SOLID BULK SHIPPING: CARGO SHIFT, LIQUEFACTION AND THE TRANSPORTABLE MOISTURE LIMIT

by

Timothy Paul Rose

A thesis submitted for the degree of

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ABSTRACT

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If some solid bulk cargoes such as concentrates, unprocessed nickel ores and iron ore fines contain sufficient moisture, then cargo compaction during a voyage may cause liquefaction. This has been known to result in major cargo displacement ('cargo shift'), causing the vessel to capsize. This has resulted in a number of fatalities. To provide context to this interdisciplinary problem, an overview of the key considerations is presented, which includes: (i) a summary of the wide range of factors that influence a cargo's likelihood to shift; (ii) the soil mechanics principles that can be used to explain cargo shift; and (iii) the regulatory controls that are used to prevent its occurrence during shipment.

Under the requirements of international maritime regulation, primarily the International Maritime Bulk Solid Cargoes (IMSBC) Code, a cargo that may liquefy must be shipped below a threshold moisture content, the 'Transportable Moisture Limit' (TML)—as determined from one of three laboratory test methods specified within the IMSBC Code. However, there are recognised problems with these tests, namely that for any given sample tested: (i) the tests give variable TML results, particularly when conducted in different laboratories; and (ii) each of the three test methods give a different TML result. As the TML determines a cargo's transportability, these issues have commercial and safety implications. To address these issues for the two most popular test methods, the Flow Table Test (FTT) and Proctor/Fagerberg Test (PFT), tests were performed on sand and iron ore fines. For each test, major sources of variability were identified, along with issues inherent in the test methodology. From these findings, a number of recommendations and several modifications have been proposed that, if implemented within the IMSBC Code, will improve the tests' reliability. The results were then compared to establish whether the different TML results obtained from the two test methods could be aligned—this showed that calibration between the methods was not possible on the basis of their TML. The test method assessment also incorporated observations at TML test facilities, interviews with leading researchers and an assessment of archive research material.

Whilst the findings related to variability will help improve the reliability of the TML test methods, the accuracy of these methods is still not understood (*i.e.* how well do they indicate the likelihood for an actual cargo to liquefy?). This thesis therefore gives consideration to the likely accuracy of the TML test methods. It presents an improved representation of the cargo shift problem, with a view of providing future researchers with a basis to further assess this accuracy and thus the suitability of the TML as a criteria to detect cargoes which may liquefy.

ACKNOWLEDGEMENTS

My last few years at Oxford could not have been possible without the support and guidance of family, mentors and friends.

Firstly, I could not have come to Oxford without the generous support from my parents. I am sincerely grateful for the countless hours they have devoted to managing paperwork on my behalf, during my time in the United Kingdom.

The research presented in this thesis would not have been possible without assistance from my supervisor Professor Byron Byrne. His geotechnical insight and academic guidance has ensured I have continued to learn and develop during my time researching in Oxford. I would also like to thank Clive and Bob in the Civil Laboratory, who have always been happy to patiently assist and entertain me over the last few years. As have the many other friends and colleagues in the Civil Engineering group. I also greatly appreciate the time spent by my examiners, Chris Macminn and Andrew Brennan, reading this thesis - and the thoroughness in which they went through it.

My initial exposure and subsequent interest in the cargo shift problem developed during my time working with Dave Linden, my old boss. When we were first presented with this research problem a few years ago, every aspect was a new and almost foreign concept. However, his engaging leadership and mentoring provided me with amazing opportunities to learn, travel and develop during my time working as a metallurgist. Without these opportunities, I would not have embarked on this research.

I extend a special thank you to Prof John Atkinson, Prof Neil Taylor and Dr Andrew Kruszewski, who were kind enough to take the time to meet with me and discuss the cargo shift research that they performed at City University and Warren Springs Laboratory in 1980 to 1990's. Their insight and experience was of great value, helping to solidify many conclusions.

My time in the United Kingdom will surely be particularly memorable because of the many experiences I have had with the many different friends, including those from college, the Civil group, housemates, and many that have moved over here from Perth. These people have provided endless support and made my last few years very enjoyable.

Finally yet importantly, I would like to thank Phoebe for her support over the last few years. After a hundred weeks of weekly travel from to Oxford to London, we can finally be back living in the same city.

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ACRONYMS/GLOSSARY

Angle of Repose: If a material is poured onto a horizontal surface, a conical pile will form. The angle of repose is the slope angle at which the pile sits to the horizontal.

BC Code: The Code of Safe Practice for (Solid) Bulk Cargoes (adopted by IMO as a recommendatory code in 1965) aimed to facilitate the safe stowage and shipment of solid bulk cargoes, by providing information on the dangers associated with shipment and instructions on the appropriate procedures to be adopted. This was superseded by the IMSBC Code, which became mandatory on 1 January 2011.

BC (BC Sub-Committee): The Bulk Cargoes Sub-Committee guided the MSC on matters related to the safe carriage of bulk solids, including those related to cargo shift. This committee was formed in the early 1960's and was replaced by the DSC Sub-Committee in 1995.

Bulk Carrier: A ship designed to carry solid bulk cargoes.

Capesize: A type of bulk carrier (100,000 to 200,000 d.w.t. tonnage capacity). It is one of the largest types of carrier and typically transports high-volume bulk commodities such as iron ore.

Cargo Schedule: Individual cargoes are listed within 'schedules' of the IMSBC Code, Appendix 1. These describe each cargo's properties and classifications (for example, 'Group A') and detail the requirements for handling, stowing and carrying it safely. Some schedules also contain tests specific to that cargo.

CCC (BC Sub-Committee): The Committee for Carriage of Cargoes and Containers, which replaced the DSC in 2014.

Competent Authority: Responsible for domestic enforcement of the IMSBC Code.

Condition of Carriage: The conditions that a Shipper must meet in order for the cargo to be shipped.

CT (Can Test): An indicative test which the ship's Master may perform (generally on an already loaded cargo) to verify that the cargo is not likely to liquefy during passage.

d.w.t. (Deadweight tonnage): A measure (normally in metric tons) of a ship's carrying capacity, also taking into account fuel, fresh water, crew and provisions.

Deck (or, 'ship's deck'): On a bulk carrier, the primary or upper deck is the horizontal structure which forms the 'roof' for the hull, which both strengthens the hull and serves as the primary working surface.

Degree of Saturation (*S*)**:** Volume of water within the inter-particle voids of a granular material (such as a dry bulk commodity). It is expressed as a percentage, where water completely fills the voids at S=100% and the material is completely dry at S=0%.

DSC (DSC Sub-Committee): The Dangerous Solids and Cargoes Sub-Committee guided the MSC for safety related matters associated with solid bulk cargoes. As of 2013, this was replaced by the CCC. Prior to 1995, cargo shift related matters were submitted to the BC Sub-Committee.

FMP (Flow Moisture Point): The minimum moisture content at which cargo liquefaction may occur, as determined from test methods specified within the IMSBC Code.

FTT (Flow Table Test): One of the three methods within the IMSBC Code used to determine the TML of a Group A cargo. It is based loosely on the slump test for cements, used in civil engineering.

Group A Cargo: The IMSBC Code's classification for cargoes that may liquefy. These are subject to the mandatory reporting, testing and carriage requirements for Group A cargoes within the IMSBC Code (for example, such cargoes must be shipped at a moisture content below the TML).

Heel: (ship's heel): See 'list'.

Hold: the space where cargo is filled in a ship. A bulk carrier contains multiple compartmentalised holds along its length.

Hold Configuration: The arrangement and geometry of holds on a ship.

IMO (International Maritime Organization): A sub-body of the UN and the international maritime regulator. Renamed from the Inter-Governmental Maritime Consultative Organization (IMCO) in 1982.

IMSBC Code: The International Maritime Solid Bulk Cargoes (IMSBC) Code is the regulatory tool used by IMO to ensure the safe carriage of solid bulk materials. This replaced the BC Code in 2008 and became mandatory on 1st January 2011.

List: When the ship assumes an angle of rotation over the transverse axis (*i.e.* the roll axis), usually due to a change in centre of gravity of the cargo (such as that from cargo shift).

Master (or, Captain): a licensed mariner in ultimate command of the ship.

MSC (The Maritime Safety Committee): One of four technical groups within IMO that oversees safety related maritime issues. The BC/DSC/CCC sub-committees guide the MSC on matters related to cargo shift and liquefaction.

P&I Club (Protection and Indemnity Insurance Club): Mutual insurance association that provides a form of marine insurance.

PFT (Proctor/Fagerberg Test): One of the three methods within the IMSBC Code used to determine the TML of a Group A cargo. It is based on the Proctor test, used in civil engineering.

PSD (Particle Size Distribution): The distribution of particles at different size fractions (often expressed as 'percent finer by weight'). The PSD may also be described in terms of grading. A ‘poorly graded’ soil refers to a narrow distribution (all particles are of a similar size). A ‘well graded’ soil refers to a wide distribution (there is a range of particle sizes).

PTT (Penetration Test): One of the three methods within the IMSBC Code used to determine the TML of a Group A cargo.

Shipper: The merchant who delivers the goods to the carrier (for example, a commodity producer).

Shipper’s Declaration: A document presented by the Shipper to the Master that declares the properties of the cargo to be loaded onto a vessel. For Group A cargoes, this includes its moisture content and TML, whereby the loaded moisture content must be lower than the TML.

Solid bulk cargo (or, *bulk solid cargo*, or *bulk cargo*): Any material, other than liquid or gas, which consists of a combination of particles, granules or any other larger pieces of material that is loaded directly into the cargo spaces of a ship without any intermediate form of containment.

Solid bulk carrier: A ship designed to carry bulk solids.

Specific Gravity (G_s): The weight of a material relative to water (no voids).

TML (Transportable Moisture Limit): A concept within the IMSBC Code that represents the maximum moisture at which a Group A cargo can be safely loaded to prevent liquefaction (TML [% moisture] = 90% × FMP [% moisture]). The TML is determined by test methods, as specified within Appendix 2 of the IMSBC Code.

Trimmed/Trimming: The selective pouring of a cargo into a hold, aiming to level the pile and thus reduce its susceptibility to slope failure.

NOTATION

Material Properties

ρ_i and ρ_f	initial and final bulk density of cargo
$\rho_{dry,i}$ and $\rho_{dry,f}$	initial and final dry bulk density of cargo
e	void ratio
w	moisture content, by dry mass
mc	moisture content, by wet mass
v	specific volume
S_i and S_f	initial and final degree of saturation of cargo
G_s	specific gravity
V_i and V_f	initial and final volume of cargo

Stress and Strain

τ'	shear stress
σ'	effective vertical stress

Strength

c'	cohesion intercept
ϕ'	friction angle

Angles

θ	angle of repose
φ	roll of hold (to horizontal)
λ	assumed heel/list of ship
α	angle of trimmed slope
i	overall slope angle

1. INTRODUCTION

Solid bulk cargoes[i] can be broadly categorised with regard to their hazards during shipping, namely: *(i)* those that may shift transversely if shipped "dry" due to static slope failure; *(ii)* those that may shift transversely if shipped "wet" due to liquefaction; and *(iii)* those that possess chemical hazards (International Maritime Organization [IMO] BCXVIII/WP.2, 2007). The research in this thesis is concerned with cargo shift, giving primary focus to cargo shift due to liquefaction. Figure 1.1(a) shows a liquefied cargo within a ship's hold.

Almost all solid bulk cargoes are transported using a *solid bulk carrier* (Figure 1.1(b)). Between 1988 and 2014, up to 24 solid bulk carriers capsized and 177 lives were lost due to cargo liquefaction.[ii] This makes it one of the greatest safety risks in bulk solid shipping. A detailed table of fatalities associated with cargo liquefaction, since 1988, is included in Appendix 1.

Figure 1.1: *(a)* What is considered to be liquefied cargo within a ship's hold (Grant, 2008) *(left)*; and *(b)* a Capesize solid bulk carrier (Golden Ocean, 2014) *(right)*.

1.1 CARGO SHIFT AND CARGO LIQUEFACTION OVERVIEW

Cargoes at risk of liquefaction include concentrates, unprocessed nickel ores and iron ore fines. These cargoes usually contain a proportion of fine particles, exhibiting low permeability when compacted. Before the loading of a ship, these cargoes are usually only partially saturated and

[i]A solid bulk cargo is a granular bulk material carried by sea (for example, a bulk commodity).

[ii]Fatality numbers are speculative, as it is usually difficult to establish conclusively if liquefaction was the cause post-capsize. Evidence is often circumstantial (for example, based on observation of a wet base, free surface water and/or collapsed pile), although in a number of cases the cause of incident has been fairly well established (Merchant Shipping Act, 1894a; Merchant Shipping Act. 1894b; Kirby, 1981).

may appear “dry”. The act of ship loading will result in the cargo compacting, whilst forces applied by the ship’s motions and engine vibrations during passage may cause particle re-arrangement and further compaction. In addition, drainage (or “moisture migration”) may occur, leading to an increase in moisture content in part of the cargo. Under these conditions, water may become "trapped” between the interparticle voids, resulting in a rise in pore-water pressures and a loss of strength, as shown schematically in Figure 1.2. In this state, shearing forces (such as those from gravity during a moment of vessel roll) can then cause major displacement of the cargo, termed ‘*cargo liquefaction.*’

Cargo displacement may also occur in “dry” cargoes if the angle of a ship’s rotation is sufficient to overcome the frictional and cohesive forces that provide the cargo pile with strength. The exact mechanisms that cause a particular cargo to shift are complex and largely unknown, as it is difficult in practice to identify the cause of shift by retrospective analysis alone (particularly following vessel capsize). Nevertheless, whilst the processes that cause shift may vary, the consequences of a significant shift are the same—listing, capsizing and/or structural damage.

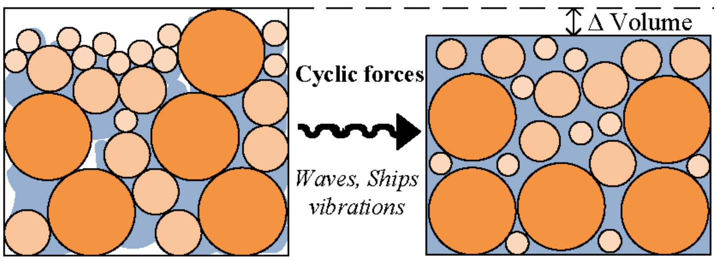


Figure 1.2: The granules of a partly saturated stable cargo *(left)* may compact due to cyclic forces, This compaction may cause the movement of water within the voids, resulting in in an increase in pore-water pressure and loss of cargo strength between the inter-granular contacts, termed ‘liquefaction’ *(right)*.

Figure 1.3 provides an illustration of cargo shift that has been developed as part of this thesis to provide an improved representation of the problem and its various components. Variation of any of the variables in this diagram will influence the likelihood of dangerous shift and/or vessel capsize. Considering the key components of the cargo shift problem, it follows that:

(a) cargo strength and/or the development of pore-pressures depend on the cargo’s *physical characteristics* (such as particles size, shape and angularity), *compaction characteristics*, *moisture content* and *drainage behaviour*;

(b) cargo displacement depends on *(a)* and on the *ship’s motions*; and

(c) the impact of a displaced cargo mass depends on *(a)*, *(b)* and the *ship’s stability*.

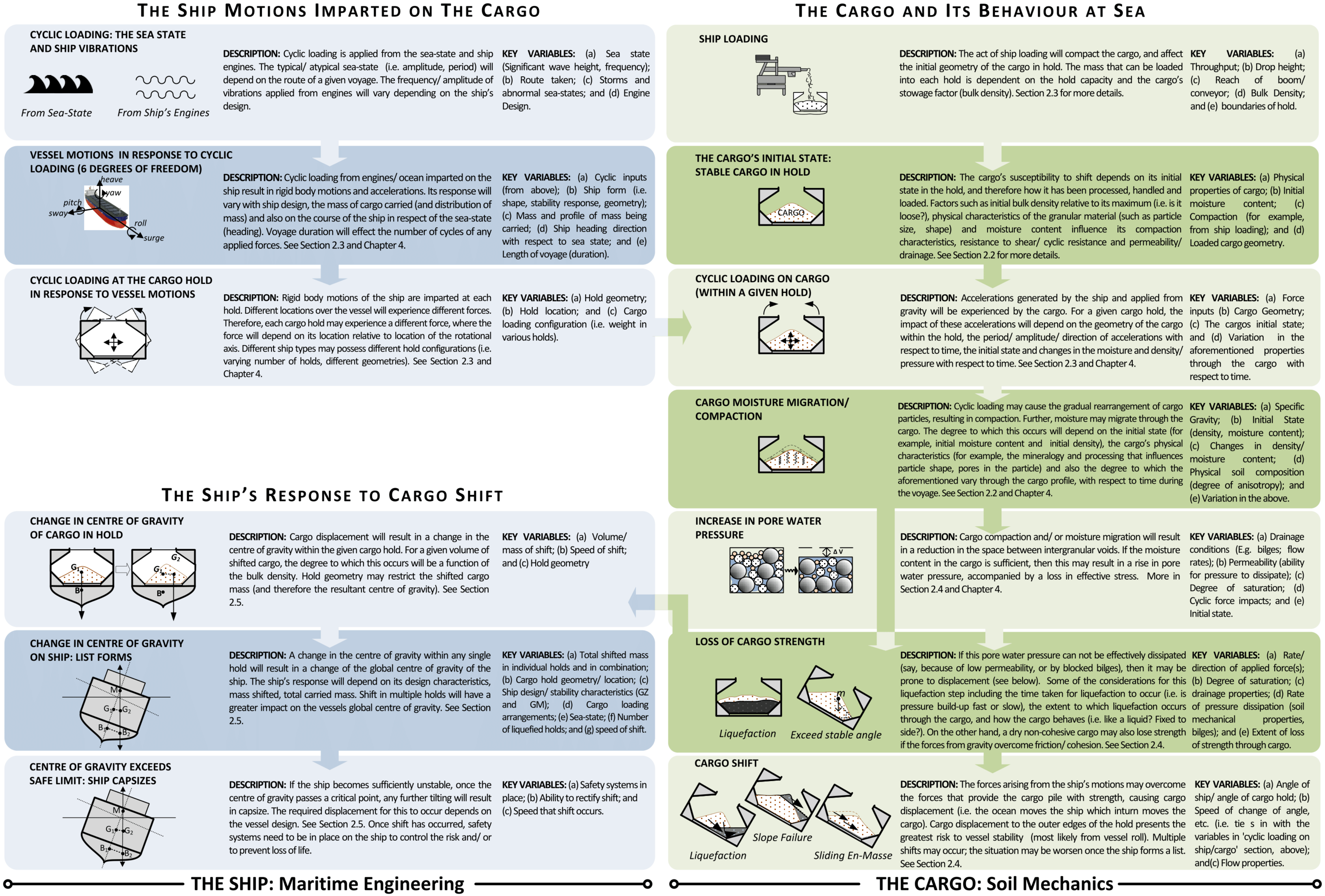


Figure 1.3: A breakdown of the processes that lead to cargo shift, considering those factors related to: (*i*) the ship; and (*ii*) cargo. Each of the key variables, considered in isolation, will influence the likelihood of shift occurring.

1.2 CARGO LIQUEFACTION REGULATION

The International Maritime Organization (**IMO**), a maritime focussed agency of the United Nations, oversees international maritime regulation. IMO's main regulatory tool for solid bulk cargoes, the International Maritime Solid Bulk Cargoes Code (**IMSBC Code**), is also its key instrument in mitigating the risk of cargo liquefaction[i] (IMO, 2009). The IMSBC Code incorporates a number of controls that aim to ensure that at-risk cargoes are loaded at a moisture content below that required to facilitate the development of pore-water pressure that leads to liquefaction, termed the *'Transportable Moisture Limit'* (or, **TML**). As shown schematically in Figure 1.4, the TML is derived from the *'Flow Moisture Point'* (**FMP**), being the minimum moisture required to induce liquefaction, but incorporating a 10% safety factor, whereby:

$$\mathrm{TML}[\%\,\mathrm{moisture}] = 90\% \times \mathrm{FMP}[\%\,\mathrm{moisture}] \tag{1.1}$$

More specifically, cargoes considered as ones that may liquefy are classified as "Group A" cargoes. These are then subject to the testing, reporting and carriage requirements prescribed for Group A cargoes within the IMSBC Code (IMO MSC85/26/Add.2, 2008). This includes a mandatory requirement that they are strictly loaded with moisture content less than the TML, determined from laboratory based testing.[ii]

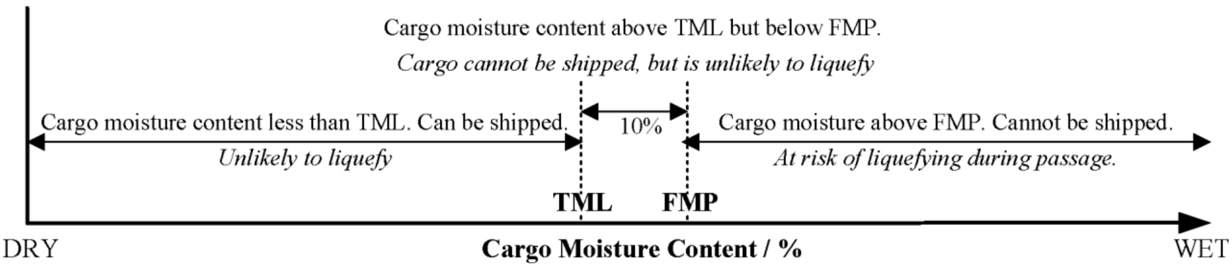


Figure 1.4: The TML and the FMP. Group A cargoes can only be shipped at moisture contents below the TML. The FMP represents the moisture content above which a cargo may liquefy during seaborne transportation.

An overview of the regulatory structure in which international shipping regulation related to cargo shift is made is shown in Figure 1.5. The Maritime Safety Committee (**MSC**) must adopt amendments to the IMSBC Code, under guidance from the Sub-Committee. Information related to cargo shift (*i.e.* research submissions, proposals and regulatory discussion) is contained

[i]The IMSBC Code was adopted by the MSC in 2008, becoming mandatory from 1st January 2011. This replaced the Code of Safe Practice for Solid Bulk Cargoes (BC Code), which was introduced in 1965 as a recommendatory Code and has been updated at regular intervals. See Appendix 2 for further detail.

[ii]Unless a custom, specially fitted ship is used (for example, a ship that is longitudinally compartmentalised to restrict significant transverse displacement). A typical bulk carrier does not meet this requirement.

within Sub-Committee documentation. A more comprehensive account of the regulatory structure and its development, with regard to cargo shift, is included in Appendix 2 of this thesis.

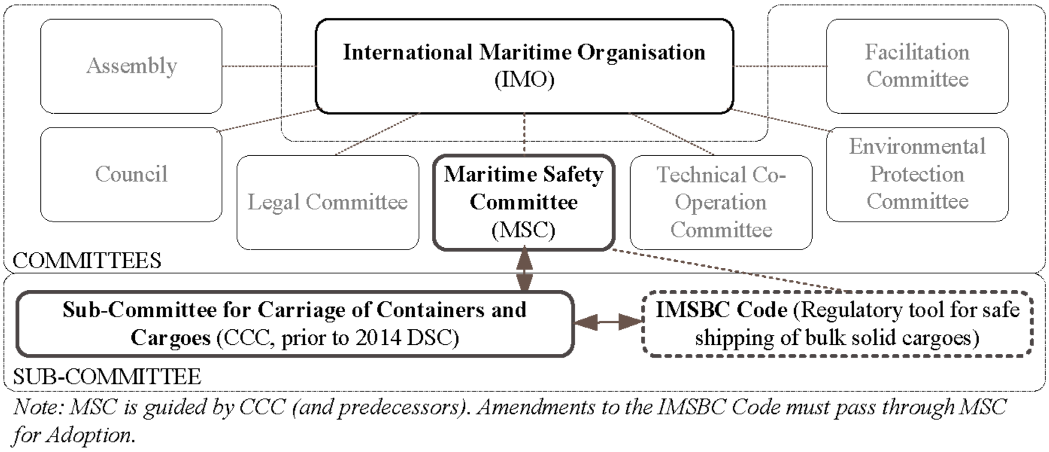


Figure 1.5: Overview of the regulatory structure[i]. See Appendix 2 for further detail.

1.3 SIGNIFICANCE OF THE REGULATION

For all stakeholders[ii] involved in the seaborne transportation of Group A cargoes, which comprise a significant portion of the approximately four billion tonnes of dry bulk cargoes shipped annually (Clarkson's, 2014), the IMSBC Code and the concept of the TML serve as one of the most important components of shipping these cargoes, as they:

(a) help prevent the carriage of cargoes that may be unsafe for shipment, mitigating the risks of loss of cargo, ship and life; but

(b) impose handling and transportability requirements on the Shipper[iii] (typically a commodity producer), which may introduce commercial risks. For example, a Shipper is unable to transport an excessively wet cargo with a moisture content above the TML and this may delay shipment and/or incur additional port fees for docked vessels.

The challenge for IMO and its Sub-Committees is therefore to implement balanced regulation that effectively addresses the safety risks of cargo liquefaction, but does not weigh disproportionately on the Shipper.

[i]Note that CCC held its first session in 2014. Submissions regarding cargo shift prior to 2014 can be found in meeting documentation from BCI to BC34 (1965-1995) and DSC1 to DSC19 (1995-2013). Submissions to the Sub-Committees pre-1998 can be obtained in hardcopy from the IMO headquarters, London.

[ii]Stakeholders include the Shipper, Master, Crew, Owner and insurer (such as P&I Clubs).

[iii]The Shipper is the merchant who delivers the goods to the carrier (for example, a commodity producer).

1.4 SCOPE OF THIS STUDY

There are recognised issues with the test methods used to determine if a Group A cargo is safe for carriage (*i.e.* the tests used to measure/derive the TML). As the TML determines whether a cargo can be transported, an incorrect TML has potential safety and commercial implications. Numerous studies have found that the TML test methods give unreliable results when testing a given sample of cargo material. There are also concerns if the results reported from the TML test methods accurately represent the liquefaction potential of cargo shipment, given that they are only performed on a small element of cargo material.

To address these concerns, this study has aimed to identify any issues inherent in the TML tests and/or provisions in the IMSBC Code so that they can be addressed in future regulation. More specifically, the research presented in this thesis has aimed to contribute to an improved understanding of the problem, by:

(a) detailing the different considerations of the cargo shift problem (**Chapter 2**);

(b) assessing the TML test methods and the associated provisions related to cargo sampling and reporting within the IMSBC Code, and identifying ways to improve the reliability of these test methods (**Chapter 3**); and

(c) exploring the importance of the many other variables that influence a Group A cargo's likelihood of shift, in order to assess whether the TML test methods give an accurate depiction of cargo behaviour (**Chapter 4**).

