquefaction. There is a lower likelihood of liquefaction when the fines content (on the order of some μm) increases.
- By analysing a number of earthquake records from different parts of the world with the same acceleration levels, liquefaction was considered to have been caused by earthquakes with low frequency and longer duration.

Mitigation of liquefaction hazard

When satisfactory performance of structures and other engineered facilities cannot adequately reliably be assured, engineered mitigation of the unacceptable liquefaction hazard is generally required. There are several procedures to mitigate or eliminate the harmful effects of liquefaction ranging from hard responses to simple avoidance.

For instance, in soil mechanics a method to tackle liquefaction is to solidify the liquefiable soils by chemical or cement injection grouting, or using vertical drainage materials that relieve the pore water pressure [8].

A brief list of selected major mitigation methods available are presented below. It should be noted that these do not have to be employed singly. However, it can often be optimal to use two or more methods in combination [8].

- **Ground Densification:** The loose grounds can be “densified” to the desired density by methods such as vibroflotation, dynamic compaction, compaction piling and other vibratory methods.
- **Pore water Relief:** Pore pressure build-up during the initiation of liquefaction can be prevented by rapid drainage.
- **Compaction Grouting:** It is a technique whereby a slow-flowing such as water, sand and cement mix is injected under pressure into a granular soil.

Of very great importance is the recognition that pore water pressure relief through the use of vertical drainage materials will assist in preventing the setup of pore pressures to cause liquefaction.

- **Site selection:** Avoid potentially liquefiable areas. The main evidences to determine the liquefaction susceptibility of a soil are based on historical, geological, compositional and state criteria.

- **Use of piling:** Bypass the potentially liquefiable zones.

- **Chemical or Cement Injection grouting:** Solidify the liquefiable soils.

However, in recent years cost-effective liquefaction mitigation technologies have been developed that could be effectively used in countering liquefaction or in preventing the build-up of the critical conditions before set up of liquefaction.

3.4.3 Offshore Engineering

In recent decades offshore engineering gains more and more attention around the world as many countries try to take advantage of their hydrocarbon reserves, using large offshore rigs. The successful exploitation of oil reserves in most cases depends on the efficiency to solve the many problems associated with the design and construction of offshore platforms in a hostile ocean environment.

Figure 3.4.10: Ekofisk oil platform

Unfortunately, offshore engineering is another discipline where the effects of liquefaction phenomenon are significant. It is likely that the sand, which is used to bury the foundations of the offshore structures or the pipelines liquefies under the influence of seismic shocks or secondarily wave loads, since both the overburden pressure and the relative density are low [9].

The concept is the same as in the soil mechanics; under undrained conditions, i.e. saturated soil, each load cycle is accompanied by an increase in pore water pressure, which reduces the effective stress [5].

As regards the offshore platforms, they are subjected to lateral wave loads apart from vertical. This can be attributed as the main difference between the offshore structures and the onshore buildings.

During an ocean storm, as a wave moves across an offshore gravity structure, it exerts a lateral force to the structure, first along the direction of its movement and then in the opposite direction. This causes the foundation soil strata to experience a series of stress cycles in both horizontal and vertical direction due to the horizontal forces and the overturning moments. The cyclic stress conditions are comparable to those induced by an earthquake loading [5].

However, some additional differences referring to the energy imparted exist. Ocean wave periods are longer than the period of earthquake cycles of shaking and ocean storm duration is considerably longer than the duration of seismic shaking. Moreover, ocean wave loading is transmitted mainly from the structure to the soil whereas some parts of earthquake loads are generated by the acceleration of the soil mass [9].

Luckily, there is not any record up to now of a serious accident involving liquefaction. However, although those structures seem to be unbeatable, the Ekofisk tank in 1973 suffered liquefaction of its seabed owing to several major storms.

The storms produced severe waves with a maximum wave height of about 21 meters. As a result, the pore pressure of the upper sand layer increased above 40 kPa. The displacement of the tank increased to 0.02 m during the storm. During the five days period of severe storms, the tank settled an additional 0.03-0.05 m [5].

With respect to the offshore pipelines, they have been constructed to serve as efficient transportation means of oil, water and gas. It is usual that the pipelines are installed in excavated trenches in the sea bottom, and then buried in sand at a depth of 2 to 3 meters to reduce the effects of anchor loading from ships and wave loads [21]. If the sea bed or the filling material among a pipeline route consists of cohesionless soils likely to liquefy under the influence of seismic shocks, a pipeline buried in such soils may lose stability and flow to the surface of the seabed.

A representative pipeline incident took place some minutes after the 1929 Newfoundland earthquake [26]. Phone cables began breaking sequentially, further and further downslope, away from the epicentre. Twelve cables were snapped in a total of 28 places. Exact times and locations were recorded for each break. Investigators suggested that a 60-mile-per-hour current of muddy water swept 400 miles down the continental slope from the earthquake's epicentre, snapping the cables.

Numerical models adopted

Apart from the FEM which is indeed used in offshore engineering as well, two of the plasticity models used in geotechnical engineering, namely the Mohr-Coulomb model and the Modified Cam-Clay model, are commonly adopted. It is believed that these models are capable of simulating a wide range of soil behaviour for many practical problems in soil mechanics.

In effect, the Mohr-Coulomb model [5] defines the stress-strain relationship, the yield surface, and the direction of plastic flow for the soil. It is certainly the best known perfect plasticity model in soil mechanics. In this model the effect of hydrostatic pressure on the strength of granular materials is taken into consideration. The Mohr-Coulomb model reduces to the Tresca model [5] if the material friction angle is set to zero.

A more complex stress-strain behaviour of soil is approximated by a more sophisticated hardening plasticity theory. The Modified Cam-Clay model [5] is an isotropic, nonlinear elastic strain-hardening plastic model. In this model, elastic volumetric strain is non-linearly dependent on hydrostatic pressure and independent of stresses. Volumetric strain is assumed to be partially recoverable.

Finally, the FEM as mentioned earlier, can easily solve most complicated soil problems. The general procedure refers to an assessment of the accumulative excess pore pressure and the flow of water in the soil.

Mitigation of liquefaction hazard

In many cases site selection is not a feasible mitigation measure, due to the abundance of hydrocarbons in the area. However, there are three stabilization techniques [21] with the predominant aim of reducing the amount of maximum upward displacement and bending stresses acting mostly on the pipelines and secondarily on the foundations of offshore platforms.

These techniques are mentioned below:

- Anchoring the pipeline.
- Increasing the weight of the pipeline.

- Burying the foundations of the structures with geologic materials which are not likely to liquefy, e.g., gravel.

Based on these, the maximum displacements and bending stresses on the pipeline can reduce to very low compared with those without countermeasures. In addition, the cost-effectiveness of the method greatly depends on the geologic conditions of the site.

Buoyancy is the most important factor for offshore pipelines since the structure is simple and the strength is relatively high. It is checked that weighting the pipeline can reduce the effects of buoyancy. However it should be noted that the concrete-coating has to be thickened to impractical level in some cases.

The last mitigation measure is obviously the less cost-effective remedy. The main drawback is that the cost of the material used to bury the foundations of those structures is usually higher than that of sand.

The latter method was implemented in one of the national crude oil underground storage stations in Japan. The pipeline was buried in gravel and crushed stones. It was expected that this would eliminate the effect of liquefaction. An applied numerical method assessed that the contribution of this method led to smaller stresses than the allowable stresses for the pipe.

Outcomes of experimental and numerical analysis

The most interesting result of liquefaction in offshore engineering is that lateral load is less detrimental than a vertical load. Thus, an earthquake load is more likely to cause liquefaction than a wave load. It is worth mentioning that generally there is a consensus of the outcomes from liquefaction in offshore engineering and in soil mechanics.

- It has been found that the shape of an offshore foundation has an important influence on the cyclic behaviour of the foundation.
- An increase in the intensity of cyclic loads applied to the foundation usually generates a greater pore pressure in the soil and a larger displacement for the foundation.
- During cyclic loading, there is a continuous increase of pore pressures.
- As the magnitude of cyclic load increases, the pore pressures generated under the foundation increase.
- The results of the analyses show that cyclic vertical loads have greater effects on the responses of the foundations than cyclic horizontal loads of the same magnitude.

- Application of a large number of cyclic loads with moderate amplitude can produce liquefaction of the soil.
- If the foundation can sustain the external load during cyclic loading, it will regain most, if not all, of its original shear strength when the pore pressures are dissipated from the soil.

3.4.4 Mechanics of Materials

Quicksand

Quicksand is a mixture of granular material such as sand and silt, clay and water. It forms in saturated loose sand, such as beaches, dunes and riverbeds, when the sand is suddenly agitated. When water in the sand cannot escape, it becomes liquefied, loosing at the same time its strength and cannot support weight. Submerged objects in liquefied sand sink to the level at which the weight of the object is equal to the weight of the displaced soil/water mix.
Liquefaction is a special case of quicksand. The concept is the same as in soil mechanics and offshore engineering. Sudden earthquake forces immediately increases the pore water pressure of shallow groundwater.
Quicksand may appear quite solid until a sudden change in pressure or shock initiates liquefaction. However, the presence of large amount of groundwater and the addition of seismic shocks can cause it to flow.

Figure 3.4.11: Sign warning for quicksand

Coffee and vacuum trapped granular materials

The coffee bricks found in grocery stores are a good example of how a granular material can behave differently based on its conditions. When the coffee pack is made, it is sealed under vacuum. This causes the grains to push against one another, locking each other in place. This creates a stiff “brick-like” material. When the package is opened, air enters and outside pressure is released. The coffee becomes very weak and soft, and moves about freely, almost like a liquid.
Moisture and air trapped within the soil also affect its behaviour if a load is applied faster than the entrapped fluid can escape. As the water pressure or air pressure within the pores increases, the effective or inter-particle stresses or pressures decrease, weakening and softening the soil. When the external loading equals the internal pore pressure, the soil liquefies.

3.4.5 Results and Comparison of Liquefaction Phenomena in Different Disciplines

The above-mentioned research of liquefaction on different areas of engineering indicates that liquefaction phenomena occur under the same circumstances. These circumstances are related to the properties of the granular materials and the excitation forces that act on them.
This is a significant outcome that will help us in subsequent experiments focus on high intensity and long duration vibrations that presumably are the most responsible for causing liquefaction in soil mechanics and in offshore engineering. These vibrations derive from wave excitation forces which are of low-frequency and high-amplitude.
Similar characteristics of liquefaction phenomena in different disciplines are quoted below:

With regard to the properties of granular materials

- Pore water pressure increases sharply in loose sands.
- Heterogeneous and gap graded materials are more susceptible to liquefaction.
- Saturation is a factor that influences liquefaction. Materials containing high moisture content are prone to liquefaction.
- Soils that contain a high proportion of fine particles smaller than 100 µm may avoid liquefaction.

With regard to the intensity of the phenomenon

- Liquefaction occurred mostly after a first few seconds of ***sufficiently strong shocks***.
- To initiate liquefaction, local ground acceleration greater than 0.10 is required.
- Application of a large number of cyclic loads with moderate amplitude can produce liquefaction of the soil.
- Liquefaction is caused by excitation forces with low frequency and longer duration.
- Liquefaction is more likely under a shaking of greater amplitude and/or multiple directions.
- The increase of oscillation amplitude corresponds with the interval of most rapid rise of pore pressure.