1.5 APPROACH OF THIS STUDY

Cargo shift is an interdisciplinary problem that demands a practical, holistic approach and an understanding that encompasses a range of disciplines, including:

(a) *Maritime regulation and policy*: The international maritime industry is guided by an established regulatory framework. If any research findings and recommendations are to be widely adopted, then it must be through this framework.

(b) *Soil mechanics* (geotechnical engineering): This explains the reasons why the cargo material may lose strength and shift during passage.

(c) *Maritime engineering*: This explains the ship's motions that are imparted on a cargo, which contribute to cargo compaction and displacement. It also informs us of the impact that cargo shift will have on a vessel's stability.

(d) *Shipping practice*: Acknowledging the differences between regulations and the practical reality ensures that any findings and recommendations can be practically implemented.

To address these requirements, and ensure that any views, findings and recommendations presented in this thesis are of practical relevance, information has been obtained from a broad range of sources and from a variety of experiences. In addition to reviewing conventional literature and undertaking test work, this thesis has attempted to address the shortfalls of previous research by incorporating a range of alternative sources of information, summarised in Figure 1.6. These include: *(i)* interviews with a number of maritime industry experts; *(ii)* site-visits to recognised testing laboratories; *(iii)* discussions with leading, influential researchers in the field; *(iv)* attendance at the international regulatory meeting; and *(v)* assessment of IMO's collection of cargo shift literature from which the regulation was developed, the complete set being available in hardcopy within IMO headquarters (London). A more complete table of these sources of information is included in Appendix 3. This information provided the basis of an assessment of the test methods used to prevent cargo liquefaction, presented in Chapter 3 and Chapter 4 of this thesis.

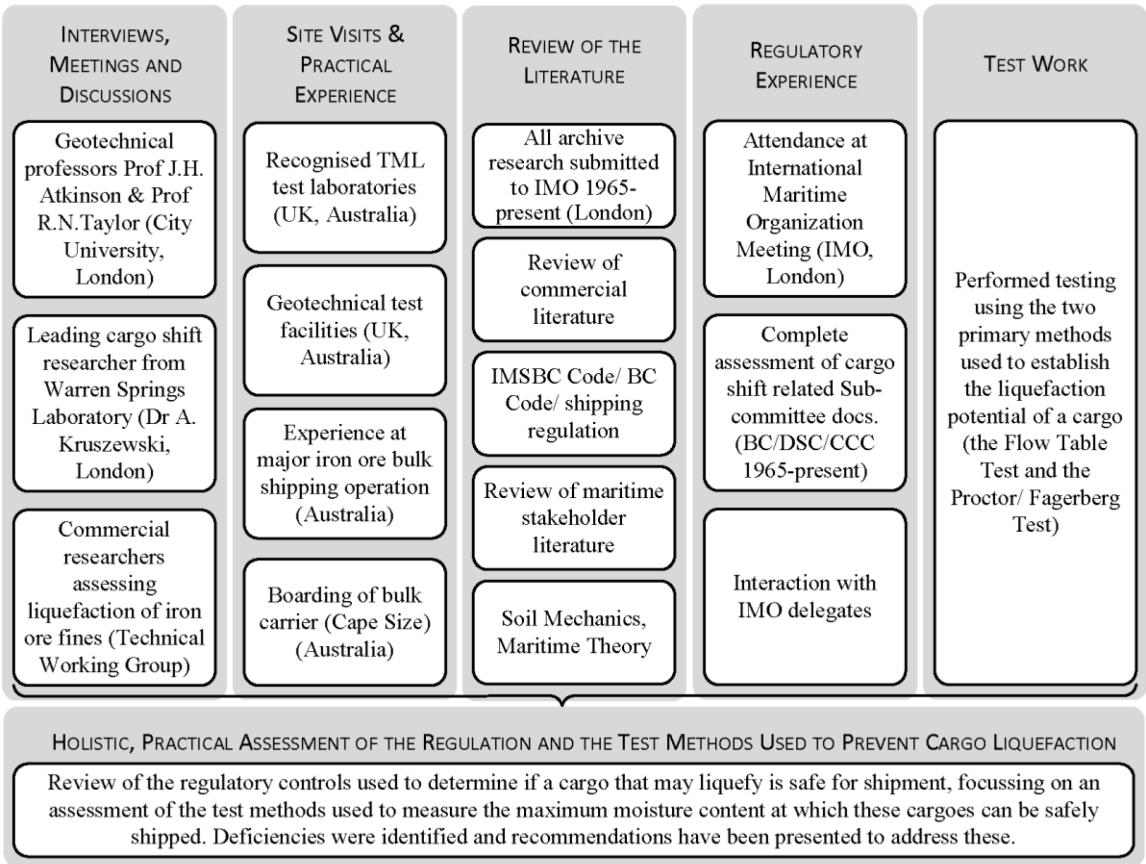


Figure 1.6: Approach taken to develop this thesis.

2. BACKGROUND

This chapter provides an overview of cargo shift and/or liquefaction. Firstly, it presents a background to some of the issues with IMO's approach to regulating the problem, which formed the basis behind the research presented in this thesis (Section 2.1). It then highlights the broad range of at-risk cargoes (Section 2.2) and ship design and motions (Section 2.3) encountered at sea—each which influence the likelihood and/or impact of a cargo liquefaction event. In addition, it presents the key soil mechanics concepts that explain the loss of cargo strength that leads to shift (Section 2.4), and the ship stability concepts that explain how cargo shift can lead to vessel capsize (Section 2.5).

2.1 RECENT DEVELOPMENTS OF THE IMSBC CODE

Cargo shift and liquefaction have been recognised issues since the 1965 adoption of the IMSBC Code's predecessor, the Code of Safe Practice for Solid Bulk Cargoes (**BC Code**). Initially only fine-grained concentrate cargoes were considered as ones which may liquefy if shipped excessively wet (IMO BCI/Conc, 1964; IMO, 1965). However, this classification has since grown to encompass a wide range of coarser cargoes. Major developments in cargo liquefaction regulation since 1965 are shown in Figure 2.1, overleaf (see Appendix 2 for further detail).

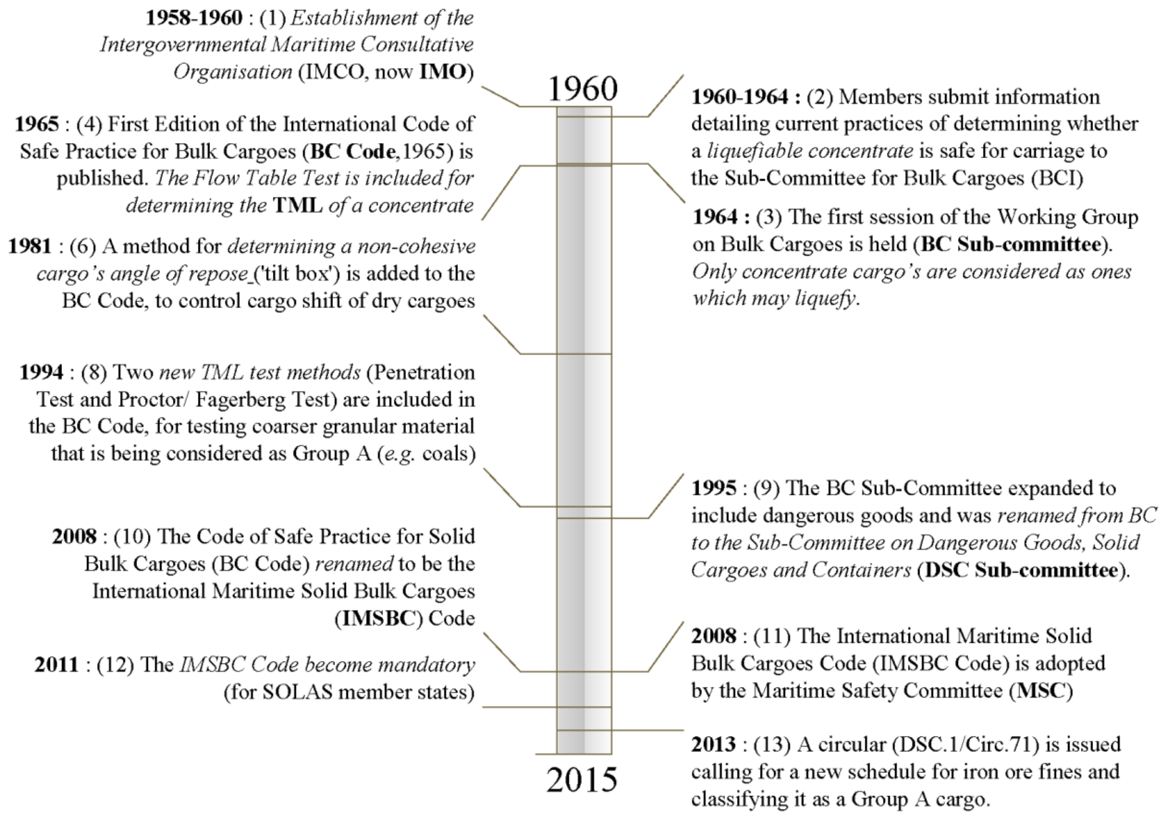
Cargo liquefaction has received significant attention in recent times, firstly as the result of a *concentrated number of fatal cargo shift events*, and secondly as a result of the *regulatory response to these events.* Between 27th October 2010 and 3rd December 2010, three vessels capsized and 44 lives were lost over 39 days, due to the liquefaction of Indonesian nickel ore (MSC90/12/3, 2012).

In response to these incidents, shipping associations and Non-Governmental Organizations called for an "*urgent review into the testing and safety processes involved in shipping hazardous cargoes [that may liquefy]"* (Intercargo, 2013). Subsequently, IMO and its Sub-Committees introduced a number of amendments to the IMSBC Code. This included the re-classification of iron ore fines (iron ore with a particle top size of typically 6.3 mm) as a Group A cargo[i] (IMO DSC.1/Circ.66, 2011). This reclassification subjects all cargoes of iron ore fines to the testing,

[i]There are two other groups of classification in the IMSBC Code. Group "B" cargoes are those which possess chemical hazards, while Group "C" cargoes are neither liable to liquefy nor possess chemical hazards.

reporting and handling requirements for Group A cargoes within the IMSBC Code, many of which were originally developed for concentrates. These new requirements present challenges to many Shippers of these cargoes, for example:

- The Shipper can now only load a cargo below the TML, but they may only be able to meet this requirement by additional processing (*i.e.* to dry the cargo) and this may require significant (and perhaps unrealistic) capital investment.
- The Shipper must now know and report the moisture content of a cargo before it is loaded onto a ship, but the supply chain may not have been designed with the necessary infrastructure to conduct the required sampling or testing.
- The Shipper must now know and report a cargo's TML, yet many laboratories are inexperienced at testing these materials. Prescribed tests may also not give adequate results.



No.	REFERENCE(S)
2	IMO: BCI/2; BC I; BCI/ 5; BCI/ 7; BCI/Conc. Xxx
3	IMO: BCI/2; BC I; BCI/ 5; BCI/ 7; BCI/Conc. Xxx
4	IMO: Code of Safe Practice for Bulk Cargoes (BC Code) 1st Edition (1965)
5	IMO: BCXVIII/WP.1 /Add.1
6	IMO: BCXII/7/1; BCXIV/4/1; BCXV/(b); BCXVII/3(d); BCXVIII/6; BCXVIII/6/2; BCXVIII/WP.1 /Add.3; BCXX/5/3; BCXXII/5/6; BCXXII/5/7; BCXXII/5/11; BC26/WP.9
13	IMO: DSC.1/Circ.63; DSC.1/Circ.66/ Rev.1; DSC.1/Circ.71

Figure 2.1: Major developments in cargo shift regulation (see Appendix II for further detail).

There have been concerns raised by Shippers about the appropriateness of these new regulations for iron ore fines for universal adoption—in part as a result of the above challenges, but also because of the absence of compelling evidence that many of these re-classified cargoes pose a significant risk to warrant these additional costs. More specifically: *(i)* many Shippers have never experienced any liquefaction events for iron ore fines (IMO DSC16/4/74, 2011); *(ii)* the overall number of cargo shift incidents has reduced substantially over the years, as shown in Figure 2.2 (Roberts, 2012); and *(iii)* eighty per cent of recent fatalities have arisen from a concentrated number of 'at-risk' cargoes that comprised only .06% of bulk cargo shipments worldwide, mainly from producers in remote locations in South East Asia (Vittone, 2013).

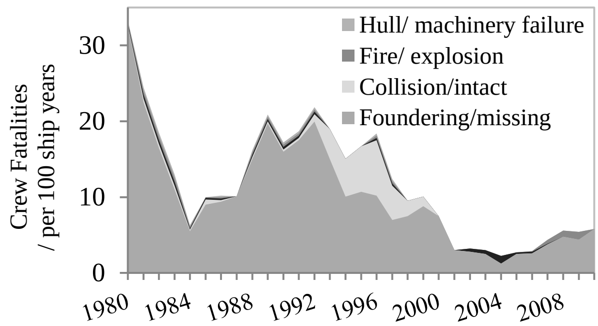


Figure 2.2: The trend of fatalities associated with bulk shipping (1980–2010). Instances of cargo shift have decreased overall, shown as 'foundering/ missing' (Roberts, 2012).

It is likely that some cargoes classified as Group A do not possess the necessary characteristics to liquefy during passage. Applying uniform testing, analysis and reporting requirements for all cargoes within the classification may therefore be unsuitable.[i] As demonstrated in the overview of cargo shift shown in Figure 1.3 and throughout this thesis, there are many variables that influence the risk of a dangerous liquefaction event occurring. Consequently, it appears that the regulation is detached from the science of cargo shift.

To address these concerns, IMO members have been working with industry groups and Shippers to improve the understanding of the science behind the liquefaction risks, and to inform improved regulation (IMO DSC18/INF.14, 2013). The recent work on iron ore fines has formed the basis of a new Group A schedule for this cargo, which was recently adopted for inclusion in the IMSBC Code (IMO DSC.1/Circ.71, 2013). This new schedule incorporates a revised Group A classification criteria that considers a cargo's mineralogy and particle size (previously only

[i]All iron ore fines cargoes that meet a basic particle size and mineralogy criteria are subject to the same requirements. However, iron ore fines cargoes can differ significantly in physical and chemical composition.

the latter was considered) and a new test method. However, these findings apply to iron ore fines only (they aren't generally applicable). Further, they still implement a 'blanket' approach to cargo classification, as iron ore properties within the classification may also vary greatly. [i]

Unlike other research efforts that have typically focussed on only a single cargo type or specific area of the interdisciplinary issue, the research presented in this thesis is aimed at a more general assessment of cargo shift, independent of commercial incentives, which can be applied to a range of Group A cargoes.

2.2 THE SOLID BULK CARGO

2.2.1 Background

International shipping transport accounts for around 90% of global trade (ICS, 2013). The shipping of solid bulk cargoes forms the largest portion of overall shipping trade (43.5%). In recent times, this sector has been expanding rapidly due to Chinese growth, with total trade increasing at an average annual rate of 3.8% since 2000 (Clarkson's, 2014). Commonly transported solid bulk cargoes include commodities such as coal, grains, sugar and unprocessed or processed ores. Of the dry granular materials, coal and iron ore represent the biggest proportion, contributing to approximately 60% of total tonnes of bulk solids shipped annually (Clarkson's, 2014). Figure 2.3 shows the growth in the four major dry bulk cargoes and the increased Chinese steel production that has driven this growth.

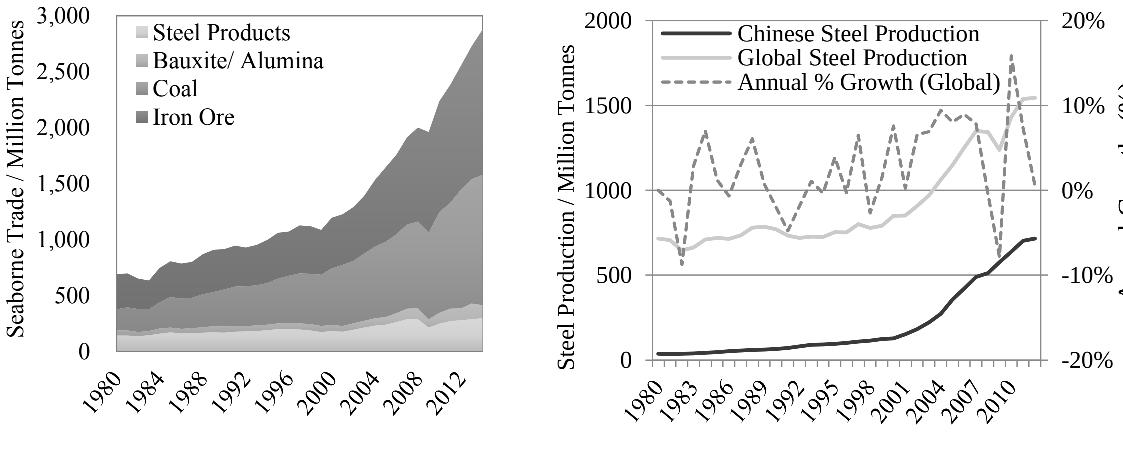


Figure 2.3: *(a)* The growth in the four major dry solid bulk cargoes, some of which may liquefy (adapted from data from Clarkson's (2014)) (*left*); and (*b*) the growth in annual steel production that has driven this increase (adapted from data from World Steel Association (2013)) (*right*).

[i]Under the new schedule for iron ore fines, the cargo is classified as Group A if D_{10} is less than 1 mm, D_{50} is less than 10 mm and the goethite content is less than 35%. This schedule was adopted 1st January 2014 and becomes mandatory on 1st January 2017 (IMO DSC.1/Circ.71, 2013; IMO DSC.1/Circ.73, 2014).

The increased demand from China has also led to significant growth in the shipped volumes of Group A cargoes used within the steel making process (for example, ores of nickel, iron, zinc, etc.). These cargoes may vary significantly in both their chemical and physical properties (for example, mineralogy, angularity, particle size distribution [**PSD**], roughness and appearance), even between any given type. This is demonstrated in Table 2.1, which lists common Group A cargoes and their typical properties (where available).

Table 2.1: Some typical properties of shipped cargoes that may liquefy during seaborne transportation. Most values adapted from BCXVII/3(d)/1 (1977).

SOLID BULK CARGO WHICH MAY LIQUEFY	TONNES CARRIED ANNUALLY (APPROX.)	STOWAGE FACTOR / m^3/t	SPECIFIC GRAVITY* en bloc	ANGLE OF REPOSE *varies with cohesion, / deg.	SATURATION / %	INTERNAL FRICTION COEFFICIENT / μ	ANGLE OF REPOSE FROM INTERNAL FRICTION COEFFICIENT = arctan μ
Alumina Hydrate (Group A and B)	201 Mt (2009)	0.933	2.88	31	62.8	0.682	34.3
Bauxite		0.719	2.21	35	37.2	0.816	39.2
Coal (Can be Group A or C)	1114 Mt (2013)	1.145	1.25	41-50	30.2	0.952	39 - 43.6
Coal Slurry							
Coke breeze		1.477	1.25	40.0	45.7	0.8	38.7
Iron Ore Fines		0.4-0.45	3.8-4.6	46-58	34.3-47.0	0.9962-10	42.8-46.8
Iron Ore Concentrates		0.375	4.05	47.5	34.5	0.889	41.6
Nickel Ore		0.71	2.9			0.85	
Lead Concentrate		0.31		42			
Silica Sand		0.6	2.62	31.5	36.4	0.727	36
Zinc Concentrate		0.56		35			

NOTE: Other Group A cargoes (which may liquefy) include Fluorspar, Ilmenite clay/ sand, nickel concentrates, some sand, peat moss and a number of other concentrates (no cargo properties could be sourced for these materials.

2.2.2 Physical Properties of Group A Cargoes

The PSD is often considered as one of the most important factors for liquefaction, due to its influence on packing density and permeability[i]—rapid draining, coarse or poorly graded materials are unlikely to liquefy. The PSD of a number of Group A cargoes are plotted in Figure 2.4. Some investigators have attempted to use the PSD to conclusively establish a criteria for classifying a cargo as Group A. Criteria based on a PSD cut-off (such as the D_{10}/D_{90}) or particle size average have been suggested (IMO BCI/Conc, 1965; Kruszewski, 1985; IMO BC26/WP.9, 1985). Whilst it is generally recognised that there is a relationship between these criteria and a material's potential to liquefy, no reliable numerical relationship has yet been developed. Defining the potential for a material to liquefy by an average or by the extremes of a PSD range

[i]More specifically, the PSD effects the volume of voids between particles, the permeability, and thus the likelihood for pore-water pressures to develop. The D_{10} is often seen to 'drive' permeability. The density of particle packing under a set of compaction conditions depends not only on the PSD, but also on other physical properties including shape, angularity, specific gravity and roughness/ smoothness.

would be misleading as it is not necessarily representative of the cargo's entire PSD range—or therefore packing and voids between particles. This criterion also ignores other key properties that influence a cargo's liquefaction potential, such as particle angularity, granular porosity, etc.

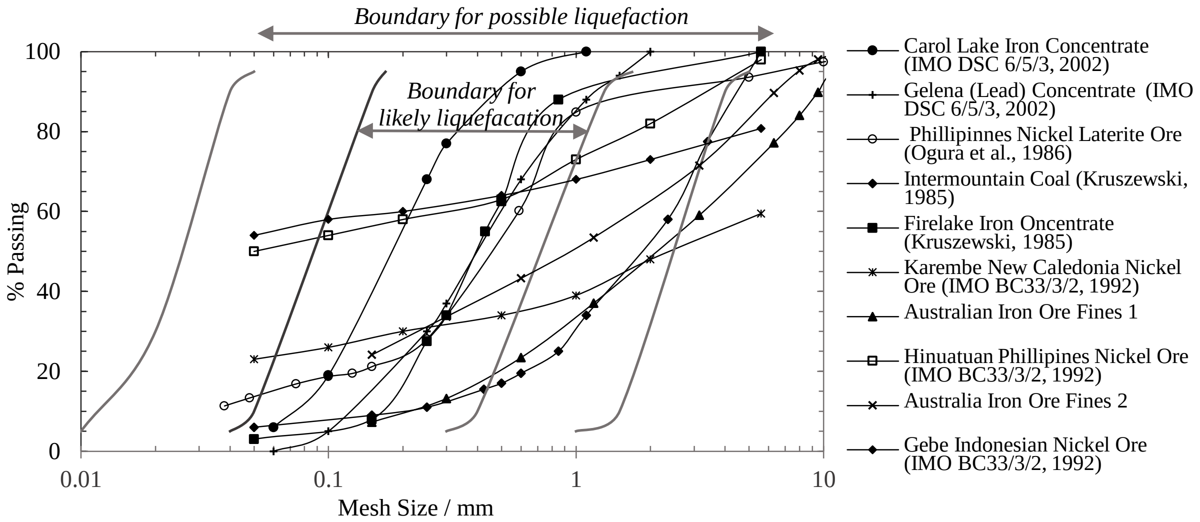


Figure 2.4: The PSD of various Group A cargoes. Also shown are the boundaries for likely and possible earthquake induced liquefaction presented by Tsuchida (1971).

A cargo's PSD, and other physical properties, are partly attributed to the processing steps involved in its production. Some Group A cargoes, such as concentrates, are characterised by a fine and uniform PSD within the middle of Tsuchida's (1971) proposed earthquake induced 'likely to liquefy' region (shown in Figure 2.4). These materials typically undergo rigorous processing (for example, grinding, separation and/or flotation). This results in a cargo of homogenous physical composition and relatively consistent properties amongst cargo consignments (Jonas, 2010). By contrast, coarser grained Group A cargoes, such as iron ore fines and unprocessed nickel ore, often possess a wider PSD that lies only partly within Tsuchida's 'likely to liquefy' region (see Figure 2.4). These contain a mixture of clay-like material, fine-grained ore, pebble-sized stones and the occasional larger lumps. Minimal processing (perhaps only crushing and screening) results in a cargo that is often physically and chemically heterogeneous (Jonas, 2010). It follows that the properties of minimally processed ores may vary significantly between cargo consignments, or even amongst a ship's holds.

Despite the significant differences that can exist between the different Group A cargo types, and consignments of the same Group A cargo type, the IMSBC Code treats them in essentially the same way. The variability in properties amongst shipments of the same consignment also has implications for any laboratory-based testing for cargo liquefaction. Assessing a cargo's potential to liquefy by testing a single sample of cargo material is unlikely to produce results that represent the behaviour of multiple cargo shipments. This is explored further in Chapter 3.

Note that although the PSD of these cargoes may resemble those of sand, gravel, or a combination of these, many of these minerals are much heavier than soils. For example, the specific gravity of Carol Lake iron ore concentrate is around 5.3 (bulk unit weight exceeding 30 kN/m^3) (Atkinson et al., 1994) and for iron ore fines is around 4.0-5.0 (bulk unit weight 22-27 kN/m^3) (IMO DSC18/INF.12, 2013). With regard to cargo shift, these characteristics will influence: *(i)* cargo geometry within the hold (it is loaded based on a mass capacity, not by volume); *(ii)* cargo compaction characteristics during a voyage, in response to the forces from a ship's motions (more energy is required to mobilise heavier material); and *(iii)* the impact on stability for a given volume of displaced cargo (the shift in a ship's global centre of gravity will be greater for heavier cargo). These differences should also be factored into any laboratory based assessment of cargo liquefaction and the TML test methods, if testing is performed using lighter materials such as gravels or sands (see Chapter 3).

2.2.3 Drainage in Group A Cargoes

Pore-water pressures will only develop, and liquefaction can only occur, if there is sufficient moisture within the interparticle voids as the cargo compacts. A Group A cargo is typically only loaded partially saturated and in this state it is unlikely that pore-pressures can develop. However, moisture migration during a voyage may increase the moisture content in a portion of the cargo, making this portion more susceptible to liquefaction.

If the cargo is loaded below a critical level of dryness, suction between particles will be great, and there will be negligible drainage within the cargo. However, above a certain moisture content, *drainage will occur*. In practice it can be assumed that most processed and unprocessed ore cargoes naturally contain inherent moisture above this critical level; lowering this moisture content to below a no drainage condition may incur significant costs and introduce operational impracticalities. Therefore, for most Group A cargoes, drainage will occur to some degree. During a voyage, the base of the cargo will become wetter whilst the top layers become dryer. The extent to which this occurs will depend on the permeability through the cargo and its initial moisture content. It is likely that during a voyage (which may vary from 1-2 days to 1-2 weeks), some cargoes reach an equilibrium (Prof. J.H. Atkinson, personal communication, Sep 2, 2014).

It follows that even if a Group A cargo is initially loaded at a moisture content well below that required to induce pore-pressure build-up and liquefaction, drainage may lead to the formation of a *saturated bottom layer* (or "*wet base*"). This was found for Canadian Carol Lake Concentrate shown in Figure 2.5 (Atkinson and Taylor, 1988; Kruszewski, 1988; IMO BC32/INF.10, 1992), Malberget A Fines iron ore concentrate shown in Figure 2.6 (IMO BC32/INF.11, 1992; IMO BC32/INF.12, 1992) and Brazilian iron ore fines (IMO DSC18/INF13, 2013). This section of the cargo may be more susceptible to liquefaction.