The literature review described in this chapter offers some detail of the theoretical background used for interpreting cargo liquefaction. It revealed the need to understand more of the nature of the liquefaction phenomenon. Examination of liquefaction events in different areas of engineering and afterwards implementing an experimental approach offers great promise in this regard. As this goal is actually accomplished, the second step is to present the experimental procedure that was adopted in this thesis and on the basis of the results of the experiments recommend and test possible solutions for this problem.

Chapter 4: Experimental Program

4.1 Introduction

In previous chapters, the theoretical background of cargo liquefaction problem was presented. Aspects of the problem such as accidents, legislative framework and research progress in other disciplines of engineering, were included in the critical review. The next step after the completion of the theoretical analysis is to design the experimental programme that will be followed. Hence, we will specify the objectives of the experiments focusing on the characteristics of the energy imparted to a cargo, which subsequently leads to its liquefaction. In addition, the experimental plan will contain the process variables of the study, both inputs and outputs. Having identified the controlling parameters, the next step is to specify their range. Finally, a detailed experimental approach describing step by step what will be done during the experiments is the core of the present chapter.

4.2 Experimental Procedure

Samples of iron ore fines and nickel ore will be placed in a model hold which is an accurate replica of a Supramax bulk carrier, simulating the energy input on a cargo during ocean carriage. The hold is manufactured at a specific model scale and its main dimensions are 30*20*15 cm. A model test rig that comprises a six-degrees=of-freedom vessel motion simulator, which produces model scale motions based on ship motion RAOs [28] and sea-state inputs, will subject the test material to multi-directional vibrations in different frequencies and duration. The critical review showed that liquefaction is more likely under a shaking of multiple directions. Additionally, due attention should be paid to low frequency-high amplitude excitation forces, since it is verified that liquefaction occurs under intense loads of low frequencies [7].

The cargo material at the fore holds of the vessel is subjected to the greatest degree of motion in terms of pitch and also due to slamming phenomena [37], [35]. On the other hand, roll and heave motions play a dominant role in imparting angular accelerations to the cargo. As a result, focus will be placed on these two angular motions and on heave. Effects of the horizontal motions such as surge, sway and yaw are not regarded as important and thus will not be included in the experiments.

The moisture content of the material will be adjusted prior to each test by adding water or drying the material as required. To check the sequence of observation the experiments will be carried out at least twice with the same controlling parameters. After the completion of a set of experiments, we will examine carefully the form of the cargo, search for any deformations and variations in bulk density which will be recorded, as well as apparent occurrence of liquefaction.

Before the performance of the experiments in the shaking table, various significant steps should be taken for the purpose of calculating the moisture content of the cargo and principally the Transportable Moisture Limit.

Calculation of the bulk density of nickel and iron ore fines according to MSC/Circ.908 [31]

Apparatus

- A container of known volume and tare weight
- A certified weighting instrument

Process

The container will be filled with a sample that is representative of the particles size, compaction and moisture content of the material to be loaded on the ship. The container will be filled with a sample of the material so that it is trimmed level with the top of the container. The material should not be tamped. Next, the weight of the filled container will be measured and the tare weight will be subtracted from this value to obtain the weight of the sample. Finally, the density of the sample will be calculated by dividing the weight of the bulk material by the volume of the container.

It is worth mentioning that the bulk densities of nickel ore and iron ore fines are expected to be between 1 t/m^3 to 1.67 t/m^3 and 1.25 t/m^3 to 4 t/m^3, respectively.

Measurement of the mean diameter of the particles

Apparatus

- A Vernier caliper

Process

This step is both simple and very important because if the average size of the particles is above 7 mm the TML will be determined only with the Penetration Test while Flow Table Method and Proctor/Fagerberg Test are not suitable for those cargoes. The simplest method to calculate the grain size is by using a Vernier calliper.

Determining the moisture content of the samples

Apparatus

- A weighting device
- A drying device
- Any pan or other container

A representative sample of the material to be tested will be selected and placed in a tared container. The suggested test sample size is between 500 g and 1000 g. The mass of the container and sample are determined and the mass of the container subtracted [42]. The mass of test sample will be defined and recorded as the "wet mass". Thereafter, the container will be dried to constant mass at 110 ± 5°C for 16 hours. The sample will be cooled to room temperature and its ''dry mass'' weighed. The mass of water in the sample is the wet mass minus the dry mass. Finally the percentage moisture – moisture content is calculated by the equation:
Percentage moisture= (water mass/dry mass)*100

Calculation of the Transportable Moisture Limit (TML)

Prior to the execution of experiments, it is important to determine the TML of the tested cargo. As described in the critical review this procedure will be carried out by implementing either the Flow Table Method or the Penetration Test. Proctor/ Fagerberg method needs complex equipment and its accuracy is uncertain.
Hence, our choice will be derived from the determination of the mean diameter of the particles that form the cargo. In case that the latter is above 7 mm the Flow Table Method is inappropriate for calculating the TML, because this method is applicable to materials with a maximum grain size up to 7 mm. Following this, the TML will be defined by using the Penetration Test, which is much more complex and the cost higher.
After the measurement of the mean diameter the TML will be determined with one of the IMO's approved methods that were outlined in Chapter 3.

Preparing samples of MC above the TML

Apparatus

- A mixing bowl with a known capacity
- A burette with a volumetric graduation

Samples having a MC below the TML are deemed non-liquefiable. Nevertheless, an experiment will be conducted on samples of moisture content 2% less than their measured TML to verify whether they liquefy or not.
The rest of the experiments will be undertaken on materials whose moisture content will gradually increase from the TML to a value approximately 55% of their mass by adding a suitable amount of water and then mixing thoroughly the test material. The increment will be up to 10% in each case.

A certain quantity of material holding specific moisture content will be placed in the mixing bowl where a precise amount of water will be added from the burette and then thoroughly mixed. Following this, the mixture will be set to the model scale hold.

Shaking Table Experiments

Objectives

- Identification of the excitation forces likely to cause cargo liquefaction.
- Under which conditions related both to the moisture content and the intensity of the excitation forces does liquefaction occur.
- Check the effectiveness of remedial factors in controlling the problem.

Apparatus

- A model hold
- A drying oven
- A mixing bowl with a known capacity
- A scale
- A burette with a volumetric graduation

The controlled and uncontrolled parameters of the experiments are described next, as well as their range in full scale. The interactions between some of the variables are strong, e.g. frequency and amplitude, and there are implemented in different levels and various combinations.

Controlled inputs

- **Excitation Characteristics**

1. Frequency
2. Amplitude, i.e. acceleration level
3. Duration

- **Sample Properties**

4. Material, i.e. iron ore and nickel ore
5. Moisture Content, MC
6. Absorbent powder

Uncontrolled inputs

- Ambient temperature
- Humidity

The experiments will be carried out indoors. Thus, there will not be any significant fluctuation in the prevailing conditions, able to affect the properties of the cargo, i.e. the moisture content.

Experimental outputs

Primary outcomes

- Liquefaction of the sample (liquid state)
- No Liquefaction of the sample (solid state)

Secondary outcomes

- Degree of deformation on the cargo
- Bulk density

Range of controlling parameters

Material

As mentioned above the tested material will be be iron ore and nickel ore fines.

Frequency

Low frequency excitation forces derive mainly from the waves, causing ship motions such as roll, heave and pitch as well impulsive phenomena such as slamming, whipping etc., while high frequency forces are attributed to engine and propeller-induced vibrations. For instance, the range of the wave frequencies is 0.2 rad/sec to 2 rad/sec, in contrast to the main engine frequencies, which stretch from 1.5 Hz to 3 Hz. In our experiments in the shaking table we will focus on the simulation of rough seas that are represented by frequencies with values up to 0.5 Hz.

Amplitude

With respect to the rotational motions, roll angle will gradually increase up to 25 degrees, while the maximum value of pitch will be 8^0.

Duration

Duration plays an important role, indirectly showing the transient or steady behaviour of the liquefaction phenomenon. Our tests will be carried out in six gradually increasing intervals from 30 seconds to 3 minutes with an increment of 30 seconds in each experiment.

Moisture content

As aforementioned earlier, the moisture content of the test samples will gradually increase, observing in each case in which MC relative to the excitation forces liquefaction takes places.

- 2% below the TML
- TML
- 5% above the TML
- 10% above the TML
- 20% above the TML
- 30% above the TML

Chapter 5: Consideration of Mitigating Measures

5.1 Introduction

An additional design feature, the efficiency of which was investigated for confronting cargo liquefaction was Safety Inflated Devices (SID). On the assumption that the cargo shifts due to cargo liquefaction, the angle of heel is limited and the vessel is not at risk of capsizing. It was proved that the implementation of these devices may be valuable for future use. The utility of the latter mitigation measure is to provide additional buoyancy, as the vessel is likely to capsize, when its cargo shift takes place following liquefaction.

Safety Inflated Devices

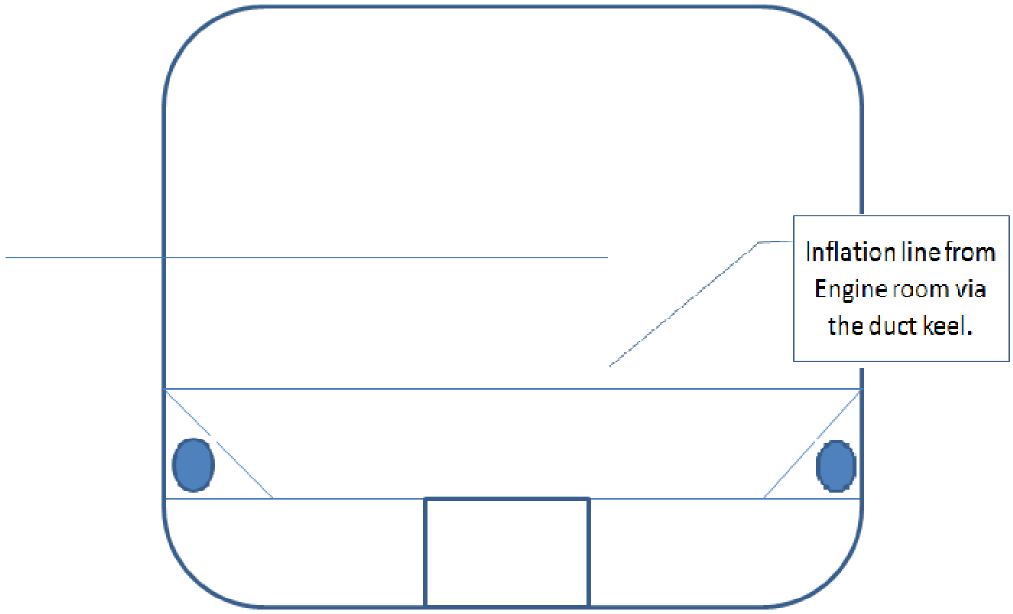


***Figure 5.1*: Air bag in the stowed condition**

When the balloon is released, it is inflated in a few seconds, producing at the same time an upwards force, resulting in additional buoyancy and righting moment. Thus, the stability of the vessel is improved. It is worth mentioning, that the value of metacentric height and maximum GZ lever is in many cases adequately high, while these devices are used.

The floating balloons are stowed in the sea chest compartments and do not occupy much space, when they are not inflated. Additionally, there is an idea of inflating them by using compressed air from the engine starting air bottle.

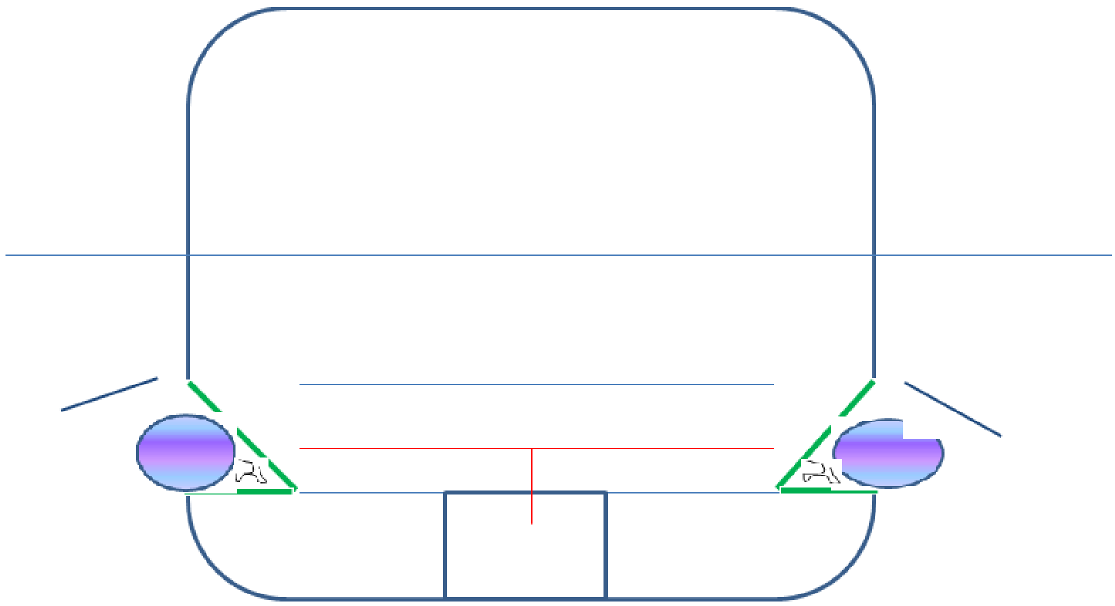


***Figure 5.1.2*: The inner plate becomes the hull plate and the SID is released**

The air bag will be secured to a special bracket, which when deployed will provide an evenly distributed lifting force to a beam welded across the ships breadth in the stool space. As the airbag is inflated, the external shell plating will be removed allowing the SID to be deployed. In this way, a special area of weak plating with hull integrity will be achieved at the inner surface like a sea chest.

Moreover, the shape of the balloons is cylindrical and the material that those devices are made of is usually reinforced plastic. That is because this material is light, cheap and quite effective in our case.

The idea of the safety inflated devices was first introduced in ROPAX vessels and particularly for mitigating damage stability problems. According to the position and the extent of the damage leading to subsequent flooding, an airbag was released obviously on the one side of the ship to avoid capsize.

As regards the bulk carrier vessels, they are located in the outer surface of the cargo holds in both port and starboard sides. Depending on which cargo hold the cargo behaves as liquid, we change the positions of the balloons. Different scenarios were deployed, with respect to the position and the size of the SID, targeting in a rough and quick optimization of post-liquefaction stability.

5.2 Handysize Bulk Carrier Case Study

As shown in the critical review, small size vessels and especially Handymax and Handysize are those which are mostly affected by cargo liquefaction problems. Thus, by using the ship design software AVEVA, we produced a Handysize model of 43,000 tonnes, which could be in danger of cargo liquefaction in real conditions.

Vessel's main particulars and hydrostatics are given below:

L_{OA}(m)	**173.630**
L_{BP} (m)	**167.000**
B (m)	**29.0**
T (m)	**10.70**
D	**15.050**
C_B	**0.8190**
Δ_Γ(t)	**43661**
LS (t)	**7567**

Figure 5.2.1: **Main dimensions of the produced Handysize bulk carrier vessel**

VOLM	42430 m^3	volume moulded
DISP	43661 t	total displacement
C_B	0.8190	block coefficient
C_P	0.8220	prismatic coefficient
LCB	87.208 m	longitudinal centre of buoyancy
VCB	5.543 m	vertical centre of buoyancy
KMT	11.986 m	transverse metacentric height
LCF	81.029 m	longitudinal centre of flotation
WLA	4393 m^2	waterline area
T	10.70 m	draught, moulded

Figure 5.2.2: **Hydrostatic calculations**

In the following figures the General Arrangement plan, tank plans and the midship section of the designed Handysize vessel are given.

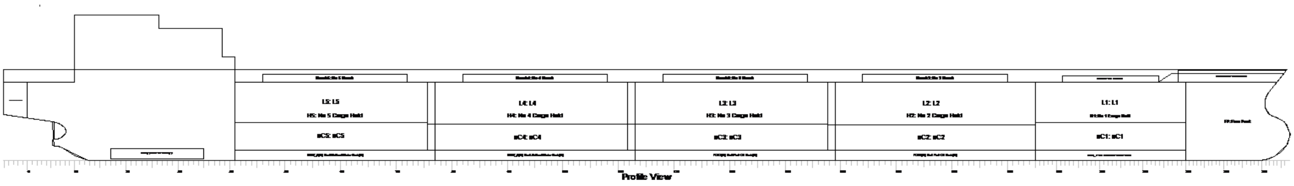


Figure 5.2.3: **General Arrangement**

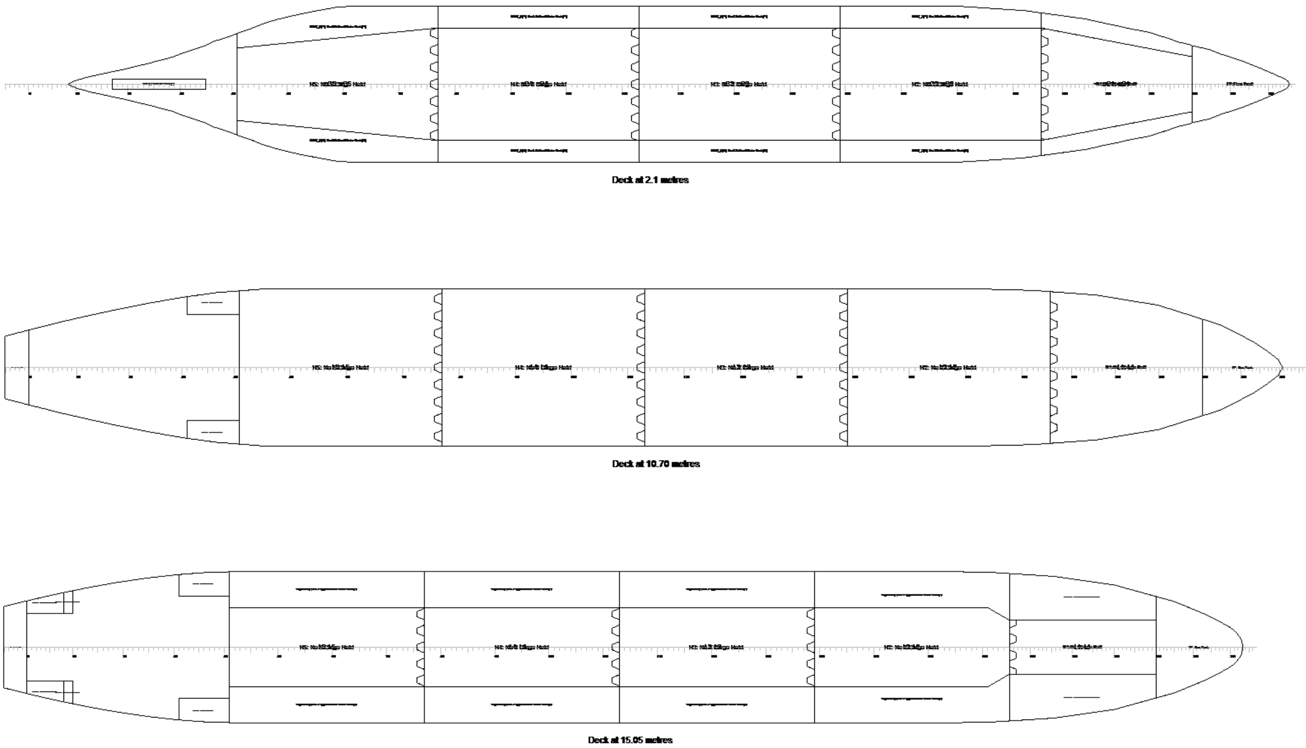


Figure 5.2.4: **Decks at db, T_{des} and MD**

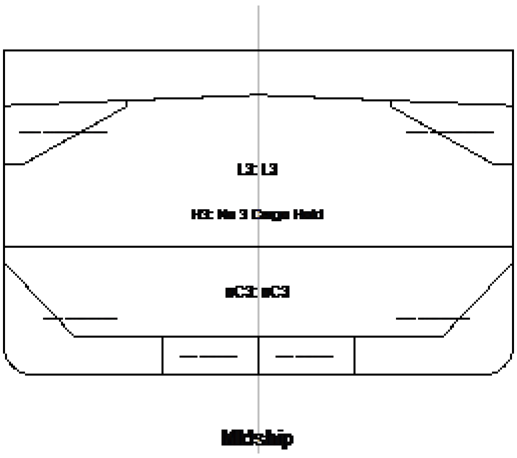


***Figure 5.2.5*:** **Midship section**

The checked loading condition was Full load departure because cargo liquefaction rarely takes place when the cargo holds are not fully loaded. The bulk density used was 1.6t/m^3 and of course the material was regarded as solid. The reason for choosing the above mentioned bulk density was because the bulk density range of iron ore fines and nickel ore according to IMO is 1.25 to 4 t/m^3 and 1 to 1.67 t/m^3, respectively.

As the cargo liquefied the stability calculations were carried out regarding bulk density of the liquefied mass 1.1 t/m^3. It was assumed that 30% of the volume of the cargo was liquefied. Free surface effects in the liquefied cargo holds were taken into consideration.

The diameter of the balloons were B/4 and B/5. In most cases, they were placed below the waterline so as to offer buoyancy. However, we tested a case that they were semi-submersed. GZ curves and required IMO criteria were compared and the results are shown in the following pages.

SID were located in four different parts of the vessel. The **first part** was from in the outer surface from mid holds **4 to mid hold 5**. The **second part** covered the area of cargo **holds 3 and 4**. The **third and fourth part** extended from the mid of **cargo holds 2 and 3 and 1 and 2**, respectively.