In other cargoes, drainage through the cargo may be very slow, and only minor variations in the moisture content will occur. This was found for Australian iron ore fines (IMO DSC18/INF13, 2013) and Savage River iron ore concentrate (IMO BC33/INF.4, 1992).

Table 2.2 (overleaf) summarises the findings on cargo drainage from previous investigations.

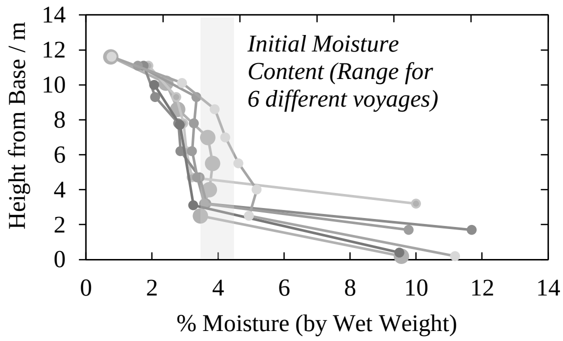


Figure 2.5: Moisture content with depth, measured for Canadian Carol Lake Concentrate after six voyages. Adaption of data presented in BC32/INF.10 (1992).

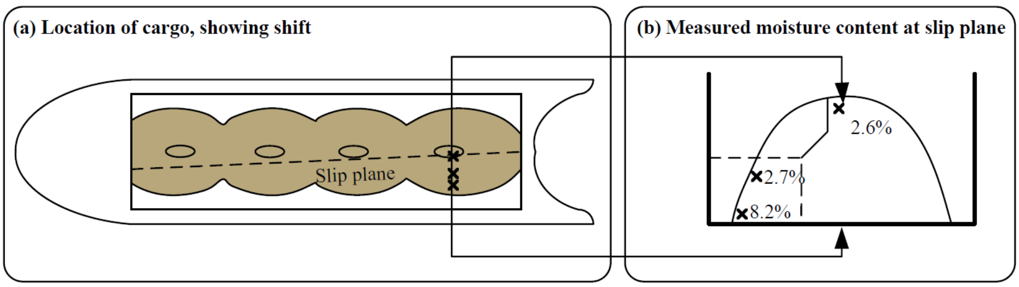


Figure 2.6: Moisture analysis of Malberget A Fines iron ore concentrate cargo, after slippage through a voyage, indicated that a saturated base had formed (slip plane shown as dotted line). Adapted from IMO BC32/INF.11 (1992).

Table 2.2: Summary of the findings from various research efforts relating to moisture migration.

MATERIAL TESTED	MEASUREMENTS TAKEN/ TESTS PERFORMED					MAIN FINDINGS	PERFORMED BY	REFERENCE
	SAMPLES OF ACTUAL CARGO PILE	BILGES?	LAB-SCALE TESTS?	SCALE MODELS?	NUMERICAL MODELS?			
Canadian Carol Lake Concentrate and some other iron concentrates	Sampled within a hold	Measured qualitatively using surveys completed by the ship's Master	Centrifuge and ship-simulator tests	Measured drainage in a cylinder under vibration	Modelled three dimensional flow; validated by centrifuge work	Numerical modelling indicated that this cargo exhibited fast drainage characteristics and a wet base formed within a 35 hour voyage. These models of flow were validated by Centrifuge work at City University, and on-board measurements.	Warren Springs, City University (for United Kingdom Department of Transport) [1982-1995]	(IMO BC32/INF.3, 1992; BC32/INF.7; Kruszewski, 1988, 1991, 1992; Atkinson and Taylor, 1998)
Canadian Carol Lake Concentrate	Throughout cargo at various heights. Also tested port stockpiles and railcars and loaded ship above FMP	Measured bilge recording in a vessel loaded above FMP	No	No	No	Canadian Carol Lake Concentrate exhibited fast drainage characteristics and a saturated wet base was measured during a voyage. They found that bilges readily became blocked during a voyage which may prevent drainage.	Canada (submitted to IMO) [1990-1992]	(IMO BC32/ INF.10, 1992)
Malberget A Fines (MAF) iron ore concentrate	At different heights in cargo	Qualitative assessment of drained water volume	Pore pressure and moisture measurements in cylinder.	Simple generating acceleration by using a 'swing'	No	Moisture within MAF fines readily drained and formation of a saturated base was measured.	Finland: Technical Research Centre of Finland and Research Centre of Rautaruuki Oy [1980's-1992]	(IMO BC32/3/9; BC32/INF. 12, 1992)
Savage River Iron Ore Concentrate	Three cargo depths (top, middle and bottom)	No	No	No	No	Savage River Iron Ore Concentrate exhibited very little drainage behaviour during the 10 day voyage. Moisture variations through the cargo were minimal and no formation of a wet base was observed.	Unknown (commissioned by Australia) [1993-1994]	(IMO BC32/3/15, 1992; BC33/ INF.4, 1994)
Brazilian, Australian Iron Ore Fines	Master recorded bilges and also took pore pressure and moisture measurements with cargo depth	Master recorded bilge measurements through journey	Lab/bench-scale centrifuges	Scale models of holds of various sizes	Finite element analysis to model three dimensional flow through voyage	Australian iron ore fines exhibited some drainage behaviour, but this was slow and the formation of a wet base was not observed. A wet base and 'pooling' was observed for Brazilian ores. Haematite and Goethite exhibited different drainage characteristics.	Technical Working Group for Iron Ore Fines (TWG) [2012-13]	(IMO DSC18/INF.11, 2013; DSC18/INF.13, 2013)

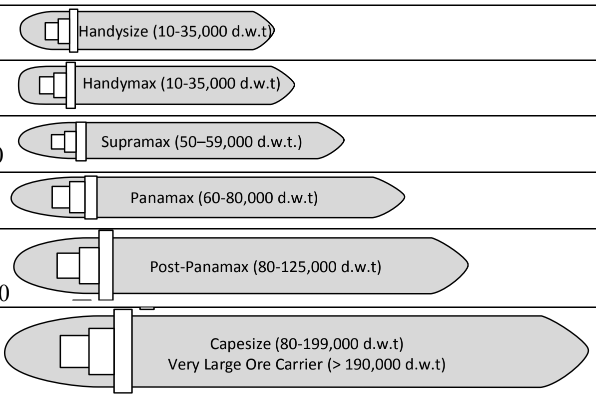
2.3 THE BULK CARRIER

2.3.1 Background

Almost all bulk solid cargoes are transported using a bulk carrier, which were developed in the 1950's. There are over nine thousand bulk carriers trading around the world (approximately 15-17% of the world's merchant fleet) (Schellenberg, 2013). These are typically constructed with a single deck, different numbers of individually compartmentalised holds, and may vary in size from small carriers (less than 10,000 deadweight tonnes (d.w.t.) [i]) up to very large bulk carriers (approaching 400,000 d.w.t.). An overview of the different types of carriers is presented in Table 2.3, and the proportional numbers and combined capacities of each of these types in operation are shown in Figure 2.7. Between 1976 and 2006 the average size of carriers increased significantly, from 31,000 d.w.t. to 56,000 d.w.t. (Stopford, 2009).

Table 2.3: Main types of bulk carriers and their basic Configurations. (Source: Multiple)

SHIP TYPE	SIZE IN DEADWEIGHT TONNES (D.W.T.)	TYPICAL LENGTH / M	TYPICAL NO. OF HOLDS
Mini Bulk Carrier	3000—9999	100—130	
Handysize	10,000—35,000	130—150	5
Handymax	35,000—49,000	150—200	5
Supramax	50,000— 59,000	200—230	5
Panamax	60,000—79,999	200—250	7
Capesize	80,000—199,000	230—270	7-9
Very Large Ore Carriers	190,000+	270—400	7—9



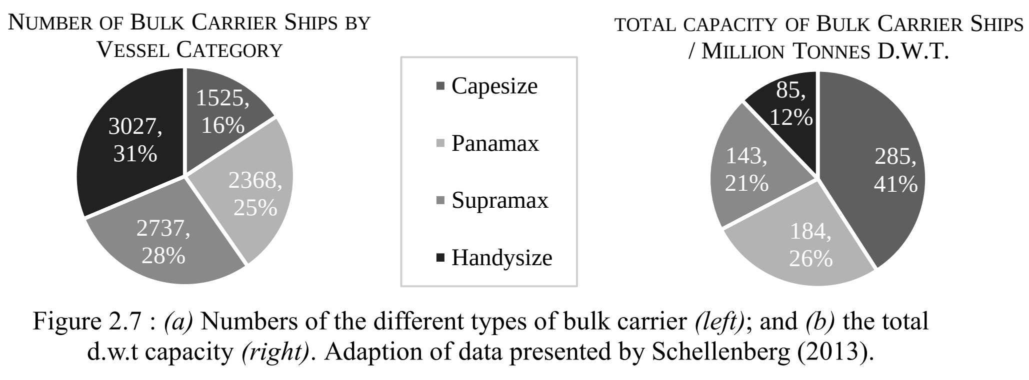


Figure 2.7 : *(a)* Numbers of the different types of bulk carrier *(left)*; and *(b)* the total d.w.t capacity *(right)*. Adaption of data presented by Schellenberg (2013).

[i]Deadweight (d.w.t.) tonnage is a measure of a ship's carrying capacity (including fuel, water and provisions).

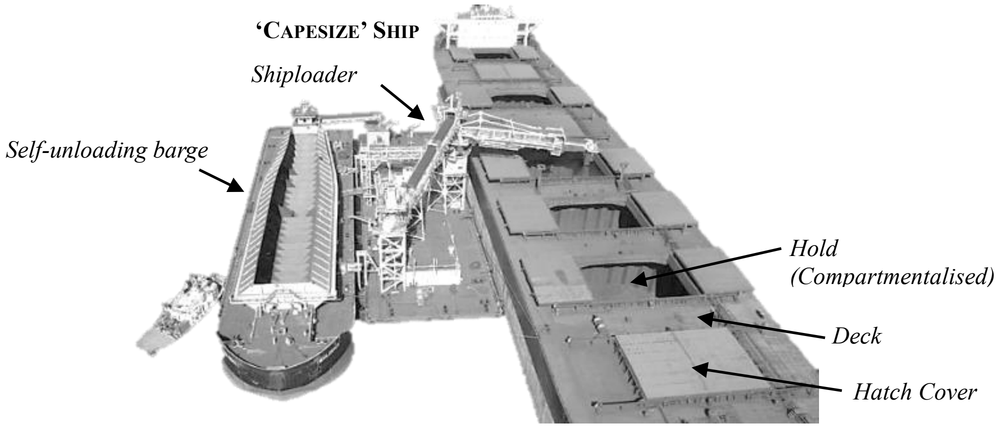


Figure 2.8: Key ship terminology (pictured is an offshore loading operation). Adaption of photograph from CSLShips (2014).

The design of a bulk carrier will influence the potential for cargo shift and/or liquefaction to occur—considerations include *hold design* (*i.e. drainage*, *hold geometry*) and the ship design factors that influence the *ship's motions* (Figure 2.8 shows key ship terminology).

2.3.2 Ship's Hold Design Considerations

In order to facilitate *drainage* of moisture and prevent the development of free surface water and/or a saturated cargo base, bilges are fitted at the base of a ship's hold. These capture any free water that might accumulate. Although bilge configuration may vary, each hold compartment will typically contain at least two small bilges located towards the rear. Concerns have been raised regarding the effectiveness of some bilge designs, which may become blocked in the presence of fine particles (IMO BC32/INF.10, 1992; IMO DSC/INF.9, 2012).

The *geometry* of the bulk carrier's hold affects the geometry of the pile of loaded cargo,[i] influencing its shear resistance. In addition, the boundaries of a hold will restrict cargo movement during a cargo shift event, preventing significant transverse mass displacement (*i.e.* displacement to the outer edges of the ship that cause a vessel to heel). A hold's dimensions may vary for the different types of carrier, and even on an individual ship. For example, the foremost hold is often smaller to account for the curvature at the front of the ship.

Most bulk carrier holds are designed so that the lower and topside wing-tanks are angled ('self-trimming' holds). This is demonstrated in Figure 2.9, which also shows common dimensions of an iron ore fines cargo pile within a Capesize bulk carrier's hold. For high-density cargoes, the angled lower wing-tanks reduce the stresses on the material at the base of the pile; helping to

[i]The geometry of a cargo in the hold will also depend on the density of the ore and the ship loading practices.

reduce the likelihood of slope failure. In low-density cargoes, which may almost fill the hold, the angled topside wing-tanks act to occupy void space and help to prevent the cargo at the top portion of the hold shifting into this area.

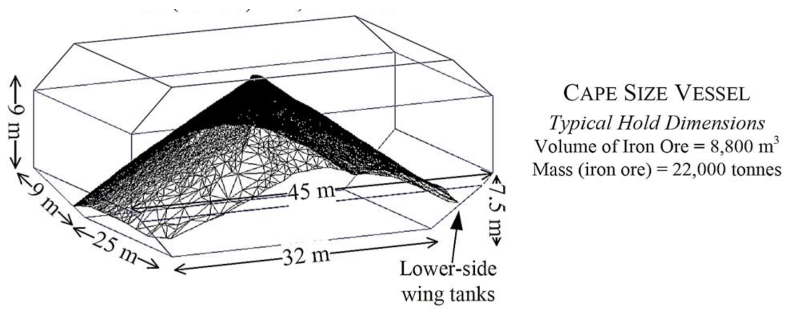


Figure 2.9: Basic geometry of a typical Capesize bulk carrier's cargo hold, showing lower and upper-side wing tanks. Shown is a hold loaded full of iron ore fines.

2.3.3 Ship Motions

The forces generated by a bulk carrier's motions cause both cargo compaction (contributing to a development of pore pressures) and possible displacement. These motions will vary for the different types of ship (its form/design) and with different conditions of load. In addition to ship design, a bulk carrier's motions at sea also depend on the *sea-state* and the *ship's behaviour* (speed, heading relative to the waves) (Robertsson et al., 1981; Isbeste, 1993). The only factors that the Master can alter are the ship's speed, heading and possibly minor changes to the loading condition (Merchant Navy Sailors Club, 2013). Figure 2.10 defines a ship's translational and rotational and motions for the full six degrees of freedom.

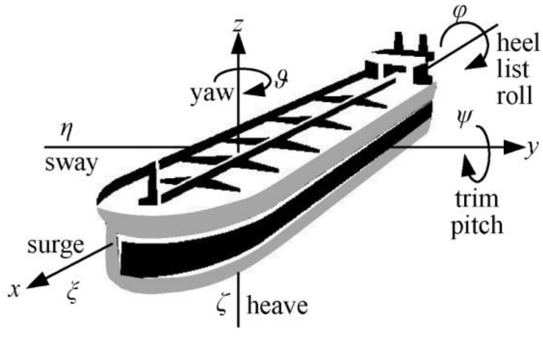


Figure 2.10: Ship motion with 6 degree of freedom (Brix, 1993).

Vessel rolling and pitching are typically considered to generate the greatest accelerations on a ship. Accelerations generated by these rotational motions increase with distance from the rolling and pitching axes, and are inversely proportional to the square of the rolling and pitching periods (Container Handbook, 2014). It follows that each hold on a ship will experience a unique force. Note that any outwardly acting centrifugal accelerations are usually considered of little significance (Container Handbook, 2014).

Whereas the compaction of a granular cargo is likely to occur from the contribution of all the ship's motion, it is likely that the forces that cause transverse cargo displacement are predominantly the result of the rolling motions. This is because displacement to the outer edges of a hold is more likely to occur during a moment of roll, where the applied forces acting on the tilted cargo pile (from both gravity and accelerations generated by the ship's motions) overcome the resisting forces that provide the cargo with stability.

A number of researchers have attempted to simulate a ship's motions within laboratory scale test-work or scale modelling, aimed at assessing a cargo's liquefaction potential (IMO BCXV/4(b), 1974; IMO BC23/5/16, 1982; Atkinson and Taylor, 1992; IMO BC32/INF.11, 1992; IMO BC32/INF.12, 1992; IMO DSC18/INF.12, 2013; Koromila et al., 2013). These investigations have varied significantly in terms of their approach, cargo type assessed and assumptions of motions. These investigators have encountered difficulties when scaling these motions (in six degrees of freedom) to a small sample of material (Atkinson and Taylor, 1992; IMO BC32/INF.12, 1992). Others have neglected to consider scaling completely (IMO BCXV/4(b), 1974; IMO BC23/5/16, 1982). Given these issues, it is likely that these would only ever give a gross approximation of the ship's motions and their impact on a cargo sample. These considerations are discussed further in Chapter 4 of this thesis.

2.3.4 Loading of a Cargo into the Hold

The loading of a cargo into a hold takes place vertically through the hatches. A ship loader will typically drop the cargo continuously into the hold by an adjustable boom positioned over a hatch, fed by a series of conveyors (Ligteringen et al., 2012). For smaller and remote mining operations without adequate port facilities, barges may be used (shown previously in Figure 2.8). Ship loading characteristics such as drop height (5 to 20 meters) and throughput (500 to 16,000 tonnes per hour) may vary significantly amongst operations (Morgan, 2011). These differences in shiploading practices impact the initial state of the cargo in the hold, whereby:

(a) the *initial cargo geometry* will depend on the shiploader design and its operator;

(b) the *mass of ore* loaded into a given hold depends on the design of the hold, the stowage factor of that material (bulk density) and its capacity; and

(c) the cargo's *initial density* will likely be influenced by the deposition characteristics of the ship loader (*i.e.* drop height, deposition intensity, spread and friction coefficient) (Lo Presti et al., 1998; IMO DSC18/INF.12, 2013). This will impact a cargo's compaction characteristics during the voyage.

Laboratory based assessment of a cargo's liquefaction potential may attempt to simulate these compaction conditions in the hold by controlling compaction and confinement conditions. However, as explored in Chapter 4, it is unlikely these conditions accurately reflect the conditions within a hold.

The cargo is usually loaded into each hold in a planned sequence, as per the 'loading plan' (to avoid overstressing the hull). The ship loader will move from hatch to hatch, executing the plan (see Figure 2.11 for example). Each hold of a ship may be loaded with a different cargo type. It follows, that liquefiable material may be loaded into some holds of a ship, whilst the other holds may contain non-liquefiable ore. A situation where only some of the holds contained liquefiable ore would clearly present a lower safety risk. However, the IMSBC Code applies a blanket rule whereby a Group A cargo is subject to the same conditions of carriage, regardless of how many holds are filled with that material.

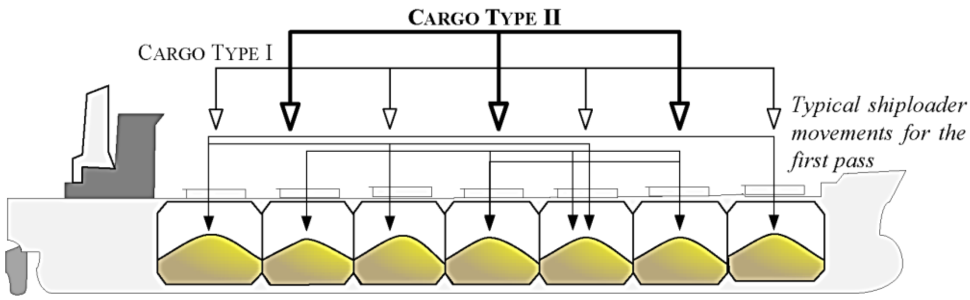


Figure 2.11: An example cargo loading plan and the resulting loading sequence.

2.4 THE SOIL MECHANICS OF CARGO SHIFT

Moisture migration, cargo compaction and/or the ship's motions may create the conditions necessary to induce major displacement of the cargo mass. The displacement results from a loss of cargo strength, which can be explained in terms of soil mechanics. Section 2.4.1 presents an overview of basic soil mechanics, whilst Section 2.4.2 then applies this to the different mechanisms that lead to a cargo shifting.

2.4.1 Cargo Strength: Soil Mechanics Overview

The strength of a **saturated** granular material is most often discussed in terms of *effective stress* (σ'). That is, the stress carried by the solid particles or the solid portion of the soil. The principle of effective stress states that various physical effects in a saturated soil, such as compressibility and distortion by shear, are related exclusively to changes in the effective stress (Terzaghi, 1936). The validity of these principles for fully saturated soils is now well established (Jennings and Burland, 1962). Effective stress is most often presented in terms of the *pore-water pressure* (u_w—the stress carried by the pore water); and *total stress* (σ—the stress which is carried partially by the solid portion of the soil and partly by the pore-water pressure), whereby: (Terzaghi, 1936; Skempton, 1960a, 1960b)

$$\sigma' = \sigma - u_w \tag{2.1}$$

Treating the problem within the effective stress framework, the equation for shear strength (τ), the resistance per unit area that the soil mass can offer to resist failure and sliding along any plane within it, is given in terms of the effective stress, effective apparent cohesion (c', normally zero) and the effective friction angle (φ') by the Mohr-Coulomb equation: (Das, 2009)

$$\tau = c' + \sigma' tan\varphi' \tag{2.2}$$

The pore-water pressures in saturatedth unloaded soils are typically positive or zero, although soils that dilate may develop negative excess water pressures if loaded quickly enough.

For most soils below a critical degree of saturation (which varies depending on the material), soil behaviour cannot be accounted for purely on the basis of changes in effective stress (Skempton, 1960b). For **unsaturated** (or 'partly saturated') materials, the presence of air and in turn the effects of suction lead to negative pore-water pressures and these must also be considered. Bishop (1959) presented a generally accepted expression for effective stress of unsaturated soils which considered not only the pore-water pressure, but also the pore air pressure (u_a), where the difference between pore-air pressure and pore-water pressure (u_a - u_w) is referred to as matrix suction:

$$\sigma' = \sigma - u_a + \chi (u_a - u_w) \tag{2.3}$$

The coefficient χ ranges from zero (dry soils) to one (saturated soils) and varies for shear strength or consolidation. Unlike saturated soils, the mechanical behaviour of unsaturated soils depends on two independent stress state variables: the stress tensor or net normal stress ($\sigma - u_a$) and the matrix suction (u_a - u_w) (Fredlund and Rahardjo, 1993).

The shear strength of a soil depends on the effective stress, drainage conditions, density of the particles and strain rate/direction. More specifically, according to Poulos (1989) the stress-strain behaviour of soils is affected by a number of factors, including (Das, 2009; Poulos, 1989):

a) *soil composition* including mineralogy, grain size, PSD, shape of particles, pore fluid type and content, and ions on grains and in pore fluid;
b) *initial state*, defined by the bulk density, initial void ratio, effective normal stress and shear stress (stress history), which for example can be described in terms of loose/dense, contractive/dilative, over-consolidated/normally-consolidated and stiff/soft;
c) *structure,* which refers to the arrangement or packing of the particles within the soil mass and which can include factors such as cementation and voids; and
d) *loading conditions*, which can be described in terms of the effective stress path and, include, for example, drained/undrained, cyclic/static, frequency and amplitude.

These well-established principles used to explain the strength of a soil can also be applied to a solid bulk cargo, which is also a granular material.

2.4.2 Possible Mechanisms of Cargo Shift

The mechanisms that cause a particular cargo to shift are complex and largely unknown. Based on a review of the literature, it is envisaged that cargo shift may be broadly categorised by three following distinct modes (shown in Figure 2.12):

(a) Cargo liquefaction;
(b) Slope failure; and/or
(c) Sliding en masse.

As described in further detail in the following sections, these modes are not mutually exclusive and may occur sequentially and/or concurrently during a voyage.

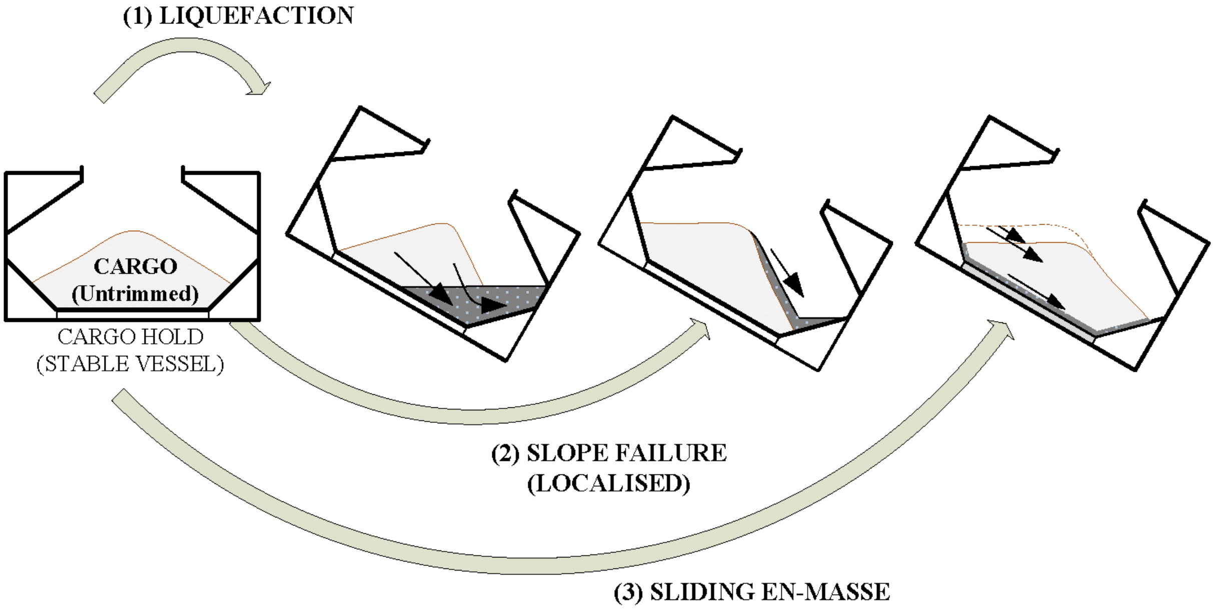


Figure 2.12: The three different types of cargo shift that may occur within a cargo hold.

It is important here to clarify what is meant by '*cargo liquefaction'*, which is a term widely misunderstood and misused within the maritime industry[i] to refer to a range of geotechnical phenomena, including: (*i*) classical liquefaction; (*ii*) localised cyclic mobility; (*iii*) slope failure; and (*iv*) cargo shift en masse (IMO DSC17/INF. 9, 2013). As explained below, the latter two of these phenomena may occur without liquefaction—that is, without a rise in pore-water pressure that contributes to a loss of effective stress and reduction of cargo strength. For example, slope failure may occur on a "dry" cargo during a rolling moment due to the effects of gravity overcoming the resisting frictional forces. The term 'cargo liquefaction', in the context of this thesis, is used to describe the phenomena whereby a rise in pore-water pressure contributes to a loss of shear strength, causing shift.

2.4.2.1 Cargo Shift Type I: Cargo Liquefaction

A cargo is typically loaded only partially saturated. During a voyage, moisture migration may occur. In addition, the cyclic stresses from a ship's vibrations and from ocean waves will cause particle rearrangement and a compaction of the mass. This results in a lowering of the void volume between particles[ii] and is accompanied by the movement of water within the pores

[i]Examples of its misuse include within official literature submissions to IMO, interactions between the Author and maritime and research personnel, and even by 'subject-matter experts'.

[ii]In other words, a reduction in the 'void ratio' (defined as the volume of voids divided by the volume of solids).

and/or by the release or compression of interstitial air. This may result in increased levels of saturation in some parts of the cargo. If drainage of this pore water is impeded (say, due to low permeability), then pore-water pressures will progressively increase with shear load. This may lead to the transfer of stress from the cargo skeleton to the pore-water (as shown previously in Figure 1.2), accompanied by: *(i)* a *loss of effective stress;* and *(ii)* a significant *reduction of shear strength.* This section of the cargo will become susceptible to displacement. If the shear resistance becomes less than the driving shear stress (say, vessel roll), the cargo may undergo significant deformation. The material is then said to have liquefied (Martin et al., 1975; Seed and Idriss, 1982; McRoberts and Sladen, 1992). Cargo displacement in significant volume can cause the ship to take on a list. Note that pore pressure development need not result in dangerous cargo shift. For shift to occur, a shearing force (say, due to roll) must be applied during the period where the material possesses low shear resistance. Given adequate drainage, a cargo may actually regain strength following a liquefaction event. However, a dangerous situation may arise if the strength of a shifted mass is restored during a moment of roll—this may result in a significant portion of the cargo mass staying fixed to one side of the hold.

The rate at which the build-up and dissipation of pore pressures occurs depends on the nature of the deformations (*i.e.* the application of strain and the characteristics of the cargo grains) (Seed, 1979) and the rate at which the soil can dissipate the excess pore-water pressures (which depends largely on the cargo's permeability). If a cargo material is very permeable, pore-water pressure will never rise, because the water will flow rapidly out of any zone of high pressure. On the other hand, elevated pore-water pressures will dissipate slowly in a material of low permeability and the potential for flow will likely remain for a long time. In the context of the stability of solid bulk cargoes, the duration of the liquefaction phase is a critical consideration, as the ability for a cargo to quickly dissipate excess pore pressures may significantly reduce the risk of shift.

Loose, moist granular materials are usually considered most susceptible to liquefaction, including cohesionless soils such as sands and uniformly graded soils (Terzaghi and Peck, 1948; Seed and Lee, 1966; Ghabousi and Wilson, 1973; Marcuson, 1978). When compacted, these materials are typically characterised by low permeability. Historically, geotechnical engineers have usually considered gravelly soils relatively safe (for example, see the liquefaction boundaries proposed by Tsuchida in Figure 2.4, p. 13). However, considerable research since

1980 has shown that gravelly soils may liquefy (Andrus and Youd, 1987; Andrus and Youd, 1992; Andrus et al., 1992; Coulter and Migliaccio, 1966; Ishihara, 1984; Harder, 1988). The recent classification of gravelly cargoes such as iron ore fines and unprocessed nickel ore as Group A reflect these recent developments in thinking. These cargo materials may be vulnerable to cyclic pore pressure generation and/or liquefaction when *(i)* their voids are filled with finer particles; or *(ii)* there is an impermeable layer such as the boundary of the hold, that prevent drainage of water from the voids.

Following a liquefaction event, the vessel response will vary depending on if a cargo behaves like a liquid, remains fixed to one side of the vessel, or otherwise (discussed further in Section 2.5). It is popularly perceived that cargo liquefaction occurs simultaneously over the entire cargo. Subsequently, a number of investigators have assumed that the cargo acts like a liquid when assessing the ship's stability response post-liquefaction (IMO BC28/INF.4, 1987; Koromila et al., 2013).

Although there have been a few reported cases where fluid-like behaviour has been observed in a ship's hold (IMO BCIX/12/1, 1970; IMO BC28/INF.4, 1987), it appears that these conclusions are typically based on the observation of free surface water overlying the cargo (IMO BCIX/12/1, 1970). However, the presence of free surface water does not necessarily mean that liquefaction or a loss of cargo strength has occurred—it only indicates that water has permeated and that the cargo has compacted. These phenomena may occur without a significant increase in pore-water pressure or with only a very brief increase in pore-pressure, and it is possible for free surface water to develop on a rapidly draining material that is not capable of liquefaction. Therefore, the cargo material that underlies the free surface water may still possess strength and not exhibit fluid behaviour. Although 'sloshing' of free surface water may in isolation compromise vessel stability, its effects are likely to be less significant than if the entire cargo mass exhibits liquid behaviour—particularly as a cargo is typically much heavier than water.

Rather than full scale liquid behaviour, it is more likely that pore-water pressures develop in a localised portion of the cargo. Alternatively, these generated pore-water pressures may be transferred to other sections of the cargo and lead to a reduction in effective stress elsewhere. These localised decreases in shear resistance may then create the conditions for larger scale cargo displacement, say due to gravity acting on the overlying mass. Unlike in the case of full-scale liquid behaviour, in this case the displaced mass will not move freely in the hold but will instead remain fixed to the side of the hold.

2.4.2.1.1 Assessing Liquefaction

Significant effort has been directed towards the soil mechanics assessment of soil liquefaction, mainly in the fields of seismic engineering, waves and structures at sea, and blast induced vibrations. Simplified methods of evaluating the liquefaction potential under earthquake loading have been presented by Seed & Idriss (1971), Ishihara (1977), Iwasaki et al. (1984) and Robertson and Campanella (1985) (apud Alla, 2009). The cyclic triaxial test is the most commonly used method, although other tests include cyclic direct simple shear and cyclic torsional shear tests. These tests are typically used to estimate the cyclic resistance ratio (**CSR**) of the soil. This ratio can then be compared to the cyclic shear stresses induced during an earthquake, or other cyclic phenomena, the aim being to assess whether the soil contains adequate resistance to failure. For most studies, these tests are typically undertaken under undrained conditions (*i.e.* dissipation of any generated excess pore pressures are prevented from occurring during cyclic loading). This is because earthquake shaking is assumed to occur sufficiently fast so that dissipation of excess pore-water pressures cannot occur. The frequency of the applied load cycling in the laboratory testing has been generally found to have no effect on the number of cycles required to liquefy the test specimens (Ishihara, 1996).

Whilst soil in an earthquake can usually be considered in a saturated, undrained condition, assessing the strength of a cargo from liquefaction at an elemental level is challenging due to the time dependent macro behaviour such as compaction and moisture migration that occurs through a voyage—particularly given that the cargo is typically loaded in an unsaturated state. Therefore, the question is not only *if* the cargo will liquefy under the conditions experienced at sea, but also *where* in the cargo will this occur (for example, does a saturated zone form?). Then if a part of the cargo does lose strength, the question is *will this lead to a shift* given the characteristics of the rest of the cargo (which may be drier, wetter, denser or less dense) and the behaviour of the ship? The problem is complex.

An overview of previous soil mechanics approaches to assessing cargo liquefaction is presented in Chapter 4 of this thesis, in addition to a discussion on the expected merits of these tests.

2.4.2.1.2 The Mitigation of Liquefaction in the IMSBC Code: Transportable Moisture Limit

As discussed in Section 1.2, the IMSBC Code requires that Group A cargoes be shipped below the TML, as determined by element testing outlined within the IMSBC Code (IMO, 2009). These tests assume that below this moisture content, pore-water pressures cannot rise in the cargo and liquefaction does not occur. An assessment of these tests is presented in Chapter 3 and Chapter 4 of this thesis.

2.4.2.2 Cargo Shift Type II: Slope Failure

Slope failure may occur when the shearing forces applied from the ship's motions (such as those applied by gravity when a vessel rolls) overcome the frictional and cohesive forces that provide the pile with static strength. Unlike liquefaction, this may occur in wet or dry cargoes, where cargo displacement may occur from shear failure along an internal surface or when a decrease in effective stress between particles causes full or partial liquefaction. The forces that cause instability of a slope are primarily associated with gravity and moisture movement, whilst resistance to failure is derived mainly from a combination of slope geometry and shear strength of the granular material.

Slope failure is usually discussed in terms of two primary types: *translational and rotational*. For a translational failure, the failure surface occurs approximately parallel to the ground surface and is typically shallow. For a rotational slide, the sliding surface is approximately circular and is often much deeper within the slope. Varying conditions, for example moisture migration in addition to the ship's cyclic rolling motions and cargo compaction, likely precipitate multiple shallow translational slope failures during passage (for example, if the angle of repose is exceeded due to the tilt from roll). These will gradually flatten out the cargo pile through the voyage. However, if the displaced mass is small, this will have negligible impact on ship stability—particularly given the symmetry around the axis of roll is likely to distribute material to both sides of the hold. According to Professor J.H. Atkinson (personal communication, Sep 2, 2014), cargo observations before and after a number of voyages indicated that minor slope failures and flattening of the pile had occurred during passage.

Of greater concern with regard to ship stability and vessel capsize is larger scale, transversely asymmetric, cargo displacement that occurs to only one side of the hold. This is probably more likely to occur when localised pore pressures and decreases in effective stress exist within the cargo, creating the conditions necessary for a deep failure plane that is required to promote significant mass movement. The formation of a saturated base during a voyage would facilitate this type of failure for materials of low permeability.

2.4.2.2.1 Assessing Slope Failure

Whereas liquefaction is often considered as a cyclic phenomenon, slope stability is usually considered as a static problem. Simple limit equilibrium analysis is the simplest and most commonly used method. This method compares those moments and stresses that resist instability, and those that cause instability. More specifically, consideration is given to the forces from gravity, the sliding plane (assumed transitional, rotational or otherwise), the slope geometry and the material's static strength properties (usually obtained from shear-box or triaxial tests). From this, a 'factor of safety' is usually determined, expressed as the ratio of resisting force down the slope to the disturbing force down the slope. This method can become inadequate if the slope fails by more complex mechanisms, and these may require more sophisticated numerical modelling solutions (for example, finite element approaches).

For a cargo, slope failure may be assessed by considering: *(i)* the angle of ship rotations; *(ii)* the cargo's angle of repose and/or static strength properties at the edges of the cargo pile; *(iii)* the cargo geometry within the hold; and *(iv)* the likely mode and/or depth of failure (*i.e.* shallow or deep loading, translational or rotational). A number of investigators have taken these into account using the limit equilibrium method, applied to an infinite slope (Atkinson and Taylor, 1998; Atkinson et al, 1991; Ohta, 1992; IMO BC32/INF.11, 1992; IMO BC33/3/2, 1994; IMO DSC7/INF.9, 2012). As for typical soil mechanics slope stability problems, these analyses have usually focussed on obtaining a factor of safety, or a derivation thereof. For example, in Japanese research presented to IMO (IMO BC33/3/2, 1994), limit equilibrium analysis was performed on a number of nickel ore cargoes (using Fellenius method). This assessment aimed to find a safe slope angle that the cargo should be trimmed, in order to prevent slope failure during passage—incorporating assumptions of cargo geometry and maximum roll angle. However, given the complexities associated with vessel motion, moisture migration and the possibility of partial liquefaction and reduced strength at the base of a pile, these conventional slope stability approaches are likely a significant oversimplification. The cargo's static strength properties measured for the nickel ore used in the Japanese study, at a range of moisture contents, is shown in Figure 2.13 (IMO BC33/3/2, 1994).

More recently, Brazilian and Australian researchers have used finite element approaches to assess a cargo's stability (IMO DSC17/INF.9, 2013; IMO DSC18/INF.13, 2013). Although this analysis accounted for dynamic changes in the voyage and the potential development of pore pressures, it is unlikely that the input parameters adopted for this modelling reflect the characteristics of a cargo during a worst-case voyage (more specifically, degree of saturation of 0.63, void ratio of 0.7, average roll of 5 degrees, 2000 cycles were used).

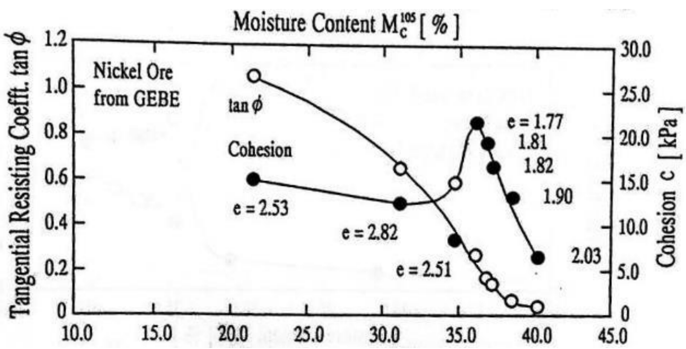


Figure 2.13: Static strength properties obtained from direct shear tests of an Indonesian nickel ore cargo at different moisture contents (IMO BC33/3/2, 1994). From these results, limit equilibrium techniques were used to create a 'safe slope angle chart' which allowed the required trimming angle to be determined based on the shear strength properties of a cargo.

2.4.2.2.2 The Mitigation of Slope Failure in the IMSBC Code: Angle of Repose and Trimming

The IMSBC Code controls slope failure of a non-cohesive cargo through consideration of the cargo's *angle of repose*, as measured by the 'tilt-box' apparatus specified within Appendix 2 of the IMSBC Code (IMO, 2009). These cargoes must be 'trimmed' within the hold, as demonstrated in Figure 2.14. This reduces the likelihood of cargo shift from slope failure by reducing the overburden pressures at the outer base of the cargo pile (*i.e.* reduces height of overlying mass). It has been demonstrated that trimming can be effective in preventing shift from sliding failure (IMO BC32/INF.11).

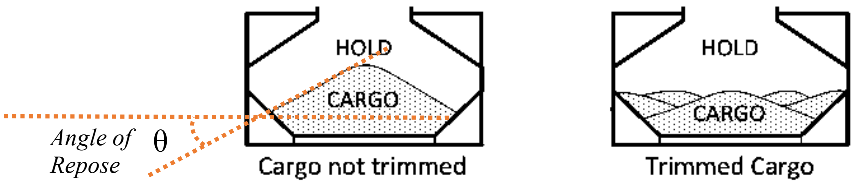


Figure 2.14: The Angle of Repose and Cargo Trimming

The extent of trimming required depends on which of the basic angle of repose cut-off criteria it falls within (more specifically, less than 30 degrees, between 30 and 35 degrees or greater than 35 degrees). Cargoes with a lower angle of repose require greater trimming (IMO, 2009). For very small vessels, trimming may be performed by hand or by machinery. However, in most bulk operations, cargo trimming is performed by controlled operation of the ship loader.

2.4.2.3 Cargo Shift Type III: Sliding En Masse

Whereas a sliding failure may occur from the loss of shearing resistance between particles within the granular cargo (*i.e.* at the 'inter-granular interface'), a shift en masse may occur if there is insufficient resistance to shear between the granular cargo particles and the steel deck of the hold ('steel-cargo interface'). A cargo slide en masse may result in a significant and rapid change in the centre of gravity of a vessel. It is therefore a very dangerous condition.

A slide en masse could occur in cargoes with both an unsaturated or saturated base layer. If the base is *unsaturated*, then the effect of gravity and/or the ship's accelerations on the overlying mass during a moment of roll may overcome the strength provided by friction between the planar cargo-steel interface, and the cargo will temporarily slide over the hold. The friction between this interface (which can be expressed in terms of the friction angle) will depend on the surface characteristics of the steel (for example roughness) and of the cargo material at the interface. If the cargo is *saturated at its base*, then the high confining pressures of the cargo may result in a build-up of pore-water pressure (*i.e.* liquefaction) and reduced shear resistance at this interface. If these pressures are not adequately dissipated, then this could lead to a rapid shift that would occur at only very small angles of roll. Even if elevated pore pressures only existed over a small section of the base, the remaining particles would then carry greater burden of the overlying material and again, the angle at which this material shifted would be less than for the dry case.

2.4.2.3.1 Assessing Sliding En Masse

The friction between the steel/soil interface is often expressed in terms of the friction angle, measured by shear box tests. Civil engineers often take the maximum value of the wall/soil friction angle as $\delta = 2/3\varphi'$, where φ' is the soil's effective angle of shearing resistance and δ is the wall/soil interface friction angle. If the steel possesses low friction (for example, a friction reduced coating) then the ratio may be lower (Steel Construction Institute [CSI], 2011).

For cargo shift, a few minor studies have been undertaken and these showed similar findings. Measurements from shear box tests on iron ore concentrate indicated that there was a lower shearing resistance between the steel-hold/cargo interface than internally within the cargo (Atkinson, 1988; Kruszewski, 1988; Rathmayer and Laaksonen, 1992; IMO BC32/INF.11, 1992). For example, Finnish investigators found that for MAF iron ore concentrate, the friction angle between the MAF/steel plate interface was 28 degrees, compared to the MAF's internal friction angle of 36 degrees (IMO BC32/INF.11, 1992). This led the investigators to conclude that cargo shift is more probable along the deck surface than inside the cargo itself (Kruszewski, 1988).

2.4.2.3.2 The Mitigation of Sliding En Masse in the IMSBC Code

Sliding en masse is not considered within the IMSBC Code. However, the aforementioned mitigation strategies for liquefaction and slope failure (*i.e.* which control moisture content and require trimming, respectively), may capture and control the material properties that, to some degree, reflect the susceptibility of a cargo to move en masse.

2.5 SHIP STABILITY

Displacement of the cargo mass will shift the global centre of gravity of the ship, resulting in it assuming an angle of heel. The impact of a given displaced mass depends on the stability characteristics of the bulk carrier. This response will vary for a range of reasons, including for different ship types, designs and conditions of load. In isolation, shift does not necessarily constitute a danger if the ship possesses adequate stability.

2.5.1 The Theory of Transverse Ship Stability

Any freely floating body, such as a ship, displaces its own weight of liquid when it is afloat. This weight (**W**) acts downward through the *centre of gravity* of the body (**G**). This force is resisted by an upward buoyant force equal to **W** that acts through the centre of *buoyancy* (**B**)—the geometric centre of the submerged volume displaced by the ship (see Figure 2.15). (Committee on Ships' Ballast Operations, 1996)

In a stable ship, the forces from B and G strive for vertical alignment. For an upright vessel, B and G remain in line and the ship is transversely stable. When an external force on a stable ship forces that ship to heel (for example, from the wind or waves, but not a cargo shift that results in a shift in G), the hull will result in B shifting to one side of the vessel—whilst G will not move. This will result in the buoyancy force working to re-right the ship, as indicated by the opposing, vertically aligned arrows in Figure 2.15 (*left*). The horizontal separation of B and G caused from this disturbance is referred to as the righting lever (**GZ**), also shown in Figure 2.15 (*left*). The resulting righting moment (W × GZ) will cause the vessel to oscillate from side to side as B and G become realigned. (Committee on Ships' Ballast Operations, 1996)

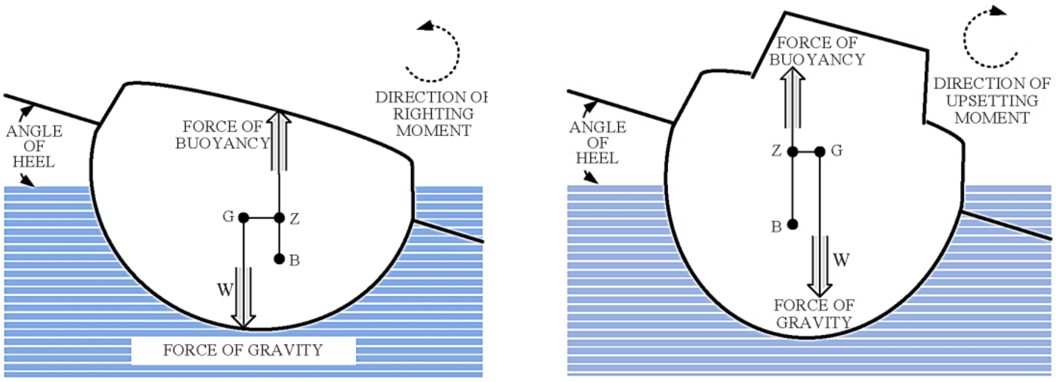


Figure 2.15: *(a)* When a stable ship inclines, the buoyancy (B) and the weight (W) acting from the centre of gravity (G) work to re-align the vessel. This is typically represented by the righting lever (GZ) (*left*); and *(b)* If the angle of heel is sufficient, GZ can become negative, and G and W will work to roll the vessel, likely causing capsize *(right)*.

If transverse cargo shift occurs, G will change position. It is possible for B and G to reverse positions. If this occurs, GZ will become a coupled turning force ('upsetting moment') that could result in the ship quickly capsizing (*i.e.* a 'negative GZ') (Committee on Ship's Ballast Operations, 1996). This is shown in Figure 2.15 (*right*).

2.5.2 Vessel Stability Characteristics: The Metacentric Height

A ship's initial *metacentre* (**M**) represents the point where all vertical forces intersect, which occurs at small angles of heel (when the angle of heel is great, M moves off the centreline). This is shown in Figure 2.16. A ship's initial stability, when upright or nearly upright, is represented by the height of M in relation to G. This is referred to as the *metacentric height* (**GM**)—heavier loads will increase the GM.

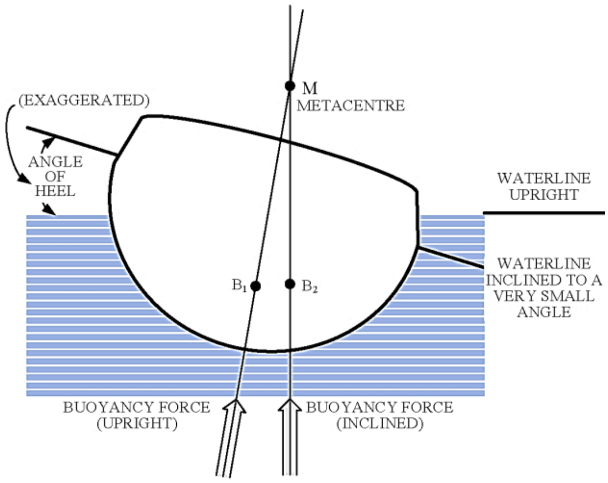


Figure 2.16: The ship's metacentre (M).

If the GM is large, the righting arm that develops, at small angles of heel, will be large. These ships are termed *"stiff"*. Stiff vessels may become excessively stable, initially opposing the heeling movement with a strong righting moment. This will result in a possibly violent roll, shorter rolling periods and high transverse acceleration forces.

Conversely, if the metacentric height of a vessel is small, the righting arms that develop will be small. These vessels are termed *"tender"* and are characterised by slow roll periods. These boats may be at risk of overturning (although note that at higher angles of heel, for example in excess of 5 degrees from the vertical, GZ is a more accurate indicator of the vessel's stability) (Committee on Ships' Ballast Operations, 1996).

Vessel design will typically consider this stability response—hull shape being one of the driving factors. The aim will be to ensure that the ship contains sufficient stability whilst not imparting uncomfortable, or possibly dangerous, accelerations on the crew or cargo.

As GM and GZ are dependent on the location of G, and G varies with condition of load, the stability of a bulk carrier will likely vary depending on the type of cargo it carries. When a ship is loaded with a high density cargo such as iron ore, the centre of gravity of the ship may be lower than for a low density cargo such as coal (*i.e.* greater metacentric height). This will then result in a comparatively stiff, more stable vessel that is easily able to right itself. Whilst this vessel may have enhanced stability, it may also lead to higher transverse shearing accelerations imparted on the cargo—this may increase the risks of cargo shift.

2.5.3 Stability Curves

A ship's stability is often expressed by the 'stability curve', which provides information about the righting lever (GZ) for any angle of heel (based on an assumed centre of gravity). From this curve, a considerable amount of stability information can be obtained, including: *(i)* the range of stability; *(ii)* the angle of vanishing stability; *(iii)* the maximum GZ; and *(iv)* the initial GM. Figure 2.17 illustrates key characteristics of the curve. It also compares vessel stability before and after a liquefaction event, as calculated by Koromila et al. (2013). Their findings showed a bulk carrier exhibits diminished stability post-liquefaction, as it is less able to right itself.

It should be noted that before a ship is permitted to go to sea it must meet the mandatory IMO stability criteria, which call for a more rigorous assessment of the ship's stability than just GZ and GM alone.

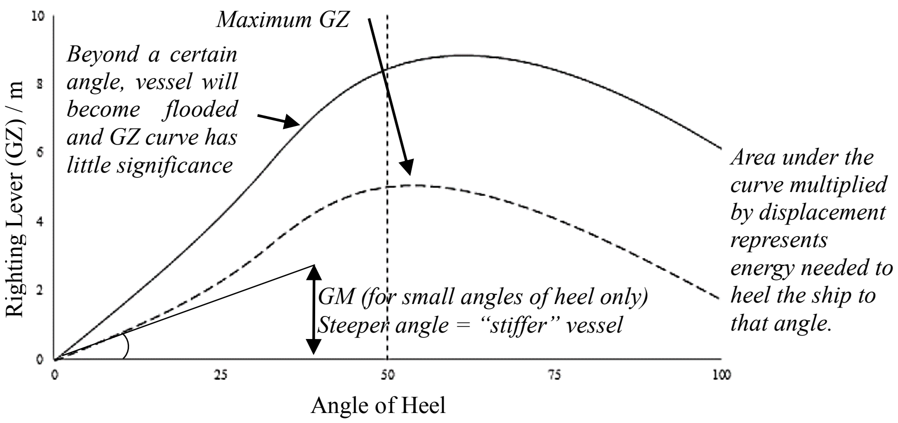


Figure 2.17: Key features of a GZ stability curve. The plot has been adapted from Koromila et al. (2013), which shows the calculated effect of liquefaction on GZ for alternate loading of a cargo (specific gravity of 3.6), before *(solid line)* and after *(dashed)* liquefaction. Assumed cargo behaviour or vessel type were not stated.

2.5.4 Stability Criteria for Cargo Shift

In the case of transverse cargo shift, stability can be considered in terms of a: (Biran et al., 2013)

(a) free surface (whereby the cargo acts like a liquid and stays horizontal to the water line);
(b) hanging load (whereby centre of gravity remains fixed following a shift); or
(c) shifting load (whereby a shift may worsen incrementally due to repeated moments of roll).

Each of these will have a different impact on the vessel's stability response. While all of these modes have been suggested to occur, the Author believes it is the latter two modes that are most likely occur in the case of a granular cargo at sea.