Cargo in solid state

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)
Cargo Holds and Hatches									
H1: No 1 Cargo Hold	185-220	CG	52.0	1.600	4705.0	145.39	0.00	5.78	[757.4]
H2: No 2 Cargo Hold	149-185	CG	52.0	1.600	7429.9	122.47	0.00	5.62	[1648.9]
H3: No 3 Cargo Hold	113-149	CG	52.0	1.600	7443.4	95.50	0.00	5.62	[1682.1]
H4: No 4 Cargo Hold	77-113	CG	52.0	1.600	7443.4	68.50	0.00	5.62	[1682.1]
H5: No 5 Cargo Hold	41-77	CG	52.0	1.600	7061.6	42.03	0.00	5.88	[1661.7]
Total Cargo Holds and Hatches					**34083.3**	**91.29**	**0.00**	**5.69**	**0.0**
Fuel Oil Tanks									
FOT1(P): No1	149-	FO	98.0	0.950	284.2	122.50	-2.75	1.03	347.3

Fuel Oil Tank(P)	185								
FOT1(S): No1 Fuel Oil Tank(S)	149-185	FO	98.0	0.950	284.2	122.50	2.75	1.03	347.3
FOT2(P): No2 Fuel Oil Tank(P)	113-149	FO	98.0	0.950	284.2	95.50	-2.75	1.03	347.3
FOT2(S): No2 Fuel Oil Tank(S)	113-149	FO	98.0	0.950	284.2	95.50	2.75	1.03	347.3
FOT3(P): No 3 Fuel Oil Tank (P)	31-41	FO	98.0	0.950	38.2	25.08	-7.00	3.26	68.6
FOT3(S): No3 Fuel Oil Tank(S)	31-41	FO	98.0	0.950	38.2	25.08	7.00	3.26	68.6
Total Fuel Oil Tanks					**1213.2**	**103.72**	**0.00**	**1.17**	**1526.4**
Diesel Oil Tanks									
DOT(P): Diesell Oil Tank(P)	31-41	DO	98.0	0.900	123.0	24.60	-11.85	12.78	43.2
DOT(S): Diesell Oil Tank(S)	31-41	DO	98.0	0.900	123.0	24.60	11.85	12.78	43.2
Total Diesel Oil Tanks					**246.0**	**24.60**	**0.00**	**12.78**	**86.4**
Fresh Water Tanks									
DWT(P): Distilled Water Tank(P)	8-10	FW	100.0	1.000	19.8	5.68	-8.31	13.28	0.0
DWT(S): Distilled Water Tank(S)	8-10	FW	100.0	1.000	19.8	5.68	8.31	13.28	0.0
FWT(P): Fresh Water Tank(P)	0-8	FW	100.0	1.000	59.9	2.75	-7.89	13.33	0.0
FWT(S): Fresh Water Tank(S)	0-8	FW	100.0	1.000	59.9	2.75	7.89	13.33	0.0
Total Fresh Water Tanks					**159.4**	**3.48**	**0.00**	**13.32**	**0.0**
Lub Oil Tanks									
LOT(P): Lub Oil Tank(P)	17-35	LO	98.0	0.900	44.7	17.50	0.00	1.40	7.4
Total Lub Oil Tanks					**44.7**	**17.50**	**0.00**	**1.40**	**7.4**
Provisions					13.0	14.50	0.00	16.07	0.0
Total					**13.0**	**14.50**	**0.00**	**16.07**	**0.0**

Wprov_dep									
Wconst									
crew					3.0	18.50	0.00	15.00	0.0
Const					95.0	18.50	0.00	14.20	0.0
Total Wconst					**98.0**	**18.50**	**0.00**	**14.22**	**0.0**
Lightweight					**7567.0**	**72.76**	**0.00**	**9.94**	**0.0**
Deadweight					**35857.6**	**90.55**	**0.00**	**5.64**	**1620.4**
Total Displacement					**43424.6**	**87.45**	**0.00**	**6.39**	**1620.4**
Grain heeling moment									**[7432.2]**
Permissible grain moment									**[54426.2]**
Buoyancy					**43424.6**	**87.45**	**0.00**	**5.52**	**280628.3**
Total Buoyancy					**43424.6**	**87.45**	**0.00**	**5.52**	**280628.3**

Figure 5.2.7a: **Full Load Departure Condition**

Draft at LCF	10.648	metres
Draft aft at marks	10.567	metres
Draft fwd at marks	10.733	metres
Draft at AP	10.567	metres
Draft at FP	10.733	metres
Mean draft at midships	10.650	metres

Trim by the bow	0.167	metres
KG	6.393	metres
FSC	0.037	metres
KGf	6.430	metres
GMt	5.548	metres
BMt	6.462	metres
Waterplane area	4385.16	sq.metres
LCG	87.447	metres
LCB	87.448	metres
LCF	81.173	metres
TCF	0.000	metres
TPC	45.123	tonnes/cm
MTC	538.970	tonnes-m/cm

Figure 5.2.7b: **Hydrostatics at FLD Condition**

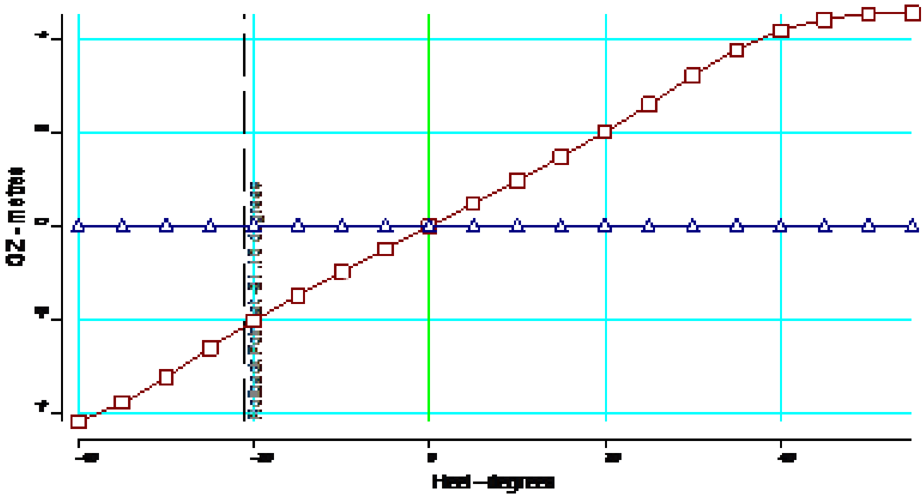


***Figure 5.2.8:* GZ curve as the cargo is still solid**

As can be noticed both from the GZ curve and the below given stability table, when the cargo is solid all stability criteria are fulfilled.

Criterion	Actual	Critical	
		Value	Value
1	Area under GZ curve up to 30 degrees > 0.055	0.801	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.654	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	1.456	0.090
4	Initial GM to be at least 0.15 metres	5.548	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	4.564	0.200
6	Max GZ to be at an angle > 30 degrees	53.262	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	0.155	16.000
8	IMO Weather Criterion (Areas)	5.574	1.000

***Figure 5.2.9*: Stability criteria are fulfilled in FLD condition**

Cargo in liquid state in all cargo holds

In our first cargo liquefaction scenario we assumed that all cargo holds transfer liquefied material. Thus, as cargo liquefaction takes place the vessel stability is lost. Free surface moments are high and lead to negative value of metacentric height and secondarily to a great degree of heeling angle. These results are shown in the following graphs.

Density of water	1.0290	tonnes/cu.m
Heel to starboard	20.27	degrees
Trim by the bow	0.494	metres
KG	6.301	metres
FSC	6.060	metres
GMt	0.862	metres
BMt	7.703	metres
BMl	212.503	metres
Waterplane area	4599.54	sq.metres
LCG	87.326	metres
LCB	87.345	metres
TCB	2.367	metres
LCF	82.761	metres
TCF	4.077	metres
TPC	47.329	tonnes/cm
MTC	552.573	tonnes-m/cm
Deadweight	35858	tonnes
Total Displacement	43425	tonnes

***Figure 5.2.10*: Hydrostatic data while the cargo in all holds behaves as liquid**

As can be easily shown from the below given graph most IMO criteria are not satisfied in this condition.

Criterion	Actual	Critical Value	Value
1	Area under GZ curve up to 30 degrees > 0.055	0.020	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.062	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.081	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	0.385	0.200
6	Max GZ to be at an angle > 30 degrees	37.193	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	-19.173	16.000
8	IMO Weather Criterion (Areas)	1.628	1.000

**** Condition does not comply ****

***Figure 5.2.11*: Stability criteria are not met**

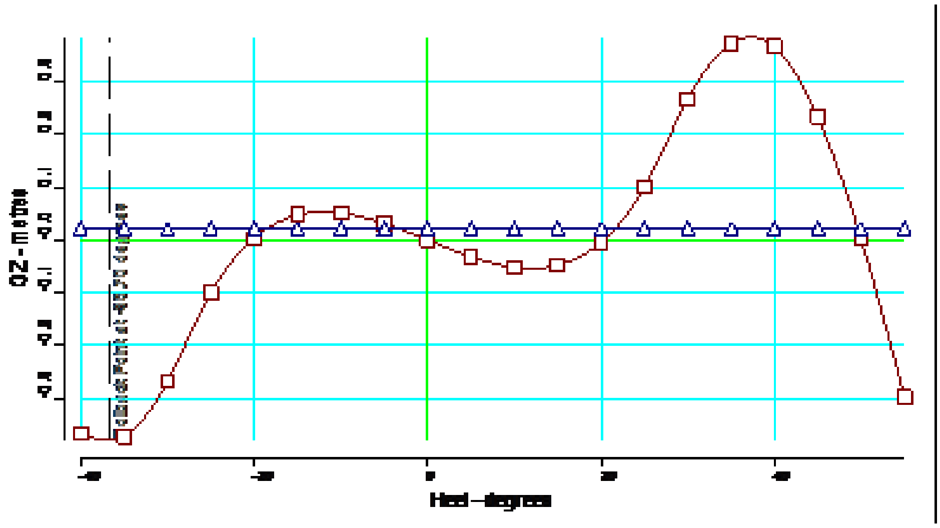


Figure 5.2.12: GZ curve as the cargo is liquefied

Safety Inflated Devices placed on 1st part

In our first try we located the balloons so as to occupy an area from the mid of cargo hold 5 to the mid of cargo hold 4. The shape, as mentioned, is cylindrical and the radius is in that case R=B/4. They were set below the waterline from draft 3.4 m to 10.6 m. The outcome is that now stability is sufficient.

As can be shown from the following figure the establishment of SID on the outer surface of cargo holds 4 & 5 ameliorated the stability problem of the vessel. All IMO criteria are fulfilled and the ship is not anymore at risk of capsizing.

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.163	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.128	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.291	0.090
4	Initial GM to be at least 0.15 metres	1.388	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	0.764	0.200
6	Max GZ to be at an angle > 30 degrees	36.382	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	0.712	16.000
8	IMO Weather Criterion (Areas)	6.119	1.000

Condition complies with the regulations

***Figure 5.2.13*: All stability criteria are met**

In the next two graphs , i.e hydrostatic data and GZ-ϕ graph we clearly demonstrate the effect of the balloons to the vessel's stability for different heeling angles. Critical parameters such as GZ_{max}, BM are higher as the blisters are implemented. As a result, GM value is now higher compared to the first case whereby liquefaction took place and no SID were established.

Density of water	1.0290	tonnes/cu.m
Trim by the bow	1.354	metres
KG	6.296	metres
FSC	6.057	metres
GMt	1.388	metres
BMt	8.408	metres
BMl	196.461	metres
Waterplane area	4539.47	sq.metres
LCG	87.339	metres
LCB	87.396	metres
TCB	0.000	metres
LCF	81.592	metres
TCF	0.000	metres
TPC	46.711	tonnes/cm
MTC	511.105	tonnes-m/cm

***Figure 5.2.14*: Hydrostatic as cargo has liquified and SID are placed on 1st part**

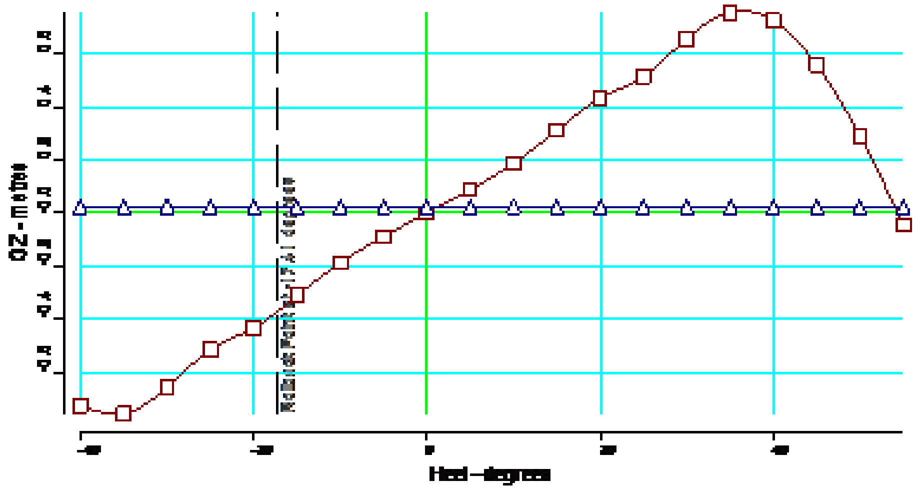


***Figure 5.2.15*: Comparison of stability curves with and without balloons**

Safety Inflated Devices placed on the 4th part (Mid Cargo 1 to Mid Cargo 2)

We changed the position of the balloons keeping them at the same size (radius). According to the results from AVEVA, stability is slightly influenced by the position change. GM is increased as well as trim which now holds a high value, more than 2 meters.