Biran and Pulido (2013) proposed a basic stability criteria for a shifting load, whereby they suggested that metacentric height (*GM*) could be considered in terms of the heel angle (λ) and the angle of repose (θ). Here, they assumed that during roll, the mass of the granular material stays in place until the heel angle exceeds the angle of repose ($\lambda > \theta$). Then, the granular load slides suddenly and its centre of gravity moves horizontally a distance, ξ, and up a distance ζ to give a metacentric height, in terms of displacement (Δ), equal to:

$$\overline{GM} = \frac{m_L(\xi \cos\lambda + \zeta \sin\lambda)}{\Delta} \quad (2.4)$$

These models make the assumption that while the ship rolls back, the load does not move until its angle again exceeds the angle of repose. However, ship accelerations may cause loads shifting when $\lambda < \theta$. Further, experience has shown that it is possible that this may then cause further material to shift, worsening the situation (Biran and Pulido, 2013). Wendel (1960) and Birbanescu-Biran (1985) showed that it is possible to consider this as a positive feedback loop (Figure 2.18). However, both these representations are a simplification of the problem and do not increase the understanding of the drivers for cargo shift nor the effect of cargo properties on the reaction of the ship, *H(s)*.

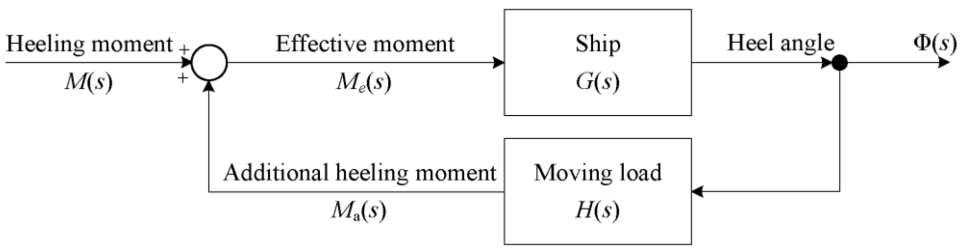


Figure 2.18: Shifting loads as a case of a positive feedback loop (adapted from Birbanescu-Biran (1985)).

3. THE TML TEST METHODS

For Group A cargoes, the Shipper must provide the Master with confirmation that the loaded cargo will not liquefy during the voyage and is safe for carriage. The Master is provided with a declaration (‘**Shipper’s Declaration**’) that specifies:

(a) the *moisture content of* the cargo; and

(b) the *maximum moisture content at which the cargo can be safely carried* to prevent liquefaction (the ‘Transportable Moisture Limit’, or **TML**).

The IMSBC Code incorporates a mandatory requirement that a Group A cargo is strictly loaded with moisture content less than the TML.[i]

The TML is determined from laboratory-based testing of the cargo, as per one of the following three test methodologies set out in Appendix 2 of the IMSBC Code (‘**TML Test Methods**’):

(a) the Flow Table Test (**FTT**);

(b) the Proctor/Fagerberg Test (**PFT**); and/or

(c) the Penetration Test (**PTT**).

These *may be used interchangeably*, provided that the cargo meets the basic top size criteria for that test (shown in Table 3.1).

Table 3.1 : The IMSBC Code TML Test Selection Parameters and Flow Indicators.

IMSBC Test Method	Recommended PSD (topsize)	Allowed PSD (topsize)	Sample Parameters	Energy Input (Compaction) Parameters	Indicator of Flow / TML
Flow Table (FTT)	0 - 1000 µm	0 - 7000 µm	*Minimum starting mass* = 3 × 2-3 kg *Conical mould volume* = 296.6 cm^3	*Tamper head* = 30mm; *Tamper pressure* = density × max cargo depth × g Table drop height = 12.5 mm *Number of cycles* = 50 *Frequency* = 25 Drops/ minute (0.62 Hz)	FMP measured from observed plastic deformation of the cone (convex or concave cone profile) and/or measurements of cone expansion.
Proctor/ Fagerberg (PFT)	0 - 5000 µm	>5000 µm if “extensive investigation for adoption and improvement is undergone”	Minimum starting mass = ~6 kg Proctor mould volume = 1000 cm^3	*Tamper head* = 50mm *Drop height* = 20cm *Hammer mass* = 350 g *No cyclic load	TML determined from intersection of the compaction curve with the 70% saturation line.
Penetration (PTT)	0 - 10 mm for small cylinder, 0-25 mm for large cylinder		1,700 cm^3 or 4,700 cm^3	*Vertical vibration Frequency*: 50 or 60 Hz *Acceleration*: 2g rms ± 10% *Vibration Time*: 6 min.	FMP measured penetration depth. >50 mm penetration is considered flow.

[i]Unless a custom, specially fitted ship is used (for example, a ship that is longitudinally compartmentalised to restrict significant transverse displacement). A typical bulk carrier does not meet this requirement.

The IMSBC Code also stipulates basic sampling requirements, which accompany the TML test methodologies. These aim to ensure that samples subject to TML and/or moisture analysis are representative of a given shipment (so that the two declared results are comparable). In practice, the *TML and moisture analysis are conducted independently of each other.* Whereas the moisture content is usually determined from a large number of samples of a cargo consignment, the TML is determined only occasionally. The merits of these requirements are examined in detail in Section 3.8.

The FTT was incorporated within the IMSBC Code in 1965, much earlier than the other two methods (1992). It is also the most frequently used test for TML determination (Kirby, 1983; Ura, 1995; IMO DSC17/INF10, 2012), although the PFT appears to be developing as the preferred test amongst some Shippers. This is perhaps attributable to the more *'favourable'* (higher) TML results the PFT produces for most cargoes (*i.e.* reducing the likelihood of a wet cargo being rejected because its moisture content exceeds the TML). In practice, the PTT is rarely used. The test equipment is more specialised, difficult to manufacture/acquire, is more expensive and is challenging to calibrate by inexperienced personnel. In addition, the PTT typically gives *'conservative'* (lower) TML results than the other methods (*i.e.* increasing the likelihood of a wet cargo being rejected on the basis that its moisture content exceeds the TML). The PTT is thus unlikely to be preferred amongst shippers, when deciding which test to use.

The research described in this thesis has focussed on assessing the two most common TML Test Methods, the FTT and the PFT. Key apparatus for the two most common TML Test Methods are shown in Figure 3.1 and are further detailed in Section 3.3.

(a) The Flow Table Test apparatus (b) Proctor/ Fagerberg Test apparatus

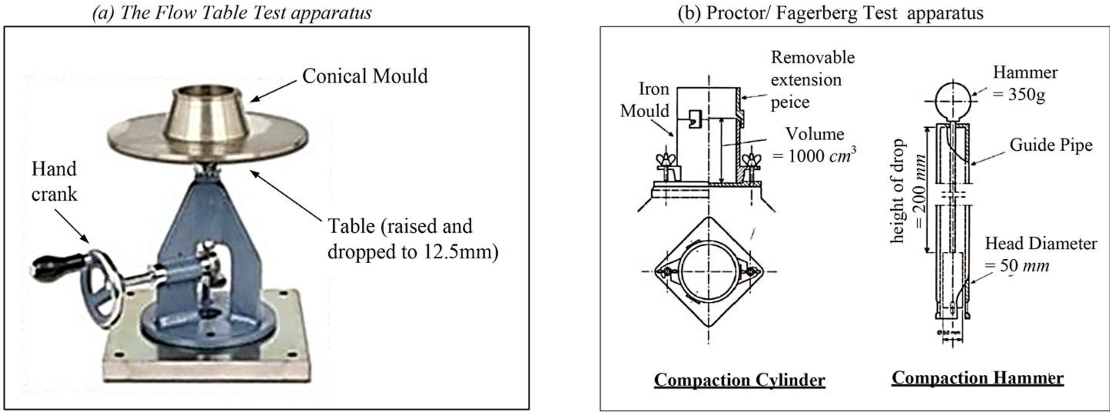


Figure 3.1: *(a)* The Flow Table Test (*left*); and *(b)* Proctor/ Fagerberg Test apparatus (*right*).

In addition to these methods within the IMSBC Code, a number of other methods have been developed for determining if a cargo is safe for carriage. Some of these methods have been used domestically, or have been adopted within the IMSBC Code for specific cargoes (set out within the relevant 'Cargo Schedules'). However, most tests were never adopted by IMO, failing to receive widespread support by IMO member states because: *(i)* of concerns of the results given by these methods; or *(ii)* they were viewed as unnecessary and possibly confusing additions to the existing test requirements. Figure 3.2 presents a timeline that outlines the development/submission of the different methods, accompanied by a brief description of significant tests in Table 3.2. These have been developed as part of this thesis from historical IMO submissions (to BC/DSC Sub-Committees), to provide context to the existing methods and to facilitate an understanding of the work that has been performed in the area. It may also serve as a useful reference for future work.

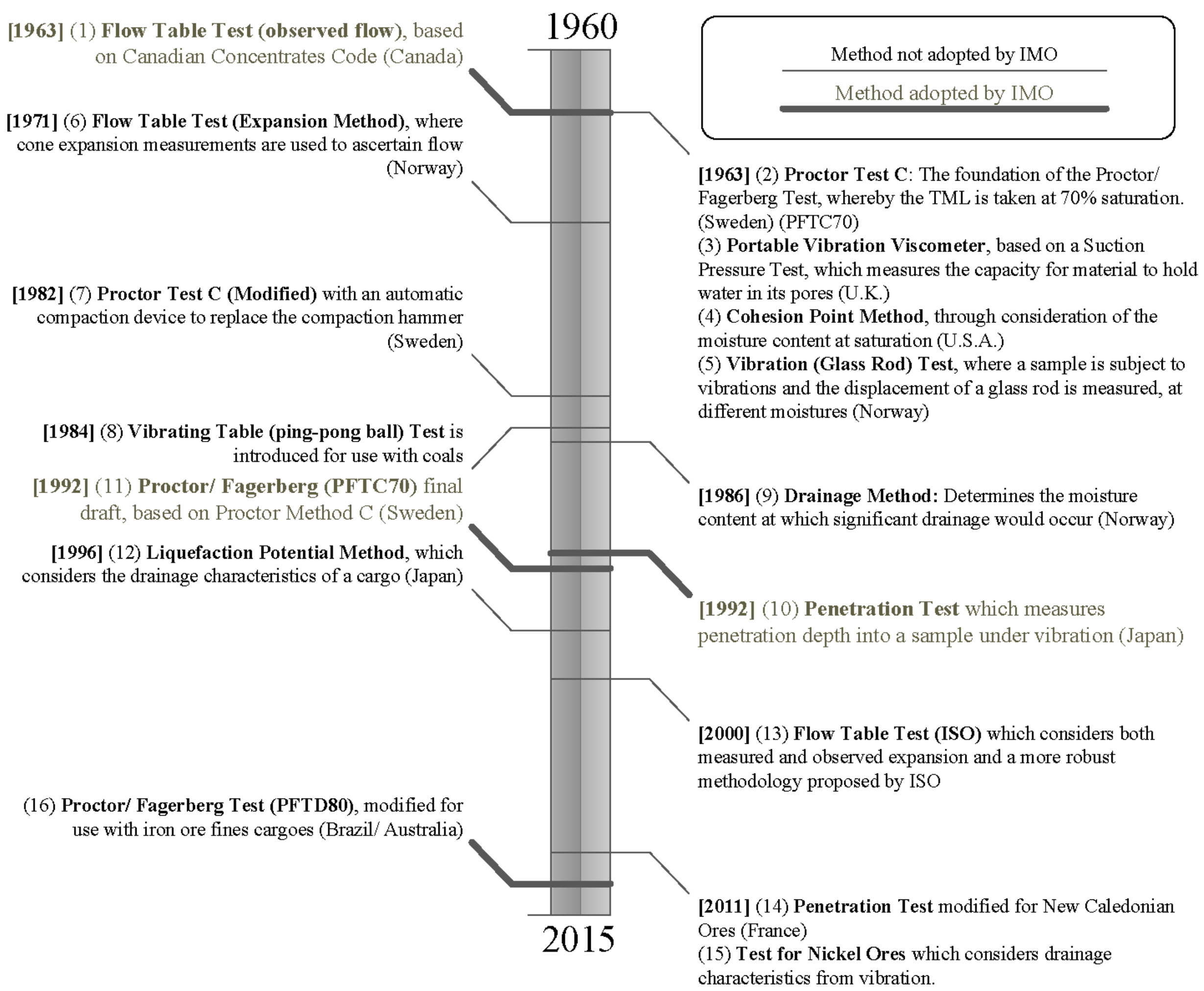
Further to these TML Test Methods, if the Master has concerns about the accuracy of the TML or moisture results presented within the Shipper's Declaration, a 'Can Test' may be performed dockside on the cargo consignment. The IMSBC Code specifies the basic methodology for the Can Test, whereby a cargo sample is placed within a can of 0.5-1 L capacity and then struck on a hard surface from a height of 0.2 m, 25 times at 1-2 second intervals. If free surface water develops, this may indicate that a loaded cargo is above the flow point and is therefore unsafe for carriage. The Master may then have grounds to prevent loading.

Differences in TML Testing and Typical Soil Mechanics Test Requirements

In addition to the physical differences between many cargoes and a typical soil (outlined in Section 2.2), the requirements of TML and typical soil testing also differ:

(a) The failure criteria in TML testing is the *moisture content* at which a loss of strength is most likely to occur (at a given initial state and fixed applied cyclic force, which intends to represent that experienced within the cargo). By contrast, in traditional soil testing the moisture content is often considered constant (often at saturation) with the endpoint being a soil strength or failure criterion;

(b) The significant financial implications that may result from even a slightly conservative FMP/TML determination make *precision and accuracy of the moisture measurement a priority*. For example, target precision for a TML result is commonly less than ±5% (relative), compared to typical precision requirements for moisture analysis in a soil compaction test (*i.e.* the PFT) in which maximum variation of reported optimum moisture content can be 4-8% (absolute). Notwithstanding, the IMSBC Code test methods are currently not achieving optimum precision.



No.	REFERENCE(S)
1	IMO: BCI/7; BC/Conc/6; BCI(II)/Conc/12
2	IMO: BCI(II)/Conc/12
3	IMO: BCI/7
4	IMO: BCI/7
5	IMO: BC/Conc/6
6	IMO: BCXIV/4; BCXV/4(a); BCXV/4(a)/1; BCXV/4(a)/; BCXV/4(a)/3
7	IMO: BC26/5/20; BC27/5/8
8	IMO: BC25/5/6
9	IMO: BC26/5/14; BC26/WP.9
10	IMO: BC32/WP.2
11	IMO: BC32/3/17
12	IMO: DSC2/12/1; DSC3/11/2; DSC2/12/1; DSC3/11/5; DSC4/5/4; DSC4/5/5; DSC6/5/3; DSC6/WP.4
13	International Standards Organisiation: ISO 1272:2000 and ISO 12742:2007
14	IMO: DSC 17/4/2; E&T17/5/1;DSC17/4/41
15	Jian-Ping, W., 2011., A Study on Safe Operation of Nickel Ore, *International Conference IMLA 19* , Opatija
16	IMO: DSC1/Circ.71; DSC18/INF.12;

Figure 3.2: A timeline showing various methods developed to ascertain if a cargo is safe for carriage, including the TML Test Methods. Most of these were proposed to IMO for use internationally. Some were never adopted and some have been adopted for use only on certain cargo types.

Table 3.2: Overview of Major Alternative TML Test Methods (also see Figure 3.2).

TEST NAME	OVERVIEW OF THE TEST METHOD
(3) **The Portable Vibration Viscometer** (Norway, 1964)	Based on the 'Suction Pressure Test', the Portable Vibration Viscometer was developed to determine the flow properties of a slurry material at sea. It measured the forces holding water into the pores and indicated the capacity of a material to retain water, under vibration. This test gave a 'Go' or 'No-Go' (not a TML) depending on whether a slurry flowed and touched an electrical contact switch, within a set time (IMO BCI/7, 1964; IMO BCI(II)/Conc/12, 1964; IMO BC/Conc/6, 1964).
(4) **The Cohesion Point Method** (U.S.A, 1964)	This method considered the saturation moisture of cargo and then deducted a 2.5% absolute safety factor to obtain the water content at maximum cohesion (termed the 'cohesion point'). Saturation moisture was determined by addition of a known amount of water to the sample, and letting it stand for 15 minutes (US Coast Guard, 1959; IMO BCI/7, 1964).
(5) **The Vibration (Glass Rod) Test** (Norway 1964)	This test worked in a similar principle to the PTT. An FMP was obtained by applying an uncontrolled vibration to the sample within a small bottle (*i.e.* only suitable for fine concentrates) and the penetration depth of a glass rod was measured with time. The turning point of the penetration depth and moisture content curve indicated the moisture content at maximum cohesion (*i.e.* the FMP). The rate of the curve provided insight into the speed at which a concentrate may lose cohesion after maximum moisture has been exceeded (IMO BC/Conc/6, 1964; IMO BC/Conc/13, 1964; IMO BCXIV/4, 1972).
(6) **The FTT Expansion Method and the 'Characteristic Moisture Content' (CMC)** (Norway, 1971)	In order to address the subjectivity associated with the FTT, Norwegian researchers investigated the effect of varying table knocks (20, 50, 100, 200 and 400) on cone expansion. They found that the turning point of all curves corresponded to the same moisture content and that this corresponded well to when 'plastic deformation' was observed. They termed this the Characteristic Moisture Content (CMC) and suggested that the TML be taken from a lower safety margin of 0.97-0.98 times the CMC as this method consistently gave lower results than other TML tests (Kvalheim et al., 1971; IMO BCXV/4(a)/2), 1971; BCXIV/4, 1972; BCXV/Inf.3, 1973; BCXIX/6, 1978).
(12) **Proposed Method to Determine the Liquefaction Potential** (Japan, 1992)	This method intended to determine whether a cargo was likely to liquefy during transit (*i.e.* a Group A Cargo) based on two criteria: (*i*) PSD; and (*ii*) drainage characteristics. If the cargo contained a sufficient portion of fine particles, and the degree of saturation after drainage was over 70% (determined from a specified test whereby a sample is saturated and allowed to drain for a fixed time), then the material would be classified as one that may liquefy, and further TML testing would be necessary (IMO DSC2/12/1, 1997; IMO DSC3/11/2, 1998; IMO DSC3/11/5, 1998; IMO DSC4/5/4, 1999; IMO DSC4/5/5, 1999; IMO DSC6/5/3, 2001).
(14) **Penetration Test for New Caledonian Nickel Ores** (France, 2011)	This research presented a modified version of the PTT for use with New Caledonian Ores. Major modifications included increasing: (*i*) the penetration bit diameter to 20 mm (from 15 mm); (*ii*) the penetration bit weight to 1500 g (from 177 g); and (*iii*) the fail criteria to 80 mm penetration (from 50 mm). Also, they proposed a 'surface confinement disk' be used to prevent material creeping to one side of the container, to control erroneous penetration (IMO E&T17/5/1, 2012).
(15) **A Study on Safe Operation of Nickel Ore** (Jian-Ping, W., 2011)	In research aimed at assessing the safe shipped moisture content for nickel ores, these researchers presented a new TML test in which vibration (20-50 Hz) is applied to a cargo sample that has been compacted into a cylindrical tube (d = 150 mm, h = 1200 mm) for 1-3 hours. Moisture analysis was then carried out in ~100 mm layers through the tube and moisture content of each layer is then plotted against height. At moisture contents approaching the flow point a wet base layer is formed and a turning point is observed on the plot, taken as the FMP. They found that the gradient of the turning point can provide insight into a material's absorbing capacity (Jian-Ping, W., 2011).
(16) **The Proctor/Fagerberg Test D80 for Iron Ore Fines** (Brazil and Australia, 2013)	Through a research project undertaken jointly by Rio Tinto, BHP Billiton and Vale, it was found that for the PFT on iron ore fines, the minimum void ratio (*i.e.* point of optimum compaction) occurred between 90-95% saturation; and that the density within the Proctor mould from the PFT was unrepresentative. They proposed that S=80% be taken as the intersection condition and that a 150 g hammer be used (replacing the 350 g hammer). These modifications increased TML by around 1% absolute. This new method was adopted within the schedule for iron ore fines (IMO DSC18/INF.12, 2013; IMO DSC.1 /Circ.71, 2013).

3.1 PROBLEMS WITH THE TML TEST METHODS

The intention of TML testing is to identify whether a cargo is safe to ship. However, there have been concerns within industry about whether this basic requirement is being effectively achieved—both in respect to: (a) the *suitability of the test methods*; and (b) the *reliability of these methods*, for the wide range of cargo and carriage conditions.

3.1.1 Suitability of the TML Test Methods: Accuracy

For the FMP/TML to be a suitable criteria for the safe carriage of a Group A cargo, then it must accurately represent the moisture content at which a cargo is likely to liquefy and shift during carriage. However, there is currently little evidence available to determine if this basic requirement is being achieved. As discussed in Chapter 2, the blanket approach to regulation ignores the many other factors that influence the likelihood of a cargo to liquefy and/or shift (for example, cargo type, ship size and stability).

An inaccurate TML result may have significant commercial and safety impacts:

(a) if the TML result is too high (*i.e.* 'underestimates' a cargo's potential to liquefy), then a *cargo may be allowed to be shipped when it is potentially not safe to do so*; or

(b) if the TML result is too low (*i.e.* 'overestimates' a cargo's potential to liquefy), then *a cargo may be unable to be carried when it is in reality safe to do so*—potentially resulting in unnecessary delays at the expense of the Shipper.

In addition to the impact on crew safety, an incorrect TML that causes a cargo liquefaction event may lead to a number of financial impacts. These include the costs and expenses associated with: (*i*) crew injury and death; (*ii*) pollution ('bunker') costs and the risk of prosecution for environmental damage; (*iii*) wreck removal costs; (*iv*) charter-party dispute and breaches of supply agreements; (*v*) property damage (*i.e.* the vessel itself); and (*vi*) cargo content insurance. As an example, the contents of a Capesize vessel carrying 200,000 tonnes of iron ore fines has a market value of around US$20–30 million, at 2013 iron ore prices of US$100-150 per tonne.

3.1.2 Reliability of the TML Test Methods: Variability

The FTT and PFT methodologies within the IMSBC code are non-specific. This in part serves a purpose because freedom in the methodology makes it easier for laboratories around the world to perform the tests on a range of cargoes, without requiring highly specialised laboratory equipment, highly skilled operators and significant time. However, non-prescriptive methodologies also lead to variability in results.

A number of coordinated test efforts have closely examined the TML Test Methods in the IMSBC Code and reported inadequacies, namely:

(a) *For a given TML Test Method, significant variability in TML results is often obtained* when repeatedly testing the same sample, both within a given laboratory, but particularly amongst different laboratories (Fagerberg, 1965; IMO BC XVII/3(b), 1976; IMO BC32/INF.15, 1992; Allen, 2012; IMO DSC18/INF.10, 2013) as demonstrated in Figure 3.3; and

(b) *Each TML Test Method gives different TML results for the same sample* of cargo material, whereby the TML result from the PFT is higher than from the other two methods (Green and Kirby, 1981; Kirby, 1981; Kruszewski, 1986; Popek, 2002; IMO DSC17/INF.10. 2012), as demonstrated in Figure 3.4 (overleaf).

A timeline that shows the major inter-laboratory studies has been included in Figure 3.5 (p. 44); developed as part of this thesis from the review of archive IMO literature. Although these studies have identified that issues exist, few have aimed at improving the test results.

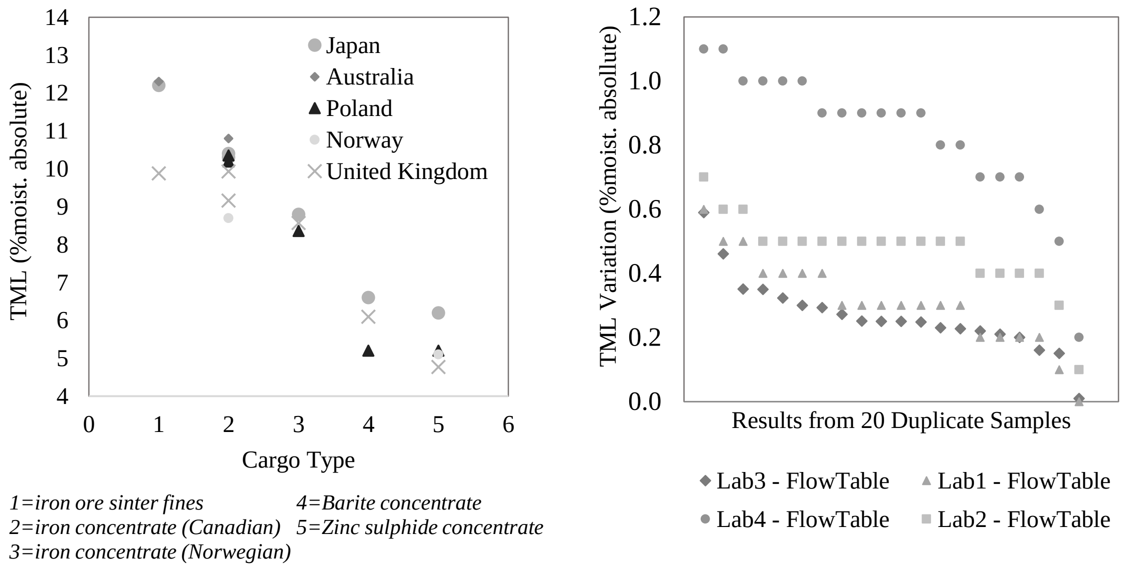


Figure 3.3: *(a)* Total TML variability of 23% (relative) was obtained for the FTT for seven different cargo materials, measured at 14 laboratories internationally (adapted from results presented to IMO in BC32/ INF.15 (1998)) *(left)*; and *(b)* the variability in TML results from an inter-laboratory trial consisting of 4 laboratories, whereby each laboratory tested 20 samples from the same homogenised bulk sample using the FTT (Allen, 2012) *(right)*.

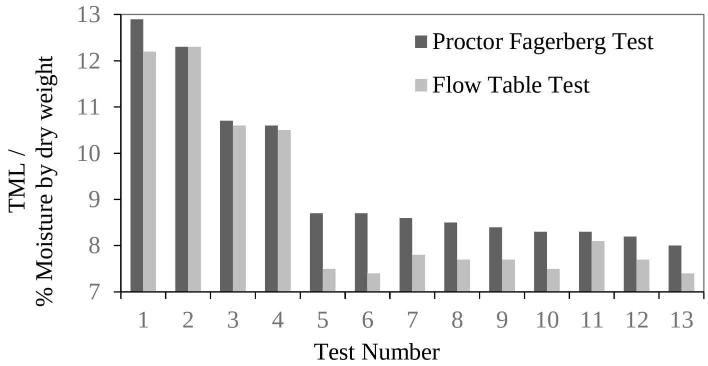
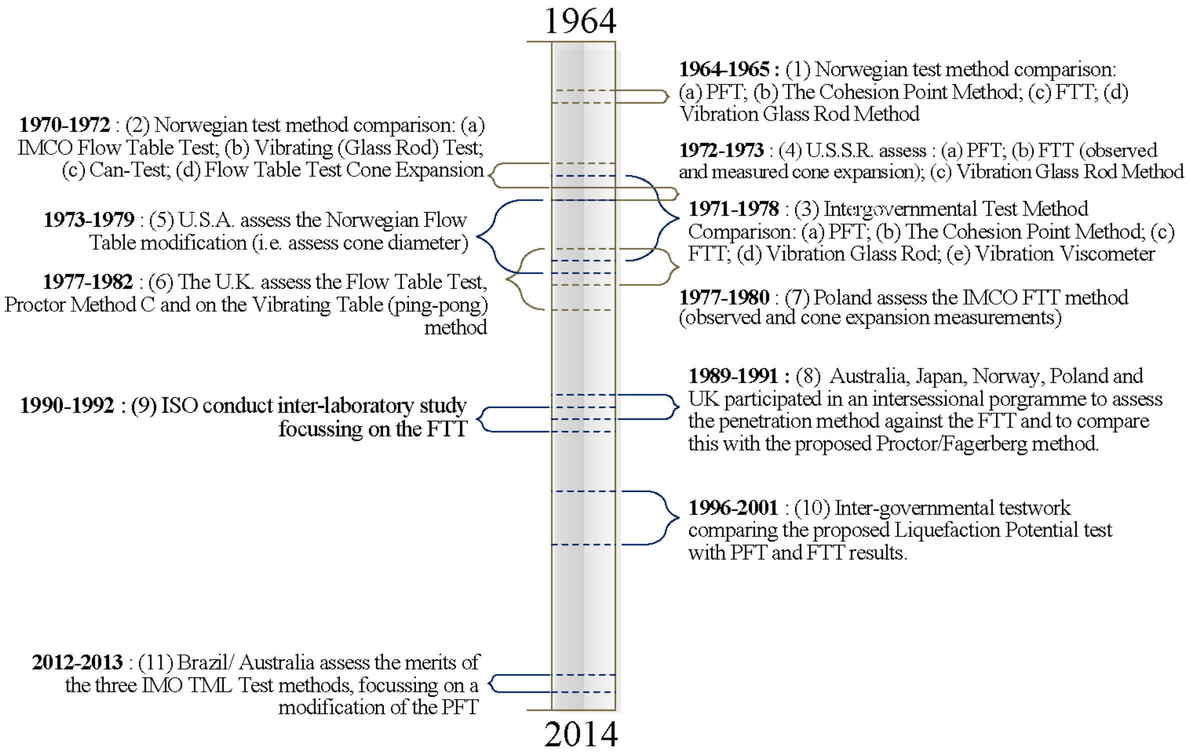


Figure 3.4: TML results from the PFT for Brazilian iron ore fines were consistently higher than those from the FTT. Adapted from data presented in IMO document DSC17/INF.10 (2012).



No.	REFERENCE(S)
1	IMO: BCI/ Conc; BC/Conc/13;
2	IMO: BCXIV/4
3	IMO: BCXVI/WP.2; BCVII/3(b); BCXVII/3(b)/Add.1; BCXVII/WP.6; BCXIX/6/1; BCXIX/6/1/ Add. 1; BCXVI/ INF.6
4	IMO: BCXV/4(a)/3
5	IMO: BCXV/4(a)/2; BCXV/Inf2; BCXVI/INF.7; BCXVIII/Inf.5; BCXX/ INF.13;
6	IMO: BCVXIII/Inf.2
7	IMO: BCXIX/6; BCXX/INF.5; BCXXII/5/12
8	IMO: BC30/5/12; BC31/3/2; BC31/ INF.4; BC31/ INF.5; BC32/WP.2
9	IMO: BC32/INF.6
10	IMO: DSC2/12/1; DSC3/11/2; DSC2/12/1; DSC3/11/5; DSC4/5/4; DSC4/5/5; DSC6/5/3; DSC 6/WP.4;
11	IMO: DSC18/INF.12

Figure 3.5: Significant bodies of work in which the TML test methods were compared and assessed. *NOTE:* Studies *prior to 1990 did not assess the three test methods in their current form, due to amendments to the IMSBC Code.*

This variability has led to concerns being raised by a number of researchers and IMO delegates that the 10% safety margin between the FMP and TML is inadequate to account for errors associated with sampling, sample preparation, testing and measurement for the FTT—particularly with regard to the reliance on operator interpretation of flow (IMO BCXV/4(a)/3, 1974; Hughes, 1977; Green and Kirby, 1981; Kirby, 1983; IMO BC28/5/16, 1987). On the other hand, export focussed member states, *i.e.* commodity producing countries such as Australia and Canada, have often argued against an increase in the FMP/TML safety margin within the IMSBC Code, largely due to the potential commercial implications (IMO BC29/5/4, 1988; IMO BC29/5/9, 1988). Norwegian researchers called for a complete abolishment of the safety margin because the results given by the FTT were significantly lower than those given by the PFT (Kvalheim et al., 1971; IMO BCXIV/4, 1972).

The inconsistencies with the TML Test Methods are problematic given that the TML imposes restrictions on whether a cargo can be transported (see Example I). In addition, the uncertainties associated with the TML Test Methods have led to doubts being expressed by certain maritime stakeholders[i] over the integrity of TML results presented by the Shipper (see Example II). For all parties to plan for and effectively manage and control the risks in a bulk commodity supply chain, it is important that the TML test methods give predictable, and therefore high precision results.

Example I: Which method to use?

According to Brazil in a submission to IMO (IMO DSC17/INF.10, 2012), 6873 voyages with (Brazilian) iron ore fines were taken between 2007-2012 (1084 million tonnes total), yet there was never a reported accident related to liquefaction. However, under the recent re-classification of iron ore fines as a Group A cargo: *(i)* 100 % of loaded materials could not have been loaded onto a vessel if the reported TML was determined from the PTT; *(ii)* less than 80% could have been loaded using a TML from the FTT test; and *(iii)* all of the cargo could be loaded using the TML result obtained from the PFT (DSC17/INF.10, 2012). Obviously, in order to be able to sell its product, this Shipper would choose to use the PFT for its TML analysis. Clearly, it appears that this test yields a safe TML result for this iron ore fines cargo, whilst the other tests give conservative TML results. However, this may not be the case for other cargo types.

[i]Including the Master, Ship Owner, shipping authorities, insurer (including the marine Protection and Indemnity (P&I) Associations), and laboratories.

Example II: Mistrust by the Master

There have been a number of reported instances following the deaths in late 2010, whereby the Master has not trusted the TML and/or moisture certification provided by the Shipper during or post loading of a vessel. The Author is aware of a situation in Australia whereby a concerned Master decided to cease cargo loading of a cargo that appeared overly damp. In response, the Master ceased loading, and a sample of the cargo was sent from Australia to the United Kingdom (UK) to be tested (by one of the insurer's preferred TML testing facilities). During this period, the partially loaded vessel (of approximately 200,000 d.w.t.) remained at anchorage for over a month, where it attracted demurrage costs payable by the Shipper. Eventually, the UK test-work revealed that the cargo was safe for carriage and the vessel was then able to sail. However, this came at a significant fiscal expense to the Shipper.

This Author believes it necessary to clarify that the intention of identifying the weaknesses of the TML Test Methods, and presenting the aforementioned examples with focus on the Shipper, is not to argue for abolishment of the TML (or even a reduction of the safety margin). The concept of a maximum moisture limit is a necessary mitigation measure to minimise the risk of cargo shift from liquefaction, and therefore reduce the probability of loss of life. However, the most effective testing and regulatory standards are not currently in place and the research presented in this thesis has considered ways to improve these.

3.2 APPROACH OF THIS STUDY

Reliable TML results provide all parties with confidence that a cargo will not liquefy during passage, whilst reducing the likelihood of unnecessary and expensive operational delays. As such, if the TML Test Methods are to be considered effective then each test must give results that are reliable, and able to be reproduced and compared with others undertaken elsewhere.

As demonstrated from previous inter-laboratory trials (Section 3.1.2), and from the test-work presented later in this chapter, these basic requirements are currently not being achieved. To address this, the FTT and PFT methodologies have been comprehensively assessed, deficiencies identified and recommendations established as part of this study.

More specifically, the factors that influence method *variability* were explored for both the FTT and PFT. Firstly, tests were performed, based on the IMSBC Code methodologies, and then controlled variations were applied to its different components. The inherent issues, ambiguity and errors (*i.e.* bias and/or variability) within the IMSBC Code have been identified, assessed and presented (Sections 3.5-3.8). Giving consideration of these findings with regard to the methodology in the IMSBC Code, a number of recommendations are suggested and an improved 'best-practice' methodology has been developed (Section 3.9). Ultimately, these findings will steer future developments to the IMSBC Code methodologies so that greater precision can be achieved, not only by a single operator within a single laboratory (*repeatability*), but also amongst different operators and laboratories (*reproducibility*).

Following from this, the two TML Test Methods are *compared* **(**Section 3.10), in order to identify suitable methods that could be used to calibrate and align their respective TML results.

This chapter assesses deficiencies of the TML Test Methods that lead to variable results or non-representative results being presented. Chapter 4 of this thesis assesses the likely accuracy of these methods, identifying their suitability for assessing whether cargo shift will occur.

Note that in addition to performing laboratory test work, the analysis incorporates the findings from observations made, by the Author, during visits to a number of different TML testing laboratories (five laboratories in total). The assessment therefore includes the findings of actual observation of a range of different methods, apparatus and operators. Accordingly, some of the methodologies presented through this chapter are not part of the IMSBC Code but reflect actual methodologies used in practice (it is stated where this is the case). These may diverge from the IMSBC Code methods because of ambiguities in the IMSBC Code, or because of the prevalent use of the ISO TML testing method (ISO, 2012) (which offers improved prescription of the methods, yet does not strictly comply with the requirements in the Code).

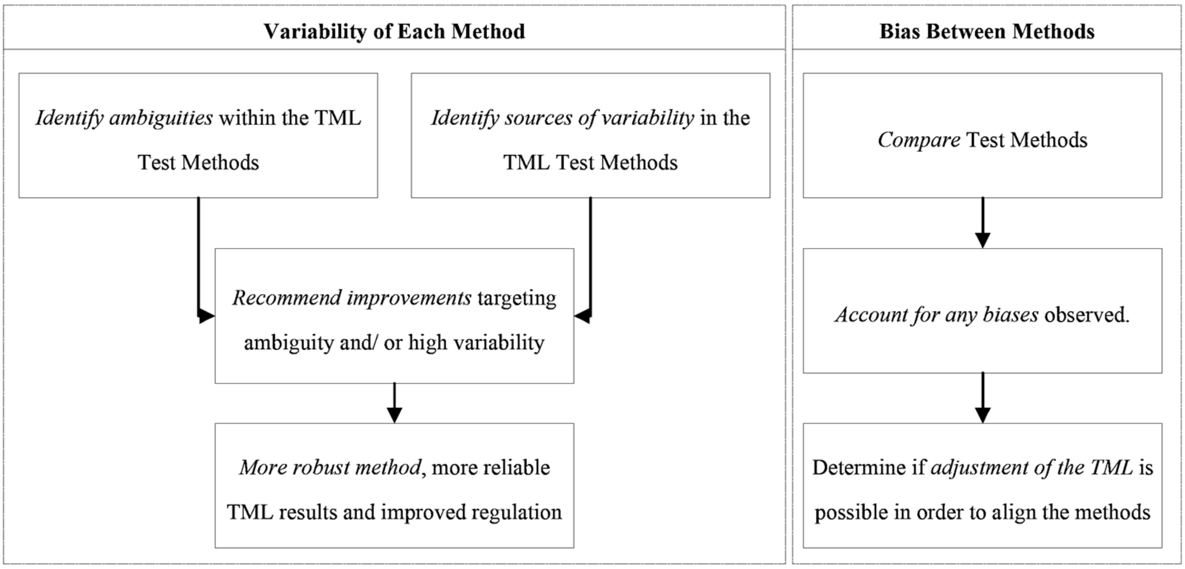


Figure 3.6: Summary of the approach taken to assess of reliability of the TML test methods.

3.3 METHODOLOGIES USED IN THIS STUDY

3.3.1 IMSBC Code Flow Table Test (FTT) Methodology

The FTT is based on a civil engineering test for hydraulic cements (ASTM, 2013). This was subsequently modified and introduced as a method to assess cargo liquefaction within the Canadian Concentrates Code in the 1960's (Canada Dept. of Transport, 1961) and was later adopted within IMO's Code of Safe Practice for Solid Bulk Cargoes (BC) Code (the predecessor to the IMSBC Code) in 1965 (IMO BC Code, 1965).

In the FTT (shown previously, in Figure 3.1), a sample is compacted in three stages into a truncated conical mould on a flow table (to ASTM designation C230-68), using a spring-loaded tamper (30 mm diameter head). The required tamper pressure (T)[i] is calculated based on cargo depth (h), bulk density (ρ) and acceleration from gravity (g) according to: (IMO, 2012)

$$T\left[\text{Pa}\right] = \rho\left[\text{kgm}^{-3}\right] \times h\left[\text{m}\right] \times g\left[\text{ms}^{-2}\right] \quad (3.1)$$

The mould is then removed, and the sample is subject to a fixed cyclic force through the raising and dropping of a table, controlled by:

(a) Drop height (12.5 mm);
(b) Drop rate (25 drops per minute); and
(c) Number of cycles (50 cycles).

When a material contains moisture below the FMP, it will usually be observed to crumble. However, if there is sufficient moisture in the sample, the action of dropping the flow table causes the grains to rearrange with possible compaction of the mass. As a result, the fixed volume of moisture contained in the material increases as a percentage of the conical samples volume as a whole (i.e. 'degree of saturation' increases). The moisture tends to migrate through the mass and the samples resistance to shear may disappear, causing plastic deformation in the conical sample. This is usually accompanied by expansion of the cone. The sample is considered to have *"liquefied"* (or the FMP has been exceeded) when plastic deformation can be observed, generally from the appearance of a *"convex or concave"* profile. (IMO, 2012)

With regard to FMP determination, the IMSBC Code methodology recommends that testing is performed in two stages. Firstly, it suggests that a *"preliminary flow moisture point test"* be

[i]Equivalent to the vertical stress. σ_v term used within soil mechanics.

conducted, which aims to determine an approximate FMP. This allows the FMP to be targeted in the subsequent "*main flow moisture point test*," which must be conducted around the FMP at smaller moisture increments of *"no more than 0.5% of the mass of the material mass"*. For the preliminary test, the IMSBC Code specifies two methods for determining the approximate FMP: *(i)* by observation of flow, or *(ii)* by taking measurements of the cone's expansion, where either can be used. For the main test, from which the reported FMP result is based, the IMSBC Code requires that the FMP be determined from taking the average between two moisture contents – one just before observed flow, and one just after observed flow.

A representation of the FTT methodology, in the form of a process flow diagram, is shown in Figure 3.8 (p. 52). Note that this has been developed from this Author's interpretation of the IMSBC Code that, as discussed throughout this chapter, contains inherent ambiguities.

3.3.2 IMSBC Code Proctor/Fagerberg Test (PFT) Methodology

In the 1930's, Proctor proposed a test method (commonly called the 'Proctor Test'), whereby changes in density are measured at a range of moisture contents. From this, a compaction curve and the optimum moisture content (OMC) can be determined, corresponding to the maximum dry density. Proctor's work focused primarily on soils. (Proctor, 1933; 1948)

Fagerberg (1965) later performed research to extend the Proctor Test for application to solid bulk cargoes (Fagerberg, 1965a; 1965b). The relationships between the void ratio, moisture and degree of saturation were explored for a number of shipped mineral concentrates. Fagerberg found that the minimum void ratio (which corresponds to the OMC) occurred at, or just above, the intersection of compaction curve and the 70% saturation line. It was therefore proposed that 70% saturation could be considered the safe moisture content at which a material could be safely carried on a vessel, *i.e.* the TML (IMO BCII/Conc/12, 1964; Fagerberg, 1965a; 1965b). An analogy between PFT compaction and actual cargo compaction is illustrated in Figure 3.7 *(left)*, on the following page.

In this regard, the PFT differs from the other TML Test Methods in that it does not rely on the identification of a flow state or a point deemed as the threshold of liquefaction (the FMP). Instead, the TML is calculated from density and moisture measurements.

The Proctor apparatus used in the PFT consists of a cylindrical mould of volume 1,000 cm^3

with an upper extension piece (shown previously in Figure 3.1). The sample to be tested is filled into the mould in five stages. Each stage is compacted by application of a fixed energy through tamping each layer 25 times with a 350 g hammer, of 50 mm tamper head diameter and drop height of 0.2 m (in a guided tube). When the last layer has been tamped, the extension piece is removed and the sample is levelled off at the brim of the mould. The weight and the moisture content of the material in the mould are determined, from which the material's dry density (ρ_{dry}) can be obtained. This process is repeated at different moisture contents, ranging from dry to almost saturated (five to ten are suggested in the IMSBC Code).

From the moisture content and density measurements, the void ratio (e_v) and degree of saturation (S) can be calculated. These are then plotted on a graph of void ratio against moisture content. This is commonly known as the *'compaction curve'*. Lines representing the cargo's degree of saturation are also plotted, as shown in an example Proctor/Fagerberg curve in Figure 3.7 (*right*) (IMO, 2012). The TML is then determined (typically graphically) from the intersection of the compaction curve and the 70% saturation line (also shown in Figure 3.7 (*right*)). Note that this TML criteria was adopted by the BC Sub-Committee in 1992, lobbied by the Swedish (IMO BC29/5/7, 1959; IMO BC29/INF.3, 1989; IMO BC29/WP.3, 1989; IMO BC30/5/2, 1990; IMO BC32/3/17, 1992)—it was originally proposed much earlier by Fagerberg during the 1960's (Fagerberg, 1965a; Fagerberg, 1965b).

A representation of the IMSBC Code PFT methodology is show in the form of a flow diagram in Figure 3.9 (p. 53). As for the FTT, ambiguities are inherent within this methodology and this diagram therefore represents this Author's interpretation.

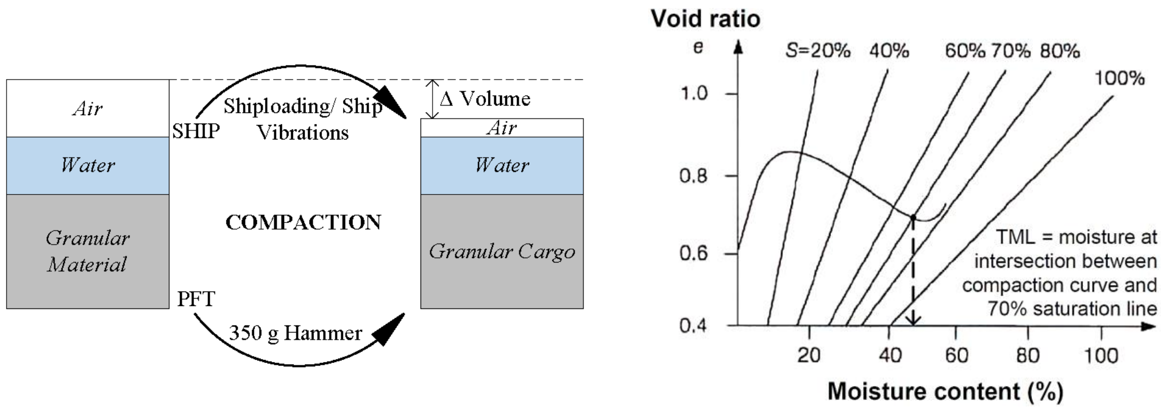


Figure 3.7: *(a)* Analogy between compaction in the PFT and compaction in a cargo *(left)*; and *(b)* Determination of the TML of a solid bulk material from the Proctor/ Fagerberg curve *(right)*, adapted from IMO (2012).

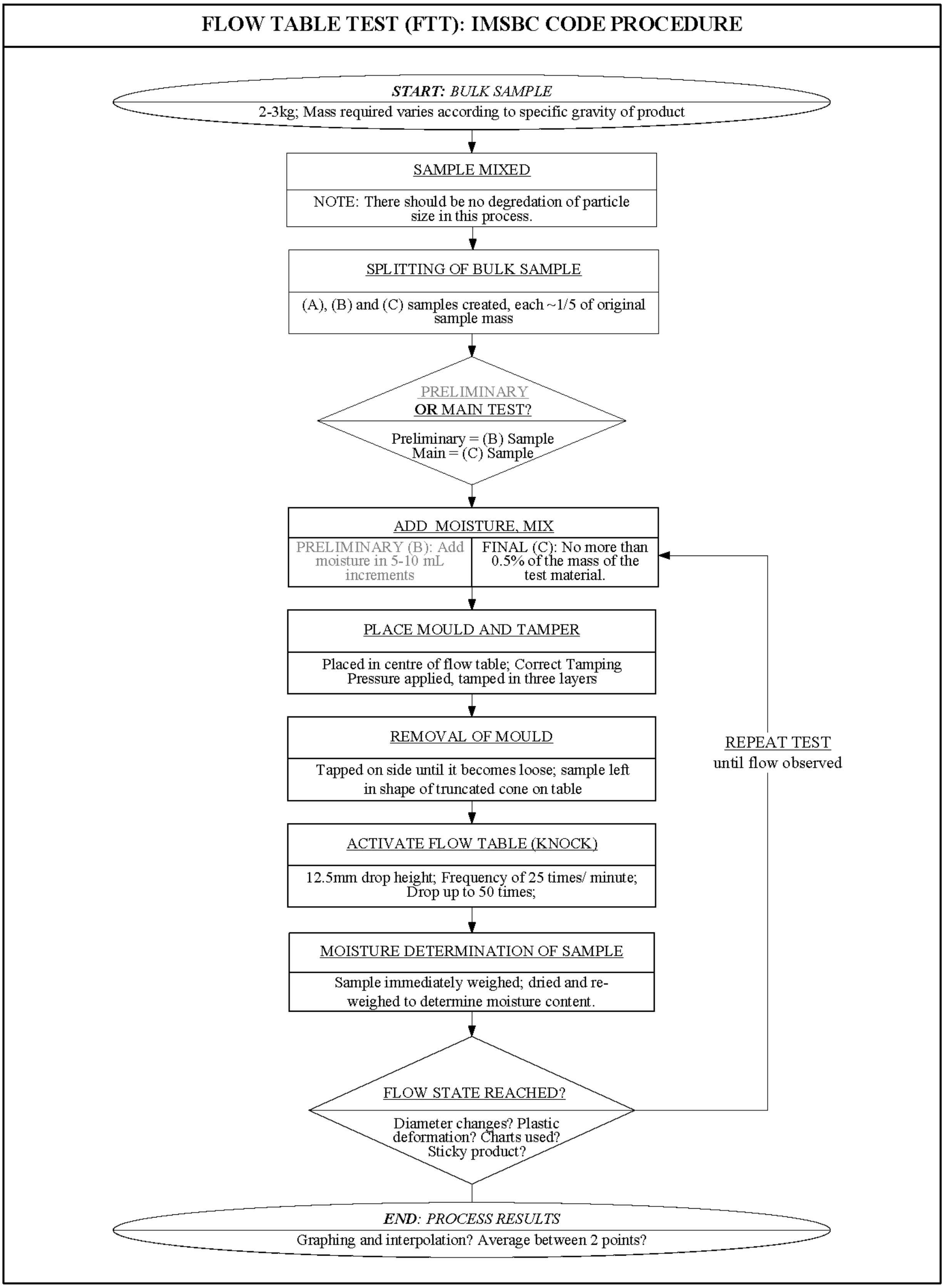
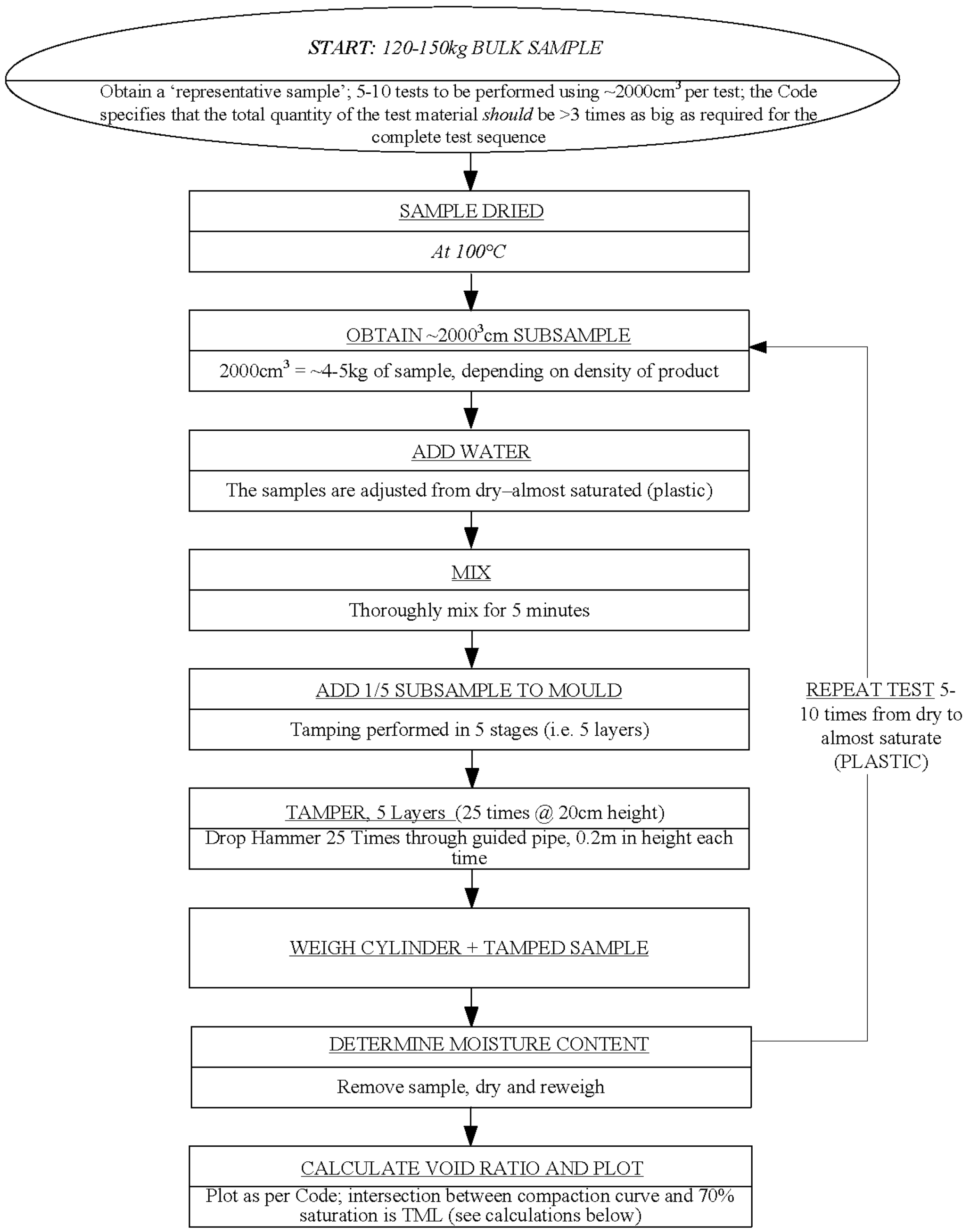


Figure 3.8: Flow diagram representation of the FTT Methodology, as interpreted from the IMSBC Code.