Density of water	1.0290	tonnes/cu.m
Trim by the stern	2.244	metres
KG	6.296	metres
FSC	6.057	metres
GMt	2.093	metres
BMt	9.099	metres
BMl	235.006	metres
Waterplane area	4749.06	sq.metres
LCG	87.339	metres
LCB	87.245	metres
TCB	0.000	metres
LCF	84.510	metres
TCF	0.000	metres
TPC	48.868	tonnes/cm
MTC	611.383	tonnes-m/cm
Displacement	43446.1	tonnes

***Figure 5.2.16*: Hydrostatics**

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.185	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.136	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.320	0.090
4	Initial GM to be at least 0.15 metres	2.093	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	0.805	0.200
6	Max GZ to be at an angle > 30 degrees	36.505	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	0.438	16.000
8	IMO Weather Criterion (Areas)	4.104	1.000

***Figure 5.2.17*: All stability criteria are met**

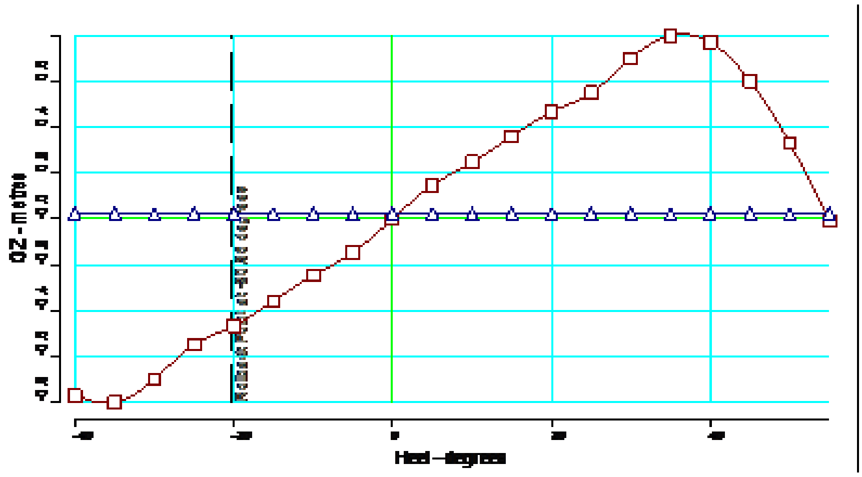


***Figure 5.2.18*: GZ curve with blisters on cargo holds 1 and 2**

Conclusion

We repeated the same procedure for the remaining two parts along the cargo holds. The outcome is that as the whole cargo is liquefied and at the same time keeping the size of the SID the same, the position of the blisters does not play any significant role. Under all circumstances, vessel's stability was adequate not only in the small heeling angles, but also in high angles.

Examination of stability for liquefaction in one cargo hold

In the following cases we conducted stability calculations, while only one of the five holds transfer liquefied material. Fortunately, this is not sufficient for causing capsizing of the vessel in all cases. Thus it is not necessary to place any balloon so as to provide additional buoyancy.

Liquefaction in cargo hold 5

In this scenario the cargo is liquefied in the aft-most hold. The ship does not capsize, as shown in the next page:

Density of water	1.0290	tonnes/cu.m
Trim by the bow	0.151	metres
KG	6.382	metres
FSC	1.362	metres
GMt	4.235	metres
BMt	6.466	metres
BMl	207.392	metres
Waterplane area	4385.19	sq.metres
LCG	87.431	metres
LCB	87.433	metres
LCF	81.169	metres
TCF	0.000	metres
TPC	45.124	tonnes/cm
MTC	538.984	tonnes-m/cm
Grain Heeling Moment	5770.534	tonnes-metres
Displacement	43401	tonnes

***Figure 5.2.19*: Hydrostatic data while mass of the cargo in cargo hold 5 is liquid**

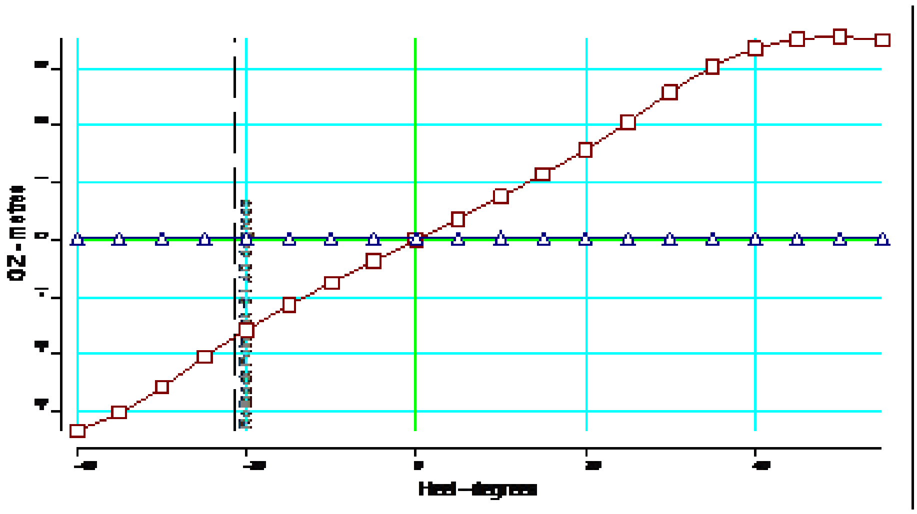


***Figure 5.2.20*: GZ curve with liquefied cargo hold 5**

Liquefaction in cargo hold No 1

Now we assumed that a part of the cargo has liquefied in cargo hold no1. The results are almost the same as in the previous case. Vessel does not face any stability problem.

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.721	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.594	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	1.316	0.090
4	Initial GM to be at least 0.15 metres	4.949	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	4.089	0.200
6	Max GZ to be at an angle > 30 degrees	51.530	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	0.174	16.000
8	IMO Weather Criterion (Areas)	5.489	1.000

***Figure 5.2.21*: All stability criteria are met**

Free surface effects as the cargo in only one cargo hold behaves as a liquid can be characterised as minor. This can be derived also from the following figure, where hydrostatic data are demonstrated.

Density of water	1.0290	tonnes/cu.m
Trim by the bow	0.210	metres
KG	6.391	metres
FSC	0.636	metres
GMt	4.949	metres
BMt	6.458	metres
BMl	207.079	metres
Waterplane area	4384.31	sq.metres
LCG	87.498	metres
LCB	87.500	metres
TCB	0.000	metres
LCF	81.195	metres
TCF	0.000	metres
TPC	45.115	tonnes/cm
MTC	538.673	tonnes-m/cm
Grain Heeling Moment	6674.864	tonnes-metres
Displacement	43441.4	tonnes

***Figure 5.2.22*: Hydrostatic as mass of the cargo in hold 1 has liquefied**

Reduction of the width of SID

The size of the balloons was reduced and instead of R=B/4 we modelled them by using R=B/5 m. Thus, the included drafts were from T=4.85 m to T=10.65 m. Notwithstanding this reduction, SID remained effective and although obviously stability, e.g. GM, is diminished, it remained at a quite satisfactory level as shown in the figures below.

Safety Inflated Devices placed on 1st part

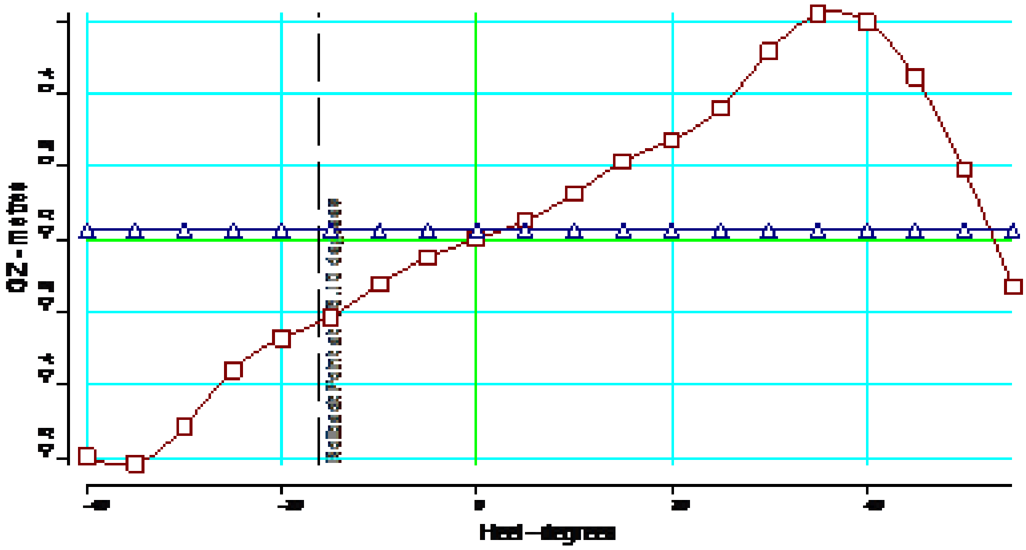


***Figure 5.2.29*: GZ curve with blisters on cargo holds 4 and 5**

Density of water	1.0290	tonnes/cu.m
Trim by the bow	0.889	metres
KG	6.296	metres
FSC	6.057	metres
GMt	0.800	metres
BMt	7.732	metres
Waterplane area	4518.27	sq.metres
LCG	87.339	metres
LCB	87.376	metres
TCB	0.000	metres
LCF	81.045	metres
TCF	0.000	metres
TPC	46.493	tonnes/cm
MTC	528.166	tonnes-m/cm
Displacement	43446.1	tonnes

***Figure 5.2.30*: SID of reduced width remain effective**

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.111	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.104	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.215	0.090
4	Initial GM to be at least 0.15 metres	0.800	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	0.626	0.200
6	Max GZ to be at an angle > 30 degrees	36.714	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	1.327	16.000
8	IMO Weather Criterion (Areas)	7.532	1.000

***Figure 5.2.31*: All stability criteria are satisfied**

The same investigation was carried out in the other three parts of the vessel and the results showed that in those cases too, different positions of the blisters lead to quite close hydrostatics and increased stability. The latter outcome is shown in the figure below, which shows a GZ curve for the 4th part of the ship.