PROCTOR FAGERBERG TEST: IMSBC CODE PROCEDURE



Measured Properties

Variable	Symbol
Mass Empty Cylinder	**A**
Mass Cylinder with Tamped Sample	**B**
Mass wet sample	**C** = B – A
Mass dry sample	**D**
Mass Water	**E** = C – D
Volume of cylinder	1000 cm^3

Calculations

Variable	Symbol	Calculations
Density:	d	d
Dry Bulk Density:	γ	$\gamma = \mathbf{D}/1000$
Net Water Content (%volume)	e_v	$e_v = \mathbf{E/D} \times 100 \times d$
Void Ratio (vol. voids /vol solids)	e	$e = G_s/\gamma - 1$
Degree of saturation (%volume)	S	$S = e_v/e$
Gross water content	W^1	$W^1 = \mathbf{E/C} \times 100$
Net water content	W	$W = \mathbf{E/D} \times 100$

Figure 3.9: Flow diagram representation of the FTT Methodology, as interpreted from the IMSBC Code.

3.3.3 Apparatus

Appendix 2 of the IMSBC Code specifies the apparatus for the FTT and PFT that were adopted for this testing. More specifically, the main apparatus for the FTT comprised of:

- Flow table (ASTM designation C230-68), as in Figure 3.1;
- Callipers (readings to .01 and of sufficient width to measure mould); and
- Spring loaded tamper with a 30 mm tamper head.

For the PFT, the specified apparatus included:

- A cylindrical Proctor mould, of volume 1000 cm^3 (20 cm diameter) with a removable extension piece; and
- A Proctor hammer with hammer mass of 350 g and drop-height of 0.2 m.

For both tests, moisture determination was performed using a calibrated mass balance of accuracy that exceeded ±0.01 g and a stainless steel oven, temperature controlled to less than 105ºC. In addition, plastic re-sealable and airtight buckets were used throughout the testing to minimise moisture loss.

3.3.4 Testing Scheme

This test work was performed in three primary stages:

(a) Initial setup and validation tests with the FTT and PFT.
(b) Step-wise assessment of the IMSBC Code methodologies to identify issues and ambiguities that lead to random errors and biases of TML results.
(c) For significant variables identified in (b), perform a targeted assessment of their impact on the TML.

For the majority of test results presented, bulk samples of the test material were homogenised and split into sub-samples, of known mass (see Section 3.3.5 for description of test material). The water content was then incrementally adjusted for each sample, ranging from almost dry to above saturation. Each of these sub-increments were then subject to testing by FTT and PFT, typically in duplicate, and the moisture content was determined by oven drying, using internationally recognised methods. In addition, a number of supplementary tests and measurements were taken at different stages throughout the test to identify their impact on the

TML results, and therefore their overall contribution to variability.

Figure 3.10 shows an overview of the typical sample preparation and testing scheme employed for the work. For Redhill 110, 74 moisture increments were tested using the FTT and 46 were tested using the PFT. For iron ore fines, seven increments were tested using FTT and 8 using the PFT. Additional tests were also performed to target certain components of the methodologies (for example, the influence of tamper pressure, mixing and moisture loss).

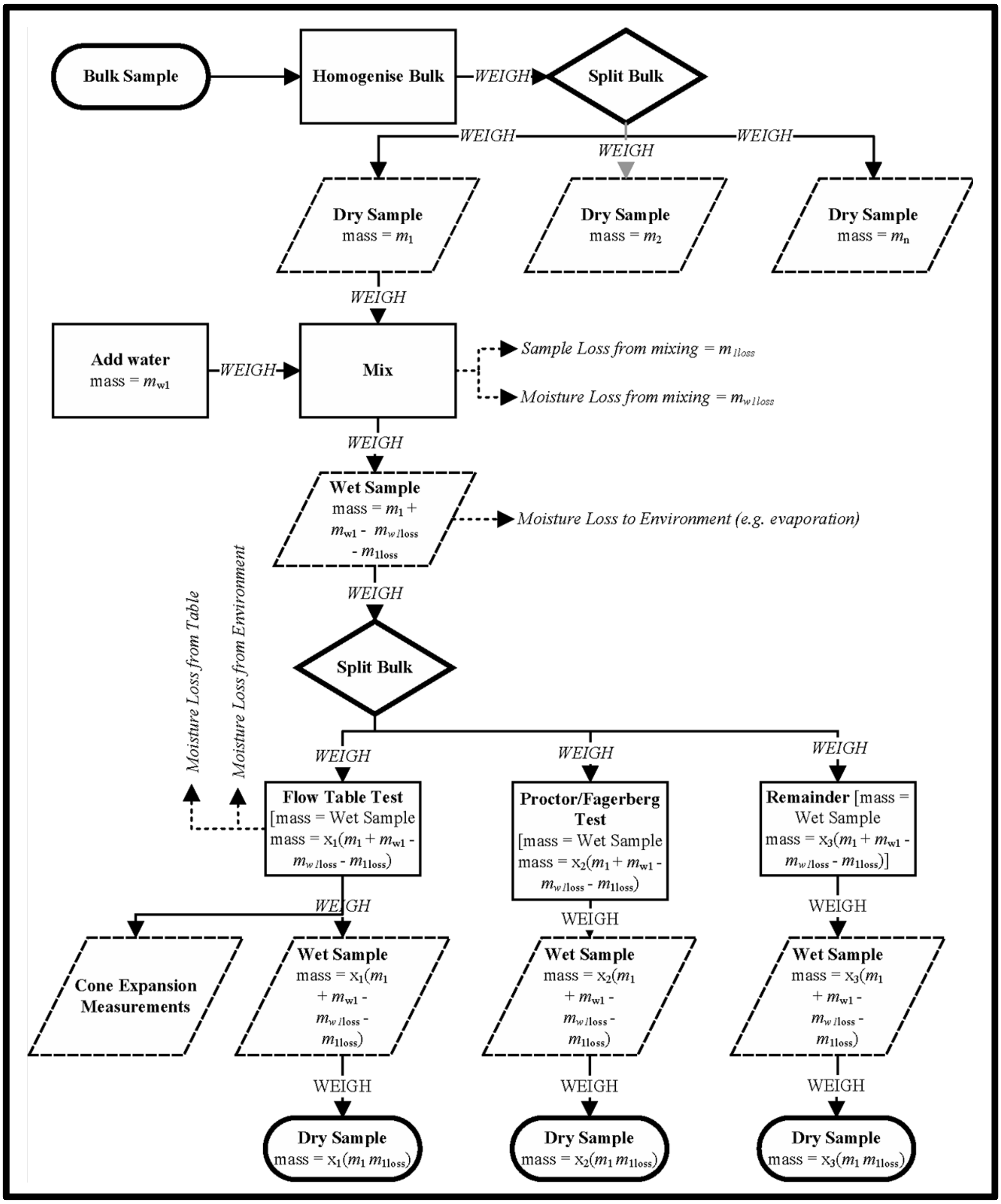


Figure 3.10: Flow diagram overview of the sample preparation scheme employed.

3.3.5 Test Material

Redhill 110 sand was used as the primary test material for test-work presented in this thesis, due to the comparative prevalence of soil mechanics literature that exists in relation to its strength and liquefaction properties. Although these studies have been almost exclusively performed in the fields of seismic or oceanic research, they provide an excellent point of reference. By consideration of the properties of Redhill 110, it would be classified a Group "A" cargo if shipped under guidance of the IMSBC Code.

In addition, testing has been performed on an *iron ore fines* cargo from the Pilbara region of Western Australia (sourced from within the United Kingdom), shown in Figure 3.11. This was selected in order to:

(a) *validate the test methods* employed on Redhill 110, by comparison with readily available TML test-work that has been performed by other researchers on iron ore fines (IMO DSC18/INF.10, 2013);
(b) *establish any differences in behaviour* that exist between the sand and a more commonly transported Group A material; and therefore
(c) ensure that findings from Redhill 110 can be more *generally applied* to cargo material.

It follows, that the findings and recommendations presented are intended to be generally applicable to all cargoes that fit within the basic criteria of these test methods (as previously shown in, Table 3.1, p. 37), unless stated. As there were difficulties attaining large quantities of iron ore fines material, the number of tests that could be performed on this cargo were limited. Ideally, it would also have been valuable to perform tests on a range of other cargoes such as nickel ores and/or concentrates, but these could not be sourced in this study.

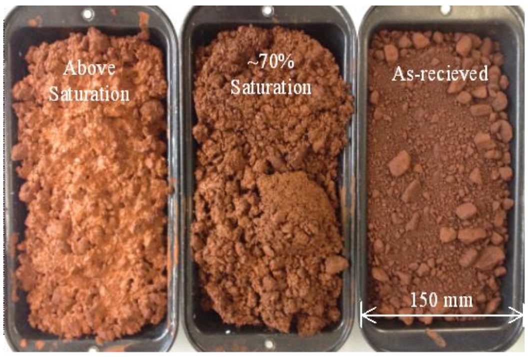
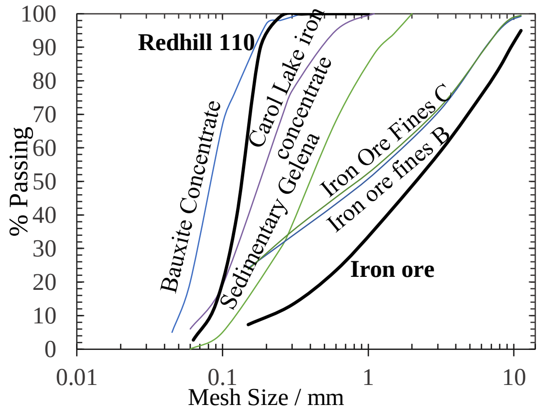


Figure 3.11: The iron ore fines material tested (Iron ore fines C).

A comparison between the PSD of Redhill 110 and the iron ore fines tested ('Iron Ore Fines A') is shown in Figure 3.12. Also shown is the PSD of a number of other iron ore fines and concentrate cargoes, and their FMP/TML and static strength properties (where available). Figure 3.12 shows that the PSD and specific gravity of Redhill 110 are similar to that of the bauxite concentrate reported by Kruszewski (1985) (specific gravity of 2.63 and 2.65, respectively). The other concentrate cargoes have similar grading to Redhill 110, but these are typically heavier (specific gravity of over 5)—as are many other commonly transported concentrate cargoes such as nickel, copper and zinc[i] (not shown in this plot).

The iron ore fines material is a coarser and heavier material (specific gravity of 3.9-4.5). Bulk densities measured for Redhill 110 and the iron ore fines tested, under the PFT compaction conditions, can be observed within the Proctor plot results shown in Figure 3.19 (p. 64).



	Redhill 110	*Iron Ore Fines A*	*Iron Ore Fines B*	*Iron Ore Fines C*	*Carol Lake Iron Concentrate*	*Sedimentary Gelena*	*Bauxite Concentrate*
TML	18.6	12.6	9.2-11	9.7-12.3	7-8	6.2	21
FMP	20.7	13.2	10.3-12.3	10.8-13.7	9		24
Specific Gravity	2.63	4	4.2	4.1	5	7	2.65
Friction Angle	36					41	37.5
Cohesion						15	14

Figure 3.12: Grading curve for Redhill 110 sand (Williams, 2014) in comparison to the iron ore fines tested ('Iron Ore fines A'). Also shown are Carol Lake iron concentrate (Kruszewski, 1985), Carol Lake iron concentrate (Kruszewski, 1988), Sedimentary Gelena (IMO DSC6/5/3, .2001) and two other iron ore fines. Note that FMP/TML values are given as percent moisture by dry weight.

Figure 3.12 highlights the large variation in TML that can be obtained, even for materials of similar PSD. The specific gravity appears to be one of the key drivers of this variation. However, the TML of iron ore fines B and C can also vary significantly, despite these materials possessing a similar PSD and specific gravity. This is likely due to the contribution of other factors, such as particle shape, porosity and smoothness/roughness.

3.3.6 Quality Assurance

Given the intention of the present work was to identify sources of error, it was important to

[i] The specific gravity of these concentrates vary with composition (high-grade materials are usually heavier).

minimise any variability 'noise' that may arise from sampling and measurement errors. For example, careful consideration was given to the following:

- *Scale Calibration*: Multiple scales were used and each of these were calibrated against each other accordingly, to within ±0.06 grams, so that net impact on moisture results were <0.0005 percent error for each scale. Where possible, the same scales were used for a given set of tests to ensure random errors were not introduced.
- *Testing in Duplicates*: To ensure that adequate sampling and moisture analysis precision was obtained, duplicate tests were performed (see example, below).
- *Drying Time*: For moisture determination, all samples were dried to constant mass.

Example III: Checking sample mass is sufficient for suitably precise TML Results

Sample mass impacts sampling precision, whereby material of larger topsize and wider grading require a larger sample mass to obtain equivalent sampling precision. An analysis was undertaken for Redhill 110 that aimed to determine whether the mass of sample within the mould (~500 g for Redhill 110) was sufficient to obtain suitably precise TML results. Testing of duplicates indicated that when two samples (A and B) of mass ~500 *g* were taken from a ~1200 g starting mass, TML variability of 0.05% absolute was obtained between the two samples (Figure 3.13). This shows that for Redhill 110 tested: (*i*) a 1000 g starting mass is sufficient to obtain acceptable sampling precision for FMP determination; and (*ii*) moisture loss during and post-test is acceptably consistent amongst tests. Note that Redhill 110 tested is a uniform, finely graded material. However, greater mass may be required for material of wider grading. Over a certain top size, the small volume of the FTT mould is unlikely to be sufficient to obtain adequately precise results.

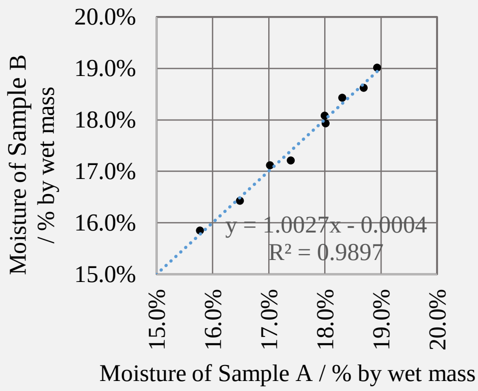


Figure 3.13: Comparison of moisture results from duplicate samples after the FTT.

3.4 FMP/TML RESULTS

3.4.1 Flow Table Test (FTT) TML Results

For each incremental moisture content tested on the FTT, the identification of flow was assessed by three methods, namely:

(a) Visual observation;

(b) Measurement of cone base expansion; and

(c) A *combination of both* visual observation and cone expansion.

These are described in detail in Sections 3.4.1.1 to Section 3.4.1.3. The average FMP and TML results from each of these determination methods are shown in Table 3.3, for Redhill 110. For iron ore, the FMP/TML occurred at 12.6%/11.3%. This was determined by observation of flow only; there was insufficient test material available for comprehensive assessment using expansion measurements.

Table 3.3: TML obtained by the FTT for Redhill 110 using different methods of flow identification, namely (A) observed; (B) measured; and (C) a combination of both observed and measured (described below).

METHOD OF DETERMINING FMP	FMP / TML % MOISTURE, BY DRY MASS
(A) Observed plastic deformation	20.7 % / 18.6 %
(B) Measured value: > 3mm expansion	20.7 % / 18.6 %
(B) Measured value: IMSBC Code intersection method	21.5-22.8% / 19.3-20.5%
(D) ISO 12742:2007 (both observed and >3mm considered)	20.7 % / 18.6 %

3.4.1.1 FMP/TML Determination by Observation

The IMSBC Code specifies that the FMP has been exceeded when the moisture content is sufficiently high to visually observe plastic deformation of the test sample. The IMSBC Code includes basic descriptors to help interpret plastic deformation (see Section 3.3.1). In consideration of these, the FMP and TML of Redhill 110 were therefore determined to be 20.7% and 18.6%, respectively—the FMP being taken as the midpoint (average) moisture between where crumbling last occurred (20.65%, as shown in Figure 3.14 (*Stage 1*)) and where plastic behaviour was first observed (20.78% moisture, as shown Figure 3.14 (*Stage 2*)). It was at this point that localised plastic deformation was observed, and 'streaking' of moisture could be seen on the table following removal of the cone post-testing (both behavioural descriptors of flow in the IMSBC Code). However, as explored in Section 3.6.1, these descriptors are subjective.

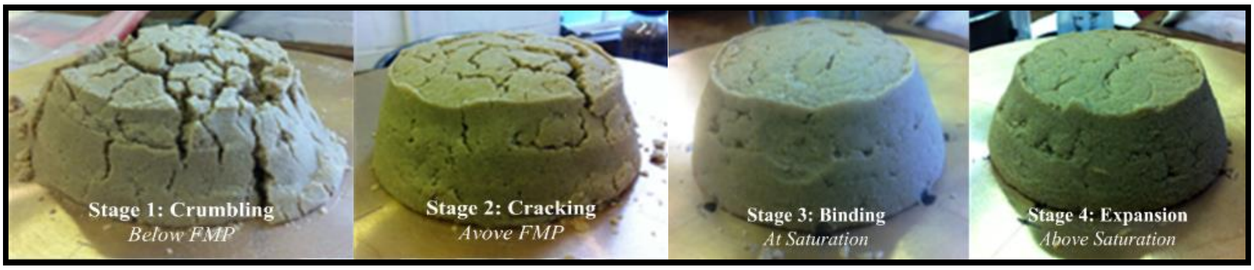


Figure 3.14: Observations on the flow table with (increasing) moisture content (left to right). The observed FMP was taken as the midpoint moisture between where crumbling ceased (Stage 1) and where plastic behaviour was first observed (Stage 2).

An example of the observed flow behaviour of the iron ore fines cargo tested is shown in Figure 3.15. This figure also shows the observed behaviour of another rapidly draining sand tested, which exhibited no flow behaviour (regardless of moisture).

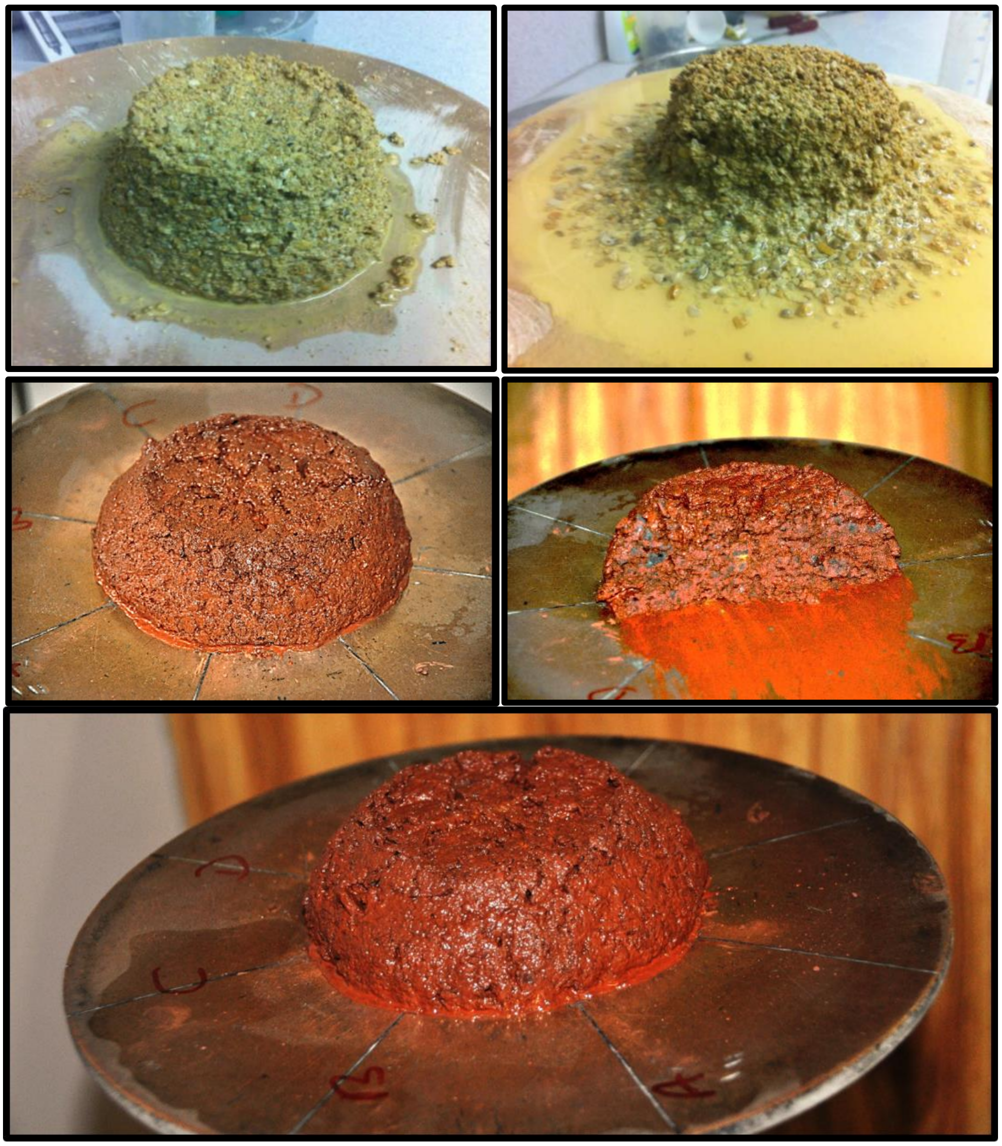


Figure 3.15: *(top) C*rumbling behaviour on 'sharp builders sand', which did not exhibit any flow due to significant drainage through the sample (preventing pore-pressure build up); and *(bottom)* observations of plastic deformation (*i.e.* 'bulging' and 'streaking') on this iron ore fines cargo.

3.4.1.2 Determination of the FMP/TML by Measuring Cone Expansion

Observation of actual laboratory practice has indicated that some laboratories determine the reported FMP/TML by considering only the measured expansion at the base of the cone. More specifically, a FMP is most often established by one of two methods (referred to hereinafter as the *'IMSBC Code Expansion Method'* and the *'Threshold Expansion Method'* for FMP/TML determination by measurement):

(a) In the IMSBC Code Expansion Method, the measured expansion of the cone (Δd) is plotted against moisture content for two moisture increments above the FMP. Then, a straight line is drawn between these two points and the FMP is taken as the intersection of this line with the moisture axis. This is illustrated in Figure 3.16, for Redhill 110, for three sets of points (*three inclined straight dashed lines*). The arrow at the end of these lines represents the moisture content which would be taken as the FMP.

(b) In the Threshold Expansion Method, the measured cone expansion (Δd) is compared to a threshold value. If expansion exceeds the threshold, then the sample is considered to be above the FMP (shown as a horizontal line in Figure 3.16).

For method **(a)**: As shown in Figure 3.16, obtaining a FMP result from this method would not be possible below around 22.5% moisture—a line drawn between two points under this moisture content would possess a flat gradient that would not meaningfully intersect the moisture-axis. Above this moisture, the exact FMP result depends on the selection of the two

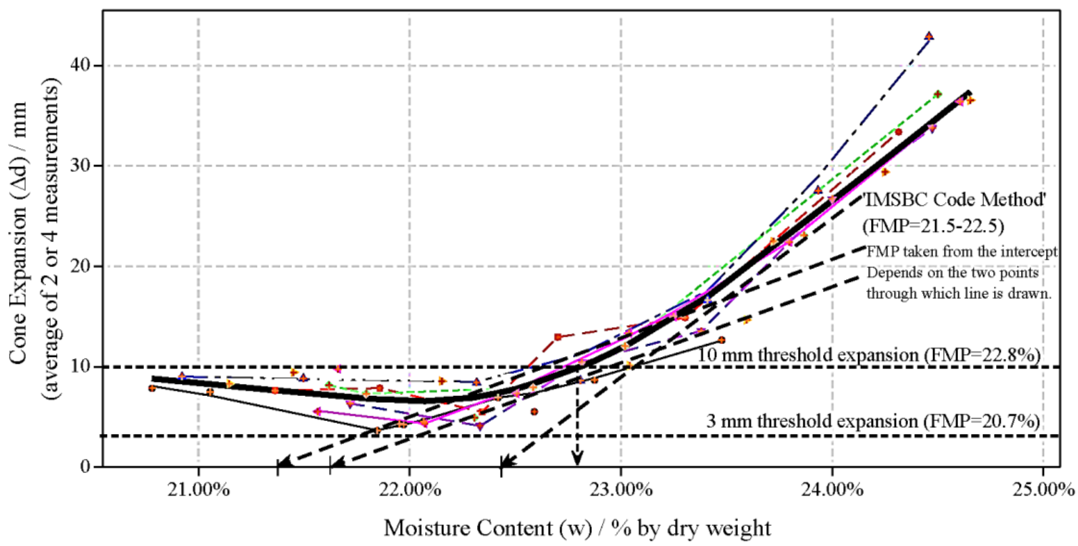


Figure 3.16: FTT cone expansion (Δd) against moisture content (w) for Redhill 110. Below 20.7% moisture the cone crumbled and expansion could not be measured. Also shown are the two common measurement methods for FMP determination, the 'IMSBC Code' and 'Threshold' expansion methods).

moisture contents through which the straight line is constructed (*i.e.* a different FMP is obtained from each of the three lines constructed in Figure 3.16). For Redhill 110, the FMP would therefore be determined to be within a range of approximately 21.5-22.8% moisture (a TML of 19.3-20.5%). Note that in normal testing practice, only a few increments are tested and a single FMP value is obtained (not a range). Alternatively, some laboratories may obtain an FMP from a linear trend-line that fits multiple points beyond flow rather than using only two. Regardless of the technique used, the reported FMP/TML for Redhill 110 could vary considerably if only a single FMP/TML was reported (up to 1.2% moisture).

For method **(b)**: Usually a 3 mm threshold is used, although according to Grant (2010) it can be up 10 mm for some laboratories. For Redhill 110, the 3 mm expansion threshold was exceeded in all cases following crumbling, as shown in Figure 3.16 (*horizontal dashed line*). The FMP is therefore determined from the lowest moisture content at which the threshold was exceeded, or 20.7% (a TML of 18.6%). Note that an increase in the expansion threshold from 3 mm, up to 10 mm, would increase the FMP significantly—from 20.7% up to around 22.8% moisture (also shown Figure 3.16).

Measured expansion for the iron ore fines tested is shown in Figure 3.17, in comparison with Redhill 110 (note that both these material have been assigned to different horizontal axes).