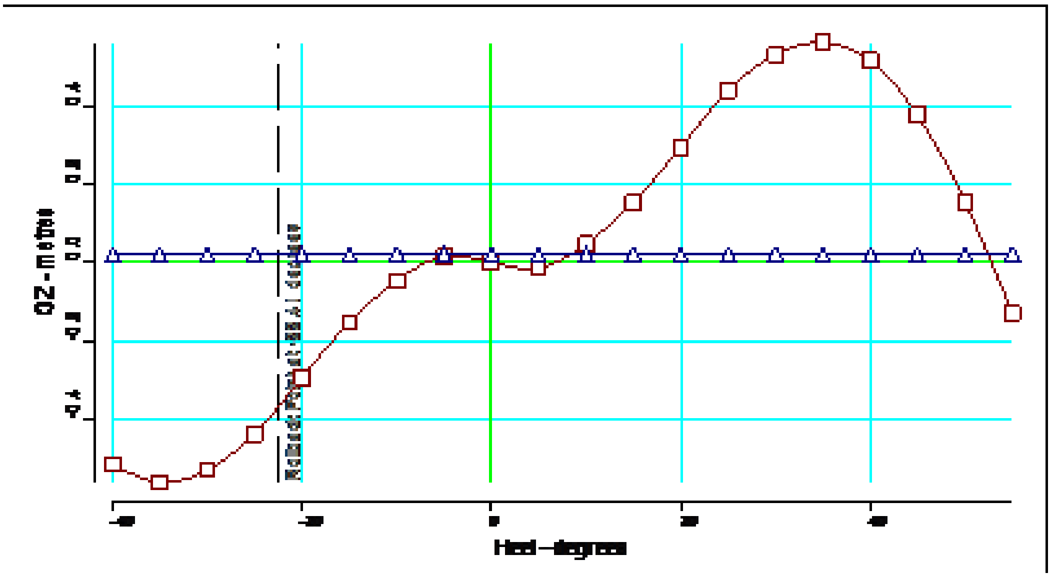


***Figure 5.2.33*: GZ curve with blisters on cargo holds 1 and 2**

SID at lower drafts

A different case investigated was to adjust the position of SID at lower drafts, specifically 1.75 to 9 meters insted of 3.4 to 10.6 m. The radius was kept the same as in the initial calculations, namely R=B/4.

Safety Inflated Devices placed on 2nd part

Density of water	1.0290	tonnes/cu.m
Heel to starboard	7.95	degrees
Trim by the bow	0.977	metres
KG	6.296	metres
FSC	6.057	metres
GMt	0.877	metres
BMt	8.084	metres
BMl	210.101	metres
Waterplane area	4587.62	sq.metres
LCG	87.339	metres
LCB	87.297	metres
TCB	0.985	metres
LCF	82.476	metres
TCF	0.848	metres
TPC	47.207	tonnes/cm
MTC	546.591	tonnes-m/cm
Displacement	43446.1	tonnes

***Figure 5.2.34*: Hydrostatics for blisters fitted at very low draft on holds 3 and 4**

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.117	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.128	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.245	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	0.762	0.200
6	Max GZ to be at an angle > 30 degrees	36.370	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	-6.786	16.000
8	IMO Weather Criterion (Areas)	4.898	1.000

***Figure 5.2.35*: All stability criteria are fulfilled**

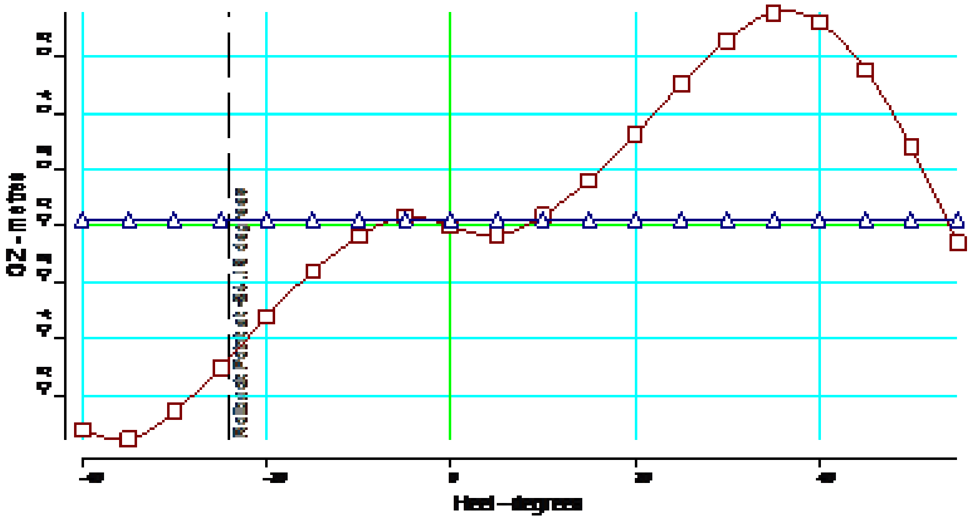


***Figure 5.2.36*: GZ curve with blisters at lower draughts**

As can be derived from the graphs, the stability criteria are satisfactory, although SID were placed at lower drafts. However, the value of attained GM is less than in the previous cases. Additionally, it is noticed that in high heeling angles, stability is adequate.

Safety Inflated Devices placed on 4th part

Density of water	1.0290	tonnes/cu.m
Heel to starboard	3.84	degrees
Trim by the stern	2.449	metres
KG	6.296	metres
FSC	6.057	metres
GMt	0.522	metres
BMt	7.683	metres
Waterplane area	4572.67	sq.metres
LCG	87.339	metres
LCB	87.235	metres
TCB	0.476	metres
LCF	82.451	metres
TCF	0.166	metres
TPC	47.053	tonnes/cm
MTC	580.398	tonnes-m/cm
Displacement	43446.2	tonnes

***Figure 5.2.38*: Hydrostatics for blisters fitted at very low draft on holds 1 and 2**

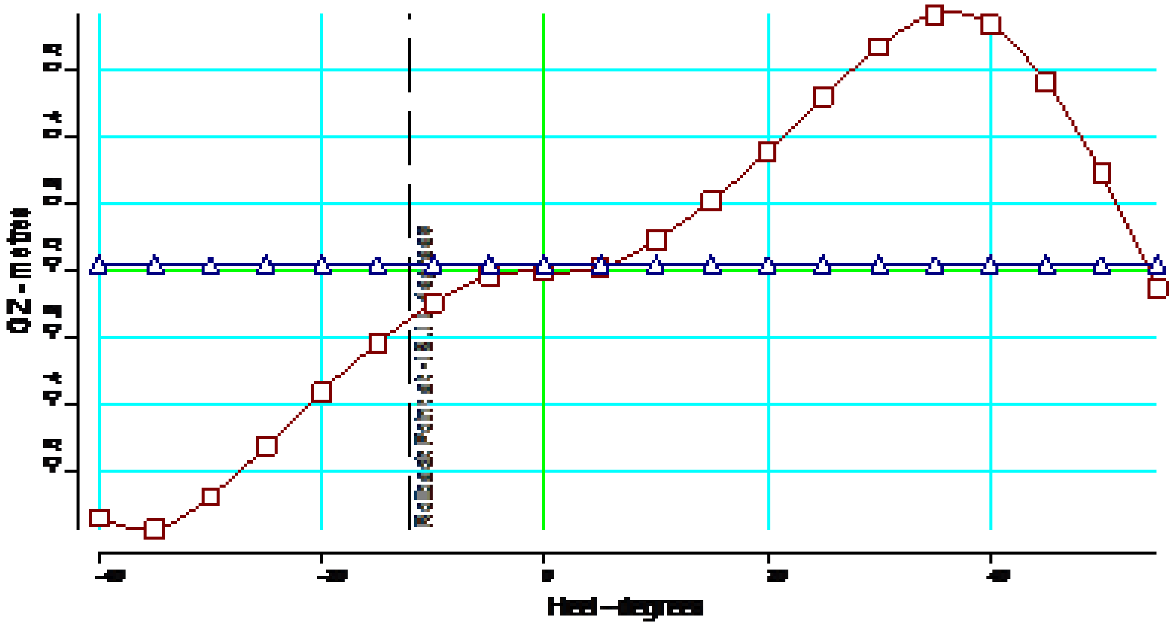


***Figure 5.2.39*: GZ curve with blisters at lower draughts placed on holds 1 and 2**

As in the previous scenario, although stability is deteriorated, still according to the regulations of IMO, stability criteria are fulfilled. The metacentric height particularly is slightly lower as SID were placed closer to bow.

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.133	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.131	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.264	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	0.776	0.200
6	Max GZ to be at an angle > 30 degrees	36.387	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	5.232	16.000
8	IMO Weather Criterion (Areas)	21.527	1.000

***Figure 5.2.40*: All IMO stability criteria are met**

Conclusion

The same procedure was followed for the rest two parts of the vessel. It can be concluded from all cases that although blisters were established at low drafts, stability was adequate. GM was reduced as SID were placed in the foremost cargo holds and was close to the critical value. It is worth mentioning that the heeling angle is quite small, but on the other hand, the trim is more than two meters.

SID above waterline

The next figures show the results of adjusting the balloon position above the waterline. The radius was kept as usual R=B/4. The vertical extent of the SID was from T=5.4 m to T=12.5 m, namely two meters above the attained draft in FLD. Apparently, as can be derived from the below given graphs, the efficacy of the blisters is less as they are semi-submersed.

SID above WL on holds 4 & 5

Density of water	1.0290	tonnes/cu.m
Trim by the bow	1.016	metres
KG	6.296	metres
FSC	6.057	metres
GMt	2.634	metres
BMt	9.567	metres
BMl	204.776	metres
Waterplane area	4722.75	sq.metres
LCG	87.339	metres
LCB	87.381	metres
TCB	0.000	metres
LCF	80.092	metres
TCF	0.000	metres
TPC	48.597	tonnes/cm
MTC	532.738	tonnes-m/cm
Displacement	43446.1	tonnes

***Figure 5.2.44*: Hydrostatics for SID fitted at high drafts on holds 4 and 5**

The graph shows that GM value and trim are sufficient (1 m). In addition, no heeling angle is noticed.

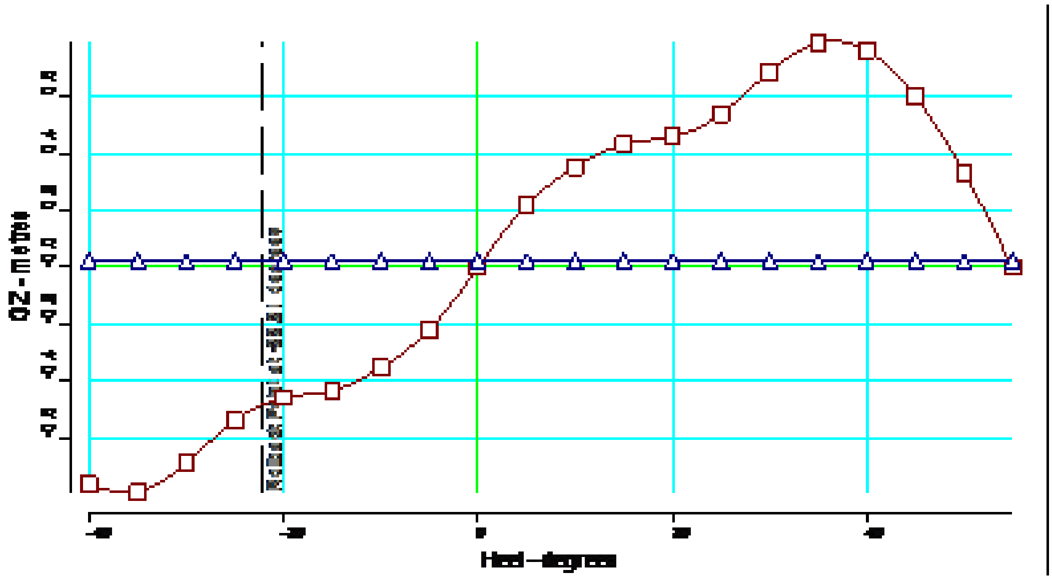


***Figure 5.45*: GZ curve with blisters at higher draughts placed on holds 4 and 5**

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.205	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.134	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.339	0.090
4	Initial GM to be at least 0.15 metres	2.634	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	0.795	0.200
6	Max GZ to be at an angle > 30 degrees	36.501	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	0.345	16.000
8	IMO Weather Criterion (Areas)	3.077	1.000

***Figure 5.2.46*: All stability criteria are satisfied**

SID above WL on holds 2 & 3

Density of water	1.0290	tonnes/cu.m
Trim by the stern	0.794	metres
KG	6.296	metres
FSC	6.057	metres
GMt	2.728	metres
BMt	9.662	metres
BMl	213.960	metres
Waterplane area	4794.05	sq.metres
LCG	87.339	metres
LCB	87.306	metres
TCB	0.000	metres
LCF	83.241	metres
TCF	0.000	metres
TPC	49.331	tonnes/cm
MTC	556.625	tonnes-m/cm
Displacement	43446.1	tonnes

***Figure 5.2.48*: Hydrostatics for SID fitted at high drafts on holds 2 and 3**

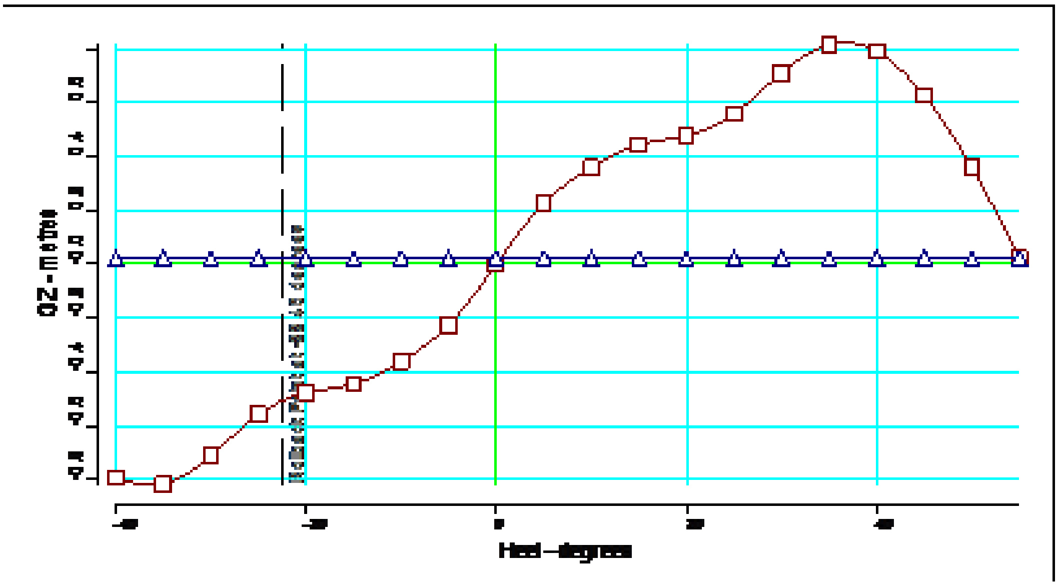


***Figure 5.2.49*: GZ curve with SID at higher draughts placed on holds 2 and 3**

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.212	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.138	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.350	0.090
4	Initial GM to be at least 0.15 metres	2.728	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	0.823	0.200
6	Max GZ to be at an angle > 30 degrees	36.608	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	0.329	16.000
8	IMO Weather Criterion (Areas)	3.062	1.000

***Figure 5.2.50*: All stability criteria are satisfied**

Improved stability criteria, regardig both small and high angles are met, as Safety Inflated Devices are placed on the foremost holds.

Width reduction of SID

In this case we decreased both the size and the drafts where we placed the balloons. Thus, SID are settled between drafts 2.9 to 8.7 m and additionally, the width is reduced to R=B/5 m. It is notable that the position of SID plays a significant role. The latter is shown in the following scenarios.

Safety inflate devices placed on the 1st part

Density of water	1.0290	tonnes/cu.m
Heel to starboard	10.27	degrees
Trim by the bow	0.941	metres
KG	6.296	metres
FSC	6.057	metres
GMt	0.910	metres
BMt	7.904	metres
BMl	204.437	metres
Waterplane area	4546.44	sq.metres
LCG	87.339	metres
LCB	87.378	metres
TCB	1.247	metres
LCF	81.542	metres

Density of water	1.0290	tonnes/cu.m
TCF	1.455	metres
TPC	46.783	tonnes/cm
MTC	531.857	tonnes-m/cm
Displacement	43446.1	tonnes

***Figure 5.2.51*: Hydrostatics for SID fitted with reduced width 2.9m to 8.7m on holds 4 and 5**

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.079	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.101	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.180	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	0.607	0.200
6	Max GZ to be at an angle > 30 degrees	36.635	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	-9.210	16.000
8	IMO Weather Criterion (Areas)	3.895	1.000

***Figure 5.2.52*: All stability criteria are satisfied**

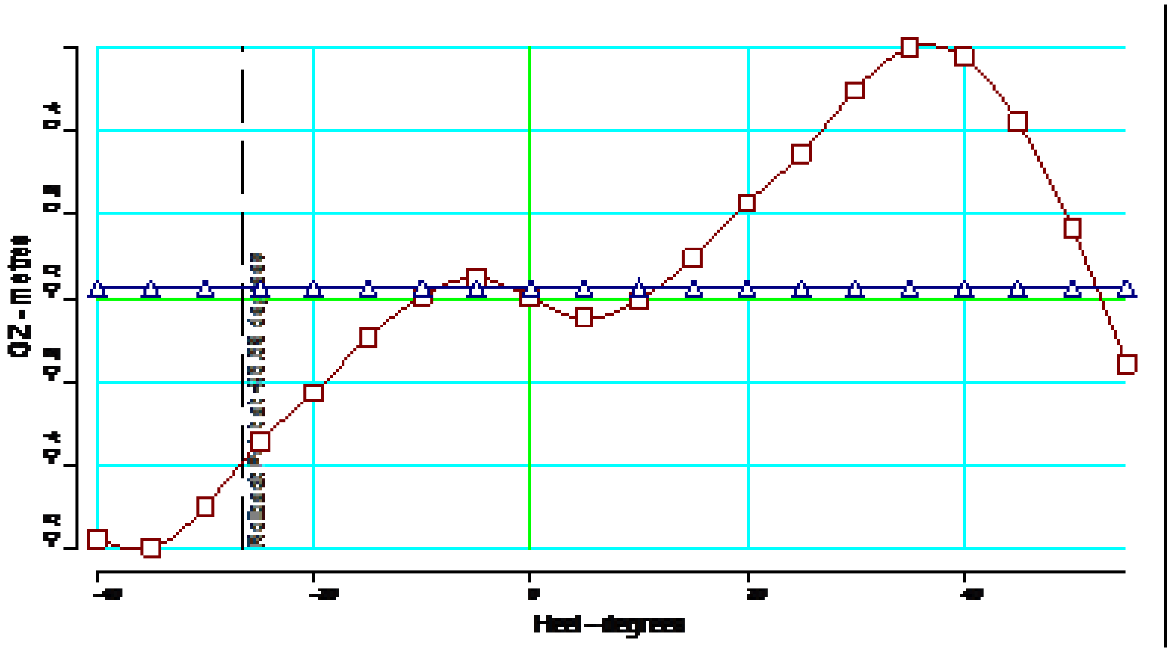


***Figure 5.2.53*: GZ curve with SID with reduced width placed on holds 4 and 5**

Safety inflate devices placed on the second part

Density of water	1.0290	tonnes/cu.m
Heel to starboard	9.77	degrees
Trim by the stern	0.503	metres
KG	6.296	metres
FSC	6.057	metres
GMt	0.890	metres
BMt	7.888	metres
BMl	209.606	metres
Waterplane area	4579.00	sq.metres
LCG	87.339	metres
LCB	87.318	metres
TCB	1.187	metres
LCF	82.515	metres
TCF	1.351	metres
TPC	47.118	tonnes/cm
MTC	545.303	tonnes-m/cm
Displacement	43446.1	tonnes

***Figure 5.2.54*: Hydrostatics for SID fitted with reduced width 2.9m to 8.7m on holds 3 & 4**

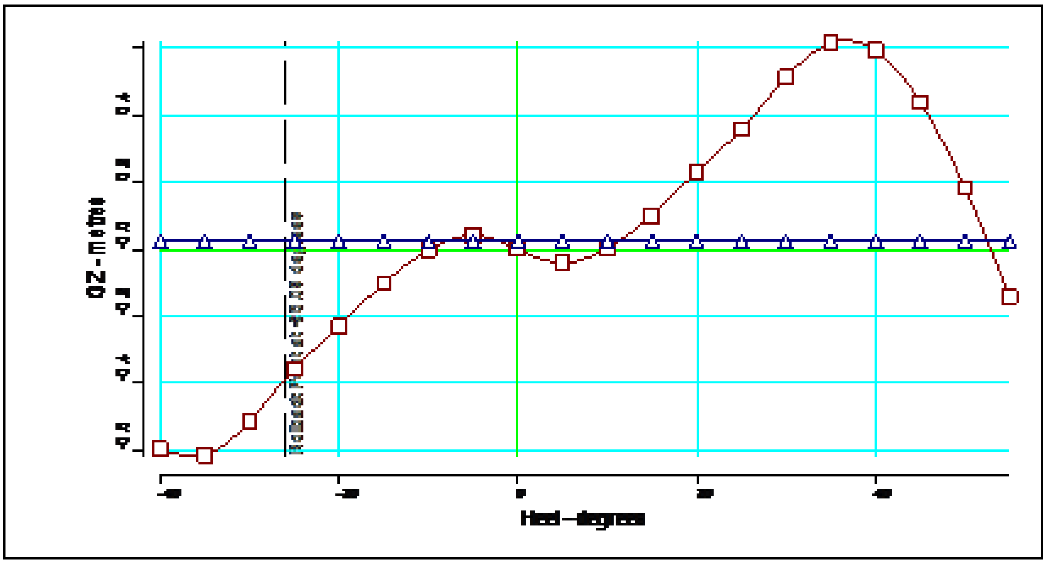


***Figure 5.2.55*: GZ curve with SID with reduced width placed on holds 3 and 4**

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.082	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.104	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.186	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	0.624	0.200
6	Max GZ to be at an angle > 30 degrees	36.709	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	-8.671	16.000
8	IMO Weather Criterion (Areas)	4.165	1.000

***Figure 5.2.56*: All stability criteria are met**

It should be mentioned that although the width is reduced and the blisters were located at lower draughts, stability criteria are met in m circumstances. An important observation is that for the aftmost part of the vessel the attained GM, i.e. stability at small heeling angels, is slightly higher than the required GM. As SID are settled closer to the stem, stability improves.

5.3 Concluding Remarks

The main outcome of the above mentioned research is that the solution of implementing Safety Inflated Devices can lead to adequate stability, even when the whole cargo is liquefied. It is not necessary to place blisters along the entire length of cargo, but only between two holds. In case that the material of a hold behaves as liquid, the installation of SID on the outer surface of that hold, prevents capsizing of vessel. Finally, B/4 is a critical value of the size of balloons, which in all scenarios, e.g. semisubmersible, lead to fulfilment of stability criteria of IMO.

Key points of our results are given below:

- Only one liquefied cargo hold cannot cause capsizing of the vessel.
- As 30% of the volume of the cargo has liquefied in all cargo holds, vessel capsizes.
- As the cargo has liquefied in all holds, the installation of blisters between the mid of two cargo holds leads to adequate stability too.
- SID are more effective when they are entirely submersed and just below the waterline.
- Although semi-submerged SID render decreased stability, as the B/4 width is implemented, stability criteria are fulfilled.
- The devices offer adequate but at the same time diminished stability, as the width is reduced from B/4 to less than B/5.
- The efficacy of SID placed at lower drafts is restricted. However, stability is rendered as adequate.
- As a general rule, when SID are placed closer to stem, they offer improved stability.

Moisture absorbing light material

After identifying the controlling parameters governing material failure, our aim is to find a remedial factor that can reduce the transport liquid mobility of the cargo. Such factor could be absorbent light material able to absorb a quantity of the wet mass of the cargo keeping it in a solid state during the voyage. Our target is to find material that is very absorbent, very light and at the same time cheap. The latter criterion should be fulfilled under any circumstances so that the examined solution to be competitive in the market.

The material that will be tested belongs to the superabsorbent polymers [53] (also called slush powder) and its water holding capacity is excellent. It may absorb 500 times its weight (from 30-60 times its volume) and can become up to 99.9% liquid. In addition, the tested powder is harmless, non toxic and nonpolluting. SAP is found in personal disposable hygiene products, such as baby diapers and sanitary towels. It is also used for blocking water penetration in underground power or communication cables, horticultural water retention agents, control of spill and waste aqueous fluid, artificial snow for motion picture and stage production.

The cost of this powder is 3,600 $ to 3,900 $ per ton. A rough research shows that for the safe carriage of iron ore and nickel ore fines holding a high value of moisture content, e.g. 40 %, transferred in a typical Handymax cargo hold with a capacity of 14,000 m^3, the cost is approximately 40,000 $ for each hold for the purpose of reducing the moisture content below the Transportable Moisture Limit. Compared with the proposal of converting the midship section of a bulk carrier by installing two longitudinal bulkheads in line with the hatch coamings, powder is much more cost-efective, because it is a temporary solution and the cargo capacity is only slightly reduced. In contrast, the conversion proposed by the Italian Classification society RINA, costs about 3 million dollars and the main drawback is the permanent reduction of DWT, because the space between the two longitudinal bulkheads and the hull needs to remain void for safety reasons.

Consequently, a certain quantity of slush powder will be placed in the model hold and mixed with the test material of high moisture content. The controlling parameters of the experiments, i.e. amplitude, frequency and moisture content, will remain unchanged compared to those that previously caused liquefaction of the sample. In case that is proved that powder is effective against liquefaction, less expensive powders with lower swelling capacity will be identified.

Chapter 6: Discussion

In the beginning of the thesis we underlined the objectives that shall be fulfilled due to the thorough investigation of the problem. The majority of the objectives were reached, but further study needs to be done so as to find an effective solution to the problem.

A detailed research on accidents attributed to cargo liquefaction, showed that the main result of liquefaction is the loss of stability and subsequently the capsizing of the ship. Structural failure seems to have a secondary role in our problem. It is worth mentioning, that a problem that we faced was the poor number of reports that describe in detail the accidents. Thus, for many accidents we sought to different sources so as to draw a conclusion. Those reports have not come to light yet and might have been confidential. However, IMO in one of the last sessions encouraged its members to publish the studies carried out on cargo liquefaction accidents. The latter will help the maritime industry to understand the phenomenon faster and solve the problem.

Furthermore, the existing legislative scheme was scrutinized in our project. As a general observation we can note that until now there are many shortcomings in the existing legislation, i.e. in the IMSBC Code. Iron ore and nickel ore which are the two cargoes most susceptible to liquefaction do not hold a specific bulk cargo shipping name, as many other cargoes, in order to be listed in one of the three groups of IMSBC Code. Last September the Sub-Committee agreed to the draft amendment 02-13 to the International Maritime Solid Bulk Cargoes (IMSBC) Code, including a nickel ore schedule, and relevant draft guideline, but the amendment was adopted in June 2013.

With respect to iron ore fines amendments to the IMSBC Code containing provisions on measure on liquefaction will not enter into force until 1st January of 15. Hence, it can be concluded that bureaucratic procedures prevent the development of the current regulation, it is compulsory in the near future to make amendments quicker.

Moreover, testing methods for the calculation of the Transportable moisture limit of the cargo are characterized as inadequate up to now. Those procedures were generated for concentrates and not for fines. Research of IMO aims to revise the methods that the TML is calculated and focus is based on the modification of the Peneration Test.

Before the cargo is shipped to vessel, it is usually stockpiled or/and transferred in open barges and trucks. Thus, in the event of a rain the MC content increases, giving more chances for a subsequent cargo liquefaction. As a result another legislative gap that should be taken into consideration is the protection of the material before its loading.

Many experts claim that specially constructed of fitted vessels is the solution for confronting the problem. A deficiency meted in a SCCS vessel is the reduced DWT and the high cost of the modification. In addition, the ship will face the disadvantage of carrying only one type of cargo. IMO has not established up to now any precise design criteria on how a specially constructed of fitted bulk carrier should be built.

A huge part of our project was focused on the careful examination of liquefaction in other disciplines of engineering so as to identify the controlling parameters of the phenomenon and check what progress has been done in areas where liquefaction renders a serious problem since decades. Soil mechanics was the main field of study, as earthquakes have caused in many sites soil liquefaction. The amount of information regarding this field was enormous and different approaches and points of views were studied, having sometimes of course ambiguities regarding a specific subject. Thus, we had to make correct judgements and choose which view was correct and objective. The most distinguished researcher in this area is Seed and the information included in my thesis concerning soil liquefaction was extracted mostly from his articles. His publication *Recent Advances in Soil Liquefaction Engineering: A Unified and Consistent Framework,* can be characterized as the state of the art for understanding all about soil liquefaction.

Soil liquefaction occurs in loose and saturated sites. Field observations indicated that liquefaction can happen after a first few seconds of sufficiently strong shocks. When the acceleration takes a certain of value of some g, pore water pressure increases and the progressive loss of strength is taking place. It verified that deformation during cyclic loading will depend on the soil's density, the magnitude, initial confining pressure and duration of the cyclic loading. Shaking in multiple directions and for longer duration is more damaging for soil liquefaction.

As regards the soil properties the long-term study concedes that the fines content influences liquefaction. But void ratio, relative density and permeability are some other crucial parameters. Specifically, an increase in predominantly fines content, saturation degree and void ratio involves a liquefiable soil. On the other hand, permeability and relative density, i.e. how dense is the soil, prevents the soil from liquefaction.

Furthermore, we examined the possibility of adopting the mitigation measures in soil liquefaction for confronting cargo liquefaction. In my opinion, the only method that can be transferred to our field is the pore water relief, where liquefaction can be prevented by rapid drainage. This can be done by establishing in the cargo holds moisture absorbing materials. One of the goals of the thesis was to test the efficacy of such material, and particularly a light powder that may absorb 500 times its weight. However, the test can be achieved only experimentally.

The numerical model that is used more and more for the complete understanding of liquefaction is the FEM. There are an increasing number of finite element (FEM) and finite difference (FDM) programs available for analysis of liquefaction-related problems. Finite element analysis can be carried out to obtain the pore pressure distribution and ground displacement along the depth of the soil deposit. The ongoing Brazilian research on iron ore fines which was described in Chapter 3 includes finite element modelling to determine the response of iron ore fines cargo in a hold of a bulk carrier subjected to roll motions.

In offshore engineering, the implemented numerical model is the Mohr-Coulomb model. In our project we did not check the possibility of identifying the controlling parameters of cargo liquefaction by using the above mentioned model.

It is worth mentioning that there is a consensus in the parameters that lead to liquefaction among the different disciplines of engineering. All agree that the combination of the soil properties of granular materials and the intensity of the phenomenon. With respect to soil properties, saturation is a factor that influences liquefaction. Materials containing high moisture content are prone to liquefaction. Additionally, soils that contain a high proportion of fine particles smaller than 100 μm may avoid liquefaction.

With regard to the intensity of the phenomenon, application of a large number of cyclic loads with moderate amplitude can produce liquefaction of the soil. Moreover, the increase of oscillation amplitude corresponds with the interval of most rapid rise of pore pressure.

As it can be easily realized, the thesis is based on theoretical and computational approach of the problem. Notwithstanding, a detailed experimental programme is developed and shall be developed in the future. Duration, amplitude, frequency of excitation forces as well as the properties of materials, regarding the moisture content, will change the result will be the entire identification of cargo liquefaction. However, the most important will be the check of the effectiveness of SAP.

The last part of the thesis is the proposal and examination of a possible solution concerning the stability of the cargo and the ensuing ship stability problem. A Supramax bulk carrier case study was introduced in Chapter 5 where safety inflated devices were established on the outer surface of the vessel so as to provide additional buoyancy when the cargo in the holds is liquefied. The examination was carried out in the sophisticated ship design program NAPA and the results can be characterised as optimistic.

Ship stability is lost in such a vessel when only one cargo hold carries liquefied material. Nevertheless, if a SID is positioned on the outer surface of the hold, the ship is saved. In our investigation we changed the position and the width of the SID conducting thus a rough optimisation. It can be concluded that while SID are placed closer to stem, they offer improved stability. On the other hand a useful observation is that SID are more effective when they are entirely submersed and just below the waterline, rather than at lower drafts where the stability is diminished.

Those devices give a solution to the problem for sure and their implementation has to be checked in the near future. They hold the advantage of being a much cheaper and easier solution than the up to now proposed solution of establishing two additional longitudinal bulkheads.

Chapter 7: Conclusions

The research carried out in this thesis shows that cargo liquefaction renders a major problem which strikes the maritime industry and especially the dry bulk market. Unfortunately, so far, the progress done for confronting the problem can be characterized as insufficient. Liquefaction as it was notably depicted has been affecting different disciplines of engineering for many decades and its effects are detrimental.

Additionally, the causes that lead to liquefaction, regarding particularly the soil properties, remain in a few cases unknown. As regards cargo liquefaction, which was the core of our study, it is a combination of the high moisture content of the cargo, the size of the particles that constitute the material and the high energy imparted to the vessel by the waves. Due to this joint pore water pressure increases, the contact forces between the particles weaken and the cargo behaves more like a liquid than a solid. Concerning the energy it is concluded that liquefaction is caused by excitation forces with low frequency, high amplitude and longer duration.

The existing legislative scheme is poor but the ongoing research focuses on determining the legislative gaps and further on the revision of the regulations. The main outcome of the thesis presented in the previous pages was there are some mitigation measures that can solve the problem. The effectiveness of the safety inflate devices was tested and it can be derived that can offer adequate stability even when the whole cargo is liquefied. It is worth mentioning that only one liquefied cargo hold can capsize the vessel, but the implementation of SID on the outer surface of the hold, saves the vessel. Another reasonable solution that shall be tested is the moisture absorbent light material.

Finally, the developed experimental program aims to embrace the detailed theoretical and computational approach given above and identify entirely the cargo liquefaction problem.

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