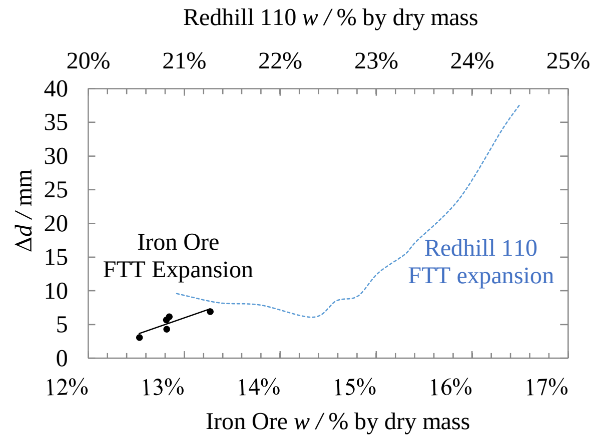


Figure 3.17: Redhill 110 cone expansion in comparison to iron ore fines (for iron ore fines, difficulties attaining material meant that only five moisture increments could be tested beyond crumbling).

It is important to note that, as presented previously in the FTT methodology description (pp. 49-50), the IMSBC Code requires that the FMP/TML in the 'main flow moisture point test' be determined from *observation only*. Laboratories that report a FMP/TML determined from only measurements do not strictly comply with the requirements of the IMSBC Code.

3.4.1.3 Determination of the FMP/TML by Both Observation and Measurement

Assessment of common practices in other laboratories (from site visits and literature) has revealed that many TML testing laboratories follow the method within ISO 12742:2007, which specifies that the FMP has been reached when either: *(i)* a flow state has been observed; or *(ii)* the cone has expanded over 3 mm (ISO, 2007). In consideration of both the visual and measured results from Sections 3.4.1.1-3.4.1.2, the FMP/TML from this method are therefore 20.7/18.6% moisture by dry weight. As for the previously described method, this does not strictly comply with the IMSBC Code requirements (*i.e.* measurements cannot be used to determine flow).

3.4.2 Proctor/Fagerberg Test (PFT) TML Results

The PFT plot obtained for Redhill 110 is shown in Figure 3.18. Taking the intersection of the compaction curve and 70% saturation line, the TML can be determined as 19.65%.

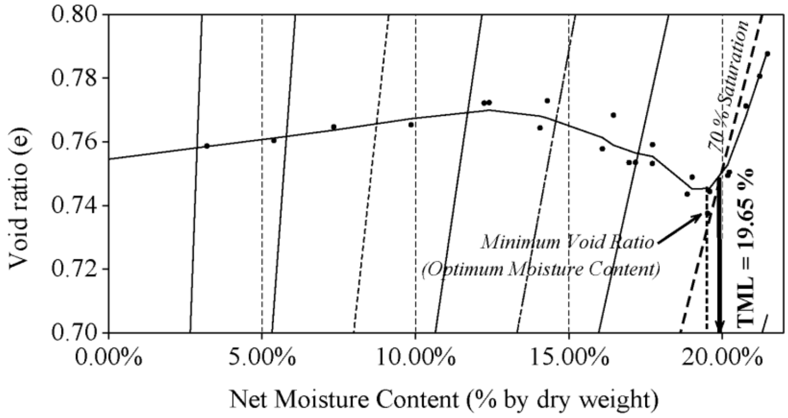


Figure 3.18: TML from the Proctor/ Fagerberg curve for Redhill 110 (shown with smoother). Also shown is the optimum moisture content (OMC).

These results can also be presented in terms of the Proctor compaction curve, in terms of dry bulk density, ρ_{dry}, or dry unit weight, γ_{dry} (instead of e_v). Figure 3.19 shows the Proctor compaction curve obtained for both Redhill 110 and iron ore fines (on right and left axis, respectively). Redhill 110 exhibits a wider, flatter curve similar to that reported for sandy soils by Das (2009) and for coarse-grained concentrates with a narrow PSD by Fagerberg (1964a). Iron ore fines, which possesses a wider PSD than Redhill 110, exhibits a greater ability to compact ($\Delta\rho_{dry}$ of approximately 14% compared to 3%, respectively). This compaction occurs over a smaller range of moisture contents (*i.e.* for iron ore fines, compaction is more sensitive to changes in moisture content).

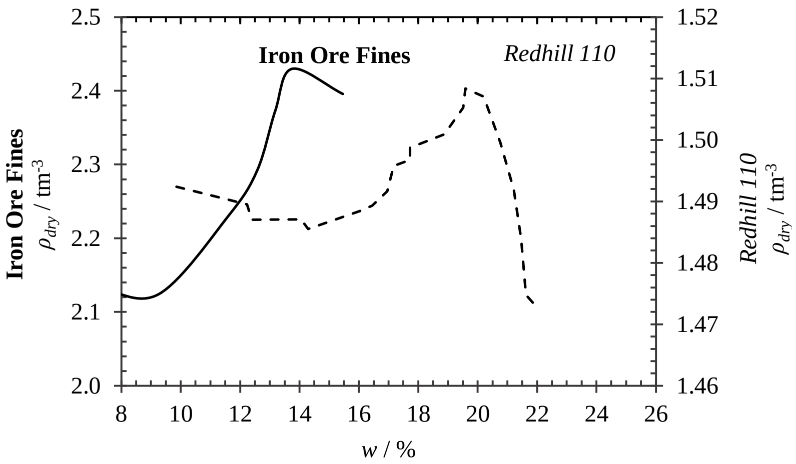


Figure 3.19 : Proctor curve of the iron ore fines *(left-hand axis)* compared to Redhill 110 *(right-hand axis)*. Redhill 110 exhibits a wider, flatter curve than iron ore fines; the latter exhibits a wider PSD that facilitates tighter packing.

3.5 FLOW TABLE TEST (FTT) VARIABILITY AND ISSUES

In order to assess the FTT's known variability issues, a detailed evaluation of the IMSBC Code methodology was undertaken. This comprised of: *(i)* performing test-work on Redhill 110 and iron ore fines; *(ii)* observing a range of operators performing the FTT in recognised laboratories, on different cargoes; and *(iii)* a complete review of FTT related literature submitted to IMO since the method was introduced in 1965. This assessment identified a number of inherent issues with the method that lead to variability in the TML results, including:

(a) The method for determining the FMP, from consideration of either visual observations or measured cone expansion alone, is subjective.

(b) Incorrect tamper pressure, resulting from erroneous settings and/or tamper technique, can result in densities that do not represent those compaction conditions on a vessel.

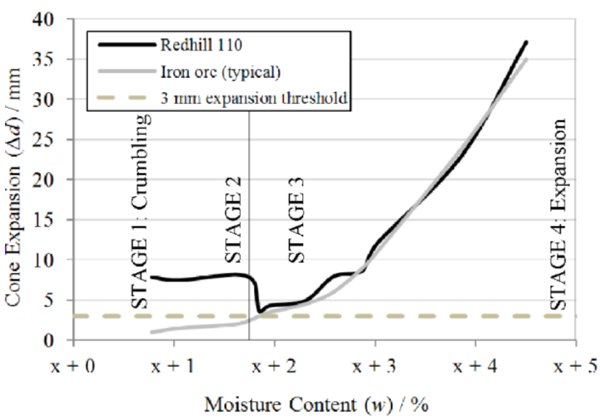
(c) Errors in cone expansion measurement can lead to errors in the identification of flow.

(d) Varying the number of drops of the flow table may influence observed and measured results.

(e) Variable apparatus setup may affect reproducibility.

3.5.1 The Method for Determining Flow: Visual and Measured

Granular materials that vary in physical properties may exhibit different behaviour when subject to cyclic loading in the FTT, in terms of both *visual appearance* and *expansion characteristics*. For example, Redhill 110 exhibits significantly different measured behaviour to that of iron ore fines. This is shown in the plot and accompanying table in Figure 3.20.



	REDHILL 110 OBSERVATION	IRON ORE FINES OBSERVATIONS
STAGE 1	Samples too dry, sample crumbles	
STAGE 2	Some localised flow observed but external cracking causes significant expansion	Sample holds together, start to expand upon moisture addition
STAGE 3	Sufficient moisture to bind together; cracking ceases, Δexpansion/Δmc increases at rate *x*	Δexpansion/Δmc increases at rate *x*
STAGE 4	Significant expansion, Δexpansion/Δmc increases at rate >*x*	

Figure 3.20: Expansion behaviour can vary significantly between materials. Iron ore and Redhill 110 show distinctly different expansion characteristics. The stages are shown in photographs in Figure 3.14.

Referring to Figure 3.20 and to the photographs presented previously in Figure 3.14 (p. 60), it can be seen that Redhill 110 expansion decreases ($\Delta d/\Delta w < 0$) upon further moisture addition between Stage 2 and Stage 3 (for a fixed number of cycles [50 knocks]). This contrasts to the behaviour of iron ore fines. For this material, an increase in moisture content is always observed to result in cone diameter expansion ($\Delta d/\Delta w > 0$), at moistures beyond crumbling. The behaviour of Redhill 110 can be explained by the cracks that appear at lower moistures, which accentuate expansion (shown previously in the photograph in Figure 3.14, Stage 2). These are then consolidated as the moisture content is further increased, likely due to increased suction (Figure 3.14, Stage 3). These contrasting expansion phenomena has also been observed in graphical TML results presented by other laboratories for different types of concentrate cargoes (IMO BCXIV/4, 1972).

The large variation in behaviour that exists amongst different materials makes it challenging to obtain repeatable assessment of flow by *observation* or *measurements* alone:

(a) *Observations* may be erroneous because the descriptors provided within the IMSBC Code (for example, 'plastic' and 'crumbling') are not precisely defined and an operator must therefore subjectively decide what constitutes 'plastic' or 'non-plastic' behaviour. Detection of flow by observation may be particularly difficult for slow expanding materials (where $\Delta d/\Delta t$, or Δd/*Number of Cycles*, is low). For these materials, plastic deformation may be undetectable after 50 drops despite the cone being at the onset of plastic deformation (more detail in '*Section 3.5.4: Effect of Number of Drops*').

(b) *Cone expansion measurements,* in isolation, are also inadequate to assess the FMP, as: (*i*) by considering only expansion at the base, any plastic behaviour that occurs around other areas of the cone is ignored (for example, concave or convex behaviour); and (*ii*) some material may not exhibit predictable, linear expansion behaviour (for example, Redhill 110 decreased in base diameter, despite an increase in moisture content from 21.6-22.4 % moisture). There are also issues inherent in the two different methods for determining flow from cone expansion measurements (described on pp. 62), more specifically:

- The *IMSBC Code Method* that considers the intercept is dependent on the gradient of Δd versus w curve. For slow expanding materials the gradient will be lower, the line will intersect the moisture axis at a lower moisture, and a conservative FMP/TML will be obtained. Further, the TML result from this method is dependent on the arbitrary selection of the two moisture contents beyond the FMP through which the straight line is drawn (*i.e.* as shown in the Redhill 110 FTT results on p. 59, the TML obtained could vary by up to 1.2% absolute).

– The FMP determined by the *Threshold Expansion Method* will also vary depending on the rate of cone expansion. Slow expanding materials may not have exceeded the chosen expansion threshold after 50 drops, despite exhibiting flow behaviour. Furthermore, the FMP result will vary depending on the threshold chosen (for example, 3 mm or 10 mm), as shown in Figure 3.16. This criteria is therefore arbitrary if applied to all materials.

3.5.1.1 Recommendations

To reduce variability of the TML results obtained for different operators/laboratories, *flow should be determined primarily by observation*, *but also aided by cone expansion measurements*—the latter approach facilitating the determination of where flow has first occurred when observed flow is borderline or unclear. However, for this to effectively improve the reproducibility obtained amongst different operators/laboratories, the methodology within the IMSBC Code needs to be amended on a number of counts:

(a) Firstly, the IMSBC Code requires that subjective visual inspection of the sample is used to determine the FMP, yet fails to provide visual examples. To reduce variation in visual interpretation between operators and therefore between laboratories, *the IMSBC Code should incorporate reference images of liquefied samples of a range of cargoes.* This will reduce subjectivity and facilitate the consistent interpretation of flow.

(b) Plastic deformation on the flow table can be determined less subjectively by complementing observation with the use of cone expansion measurements. However, under the requirements of the IMSBC Code, the reported FMP can only be determined by observed flow (*i.e.* in the main FMP test[i]). Therefore, it is recommended that the IMSBC Code *incorporate a measurement method within the main FMP test* that can be used to determine the reported FMP by *complementing the observed method.* More specifically, it should firstly specify that only *clear and conclusive* observation of plastic behaviour be considered indicative of flow (as guided by the recommendation in (a)). However, if observation is inconclusive, *cone expansion measurements should also be used as a flow indicator* (as per the method proposed in (c), below). The final FMP should be taken at the *lowest moisture content* at which flow is observed or measured. Ultimately, this will improve the reproducibility of the FMP/TML obtained from

[i]This requirement was described previously in the description of the FTT methodology (Section 3.3.1, pp. 49).

this method. By ensuring that only *clear* flow is used to ascertain the FMP it will help improve reproducibility, as the more subjective flow states are ignored. If observed flow is inconclusive, the measured value (which is more reproducible but less conclusive) will then prevent the FMP from being erroneously surpassed.

(c) Further to (b), to address the deficiencies of the two commonly used measurement methods (which are sensitive to expansion rate) it is proposed that *the IMSBC Code measurement method be amended so that the FMP is obtained from the turning point of the expansion versus moisture curve* (rather than from the intersection). This is discussed in further detail in Section 3.5.4, which shows that the turning point is independent of expansion rate.

3.5.2 Tamping Pressure

Tamping is intended to apply compaction energies similar to those experienced by the cargo at the base of the hold, as calculated using Equation (3.1) on p. 49 (IMO, 2009).[i] Incorrect and/or variable tamping pressure will influence the strength characteristics of a test material, which depend on these conditions[ii]. It follows that this will also influence the TML result.

Test-work on Redhill 110 and observations at other laboratories have indicated that tamper pressure variation is common and can be attributed to:

(a) *incorrect input of cargo height or density* into Equation (3.1);
(b) *inaccurate scaling* of the readings on the tamper apparatus to a 30 mm tamper head;
(c) incorrect or inconsistent *operator technique*; and/or
(d) *instrument errors* inherent in the tamping apparatus.

On **(a)**: When calculating the required tamping pressure, it has been observed first-hand that many TML testing laboratories may *estimate* or *guess* the cargo height and density inputs into Equation (3.1). These details are often not provided by the Shipper and a test laboratory may not be familiar with the Shipping operation. The variation of this setting was found to be significant. Some operators have been observed to apply over double the height and/or density input than other operators for the same cargo tested (*i.e.* a twofold variation in the applied tamper pressure).

[i]The Author does not believe that this compaction (and equation) accurately represent conditions within a hold, as discussed in Chapter 4. Regardless, it introduces variability.

[ii]Compaction effects the packing density, void ratio, degree of saturation and permeability; each which may impact shear strength and/or the likelihood for pore-pressures to develop.

For **(b)**: As the tamper specified within the IMSBC Code is rarely available 'off-the-shelf', often the prescribed 30 mm tamper head is retrofitted onto a comparable apparatus such as a hand-held penetrometer[i]. This penetrometer applies a controlled force through the factory fitted head, according to the scale shown on the apparatus. However, if the area of the head on the penetrometer is increased, the applied pressure will be lower, unless the applied fixed force is increased. If this force is not scaled the error can be significant. However, observation of other laboratory practices has indicated that this is sometimes completely unaccounted for, typically due to lack of operator expertise. For example, a systematic underestimation of the applied force on the sample by approximately *25 times* may occur if scaling of this force is overlooked when retrofitting the 30 mm tamper head onto an off-the-shelf spring-loaded penetrometer with a factory penetration diameter of 6 mm.

In regards to **(c)**: Cone compaction is susceptible to kneading effects, whereby the compaction energy may not be equally applied over the entire tamper head. This will result in localised variation of compaction over the mould. For the tamper used in the testing on Redhill 110, variability of up to 3 kgf (~33 kPa) was observed due to the operator, as shown by the spread of results in Figure 3.21 (measurements taken by repeated tamping on a mass balance). These effects are likely greater for high-density cargoes such as iron ore or lead concentrates, which require an operator to apply high tamping forces of up to 30 or 50 kgf over the 30 mm head.

On **(d)**: Tampers are typically purchased uncalibrated and this can result in tamping bias. The tamper used in the testing described here possessed a small inherent bias of approximately ~3-5 kPa, in conjunction with operator bias (in these experiments it appears there was a tendency for the operator to over exert).

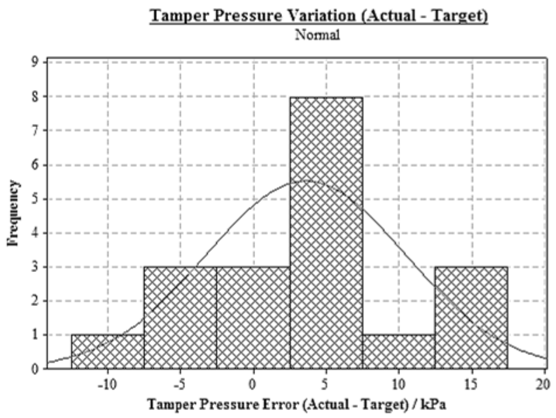


Figure 3.21: The measured variability and bias of the tamper used in the present study. Measurements were taken by repeated tamping on a mass balance.

[i]Under the IMSBC Code, any calibrated apparatus capable of applying a controlled pressure can be used.

Giving regard to **the impact of these tamping errors on the TML**, it was found that compaction energy had a significant, non-linear, effect on cone expansion. Tests on Redhill 110 over a range of tamping pressures showed that at a given moisture content, increasing the tamping pressure increased the strength of a sample up to a point (cone expansion decreased)—see Figure 3.22. Beyond this tamping energy, if the sample moisture content was sufficient, the void ratios obtained would result in the sample approaching saturation before the test begins. At this point, it is further increases in the tamping pressure resulted in the reduction of strength (cone expansion increased), likely because this facilitated the development of pore-water pressures.

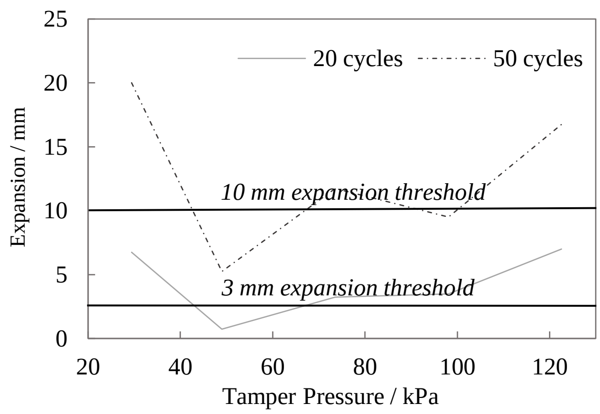


Figure 3.22: Effect of tamper pressure on cone expansion, for a different number of flow table drops (initial moisture content of 24.5%).

To explain these observations:

(a) A tamper pressure systematically too low (<40 kPa in Figure 3.22) resulted in a low density test sample that could readily compact upon the application of cyclic force. The conical sample exhibited a low resistance to shear and readily expanded under the unconfined conditions on the flow table.

(b) At moderately higher tamping pressures at the same moisture content (~40-60 kPa in Figure 3.22), an optimum density was approached before the test began. Upon the application of cyclic force, the cone exhibited greater shear resistance and expansion was less than for (a).

(c) Beyond a certain tamping pressure (approximately 60-110 kPa in Figure 3.22) the void ratio had sufficiently reduced so that the voids began to become consumed with water before testing (some seepage of water was observed during tamping). The cyclic force applied through the test facilitated the development of pore-water pressures, a reduction in effective stress, decreased shear-resistance and greater cone expansion than for (c), for equal number of cycles.

(d) A critical tamping energy was reached (~110 kPa in Figure 3.22), whereby the resulting reduction in the void ratio was sufficient to achieve complete saturation in the sample prior to the test (significant seepage was observed). Further increases in tamping pressure beyond this point will not necessarily result in tighter packing and cone strength/expansion will plateau (this point can only be reached if the initial moisture content is sufficient).

Therefore, compaction energy has a non-linear impact on the TML result. It follows that if different testing laboratories apply different tamper pressures, one laboratory may observe flow whilst another does not. However, over a certain maximum tamping pressure a minimum possible void ratio will be achieved. The TML obtained from this maximum tamping pressure will represent the minimum possible TML for that sample (given that the energy applied through the apparatus is fixed).

Findings from the present study on Redhill 110 may help to explain recent results reported from Brazilian and Australian test work on iron ore fines, shown in Figure 3.23 (DSC18/INF.10, 2013). Although their results confirmed that the TML is sensitive to tamper pressure (doubling the tamper pressure resulted in a variation in TML of up to 8% relative), they found that this variation was inconsistent for the different size fractions and could offer no explanation for these inconsistencies.

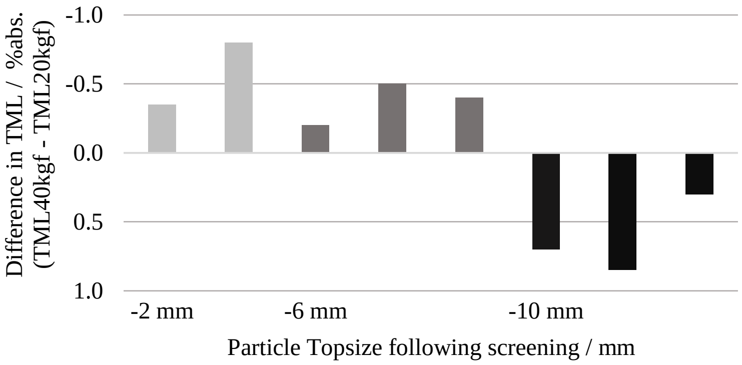


Figure 3.23 : Effect of changing tamper pressure from 20 kgf to 40 kgf on TML.
Adapted from TML results presented within DSC18/INF.9 (2013).

It is envisaged that these results can be explained in consideration of the findings for Redhill 110 shown in Figure 3.22, whereby:

(a) *For the -2 mm and -6 mm screened samples, doubling the tamper pressure from 20 kgf to 40 kgf reduced the TML:* At a sample moisture content of FMP_{40kgf}, the greater 40 kgf tamping pressure resulted in tighter packing (lower void ratio) and facilitated the development of pore-pressures, resulting in lower strength and the onset of flow. These had not yet developed for the 20 kgf tampered sample at the same moisture (*i.e.* greater void ratio) and flow was not observed. For this sample, it was not until moisture the content was increased by around 0.3-0.8% that pore-water pressures began to develop and flow was observed.

(b) *For an unscreened sample of 10 mm topsize, doubling the tamper pressure increased the TML:* At a sample moisture content of FMP_{20kgf}, it is likely that the lower 20 kgf tamping pressure resulted in a more permeable sample of lower static strength. When subject to cyclic forces, this sample then rapidly reduced in volume, pore pressures developed and flow was observed. Conversely, at the same moisture the 40 kgf tamping resulted in tighter packing and a sample with lower compressibility. Although this sample exhibited a greater degree of saturation before the test, this was not yet sufficient to facilitate the development of pore pressures and flow was not observed (it was not until the moisture content was increased by around 0.8% until pore-pressures developed and flow was observed).

3.5.2.1 Recommendations

Variations in tamping amongst laboratories will lead to low repeatability and reproducibility of TML results. To address these errors:

(a) To reduce random tamping errors that lead to low repeatability for a given operator (*i.e.* measurement errors such as kneading effects), the IMSBC Code must include a *commentary that informs an operator of the need to consistently apply even force and coverage*.

(b) More importantly, to reduce the high variability in tamper settings that may be applied at different laboratories when testing the same cargo, the IMSBC Code must incorporate provisions that address: *(i) biases arising from variations in equation input*, for example by introducing a requirement for a Shipper to provide details on a cargo's geometry and density prior to testing; *(ii) scaling errors*, for example by including a method that specifies a procedure for scaling a retrofitted tamping apparatus; and *(iii) instrument errors*, for example by requiring the operator to perform a precision/ bias assessment of the tamper.

It is of note that in the inter-laboratory trial shown previously in Figure 3.3, a fixed tamper pressure was prescribed amongst the laboratories. Despite this, variation of 2.5% absolute (or 22% relative) was obtained for the same cargo sample tested by two different laboratories (IMO BCXVII/3(b)/Add.1, 1977; IMO BCXVIII/6/1, 1977). This indicates tamper pressure is unlikely the largest contributor of FTT variability. The present work has indicated that the biggest contribution to this error is likely to be method ambiguity, which contributes to a significant variation in practices amongst laboratories.

3.5.3 Variability from Expansion Measurements

When using a measurement based (graphical) approach to determine flow, the FMP/TML results will be influenced by the accuracy and precision of cone expansion measurements. For example, measurement errors may lead to the miscalculation of when the ‘cut-off’ expansion threshold has been surpassed. Observations during these tests revealed the following sources of error from cone expansion measurement:

(a) *Suction* (adhesion) between the wet sample and the brass mould (at high moistures) can result in degradation or swelling of the sample upon removal of the mould. For Redhill 110 this led to expansion of approximately 3-4 mm following mould removal (prior to testing).

(b) *Unsymmetrical expansion* or *cone degradation* can lead to inconsistent measurements. For Redhill 110, variations in diameter of up to 10 mm were measured.

(c) *Expansion at middle-height of the cone* (‘bulging’) instead of at the base. This indicates ‘plastic’ behaviour and likely liquefaction, yet base diameter measurements do not capture this behaviour.

(d) Measurement errors (i.e. calliper’s/ruler).

3.5.3.1 Recommendations

Considering the above, the IMSBC Code must incorporate prescription that ensures test laboratories perform FTT according to the following practices:

For **(a)**: While adhesion to the mould is unavoidable to a degree, it is important to reduce deformation by *careful removal of the mould.* Gentle tapping was found to help. Furthermore, the *initial diameter should be measured at the start of each test* so that swelling can be accounted for (*i.e.* cone expansions, Δd, should be taken as $\Delta d = d_{final} - d_{initial}$).

For **(b):** There may be little that the operator can do to prevent errors from drastic uneven expansion and if this occurs then *the test should be repeated* (say, if variation around the cone is greater than 5 mm). Otherwise, for a conservative FMP result, the *greatest measured diameter should be taken as the indicator of flow*.

On **(c)**: Where measurements at the base do not detect flow, flow determination by observation may be more appropriate. This issue highlights the need for an IMSBC Code method in which flow is determined by complementary use of observation with measurements.

On **(d)**: Figure 3.24 shows that cone measurement errors for Redhill 110 were less than ±2 mm absolute (note that unsymmetrical cone expansion was also captured within this data set). This error is therefore insignificant in comparison to the other errors. For this material, *measurements over only two axes appear sufficient to obtain acceptable precision*.

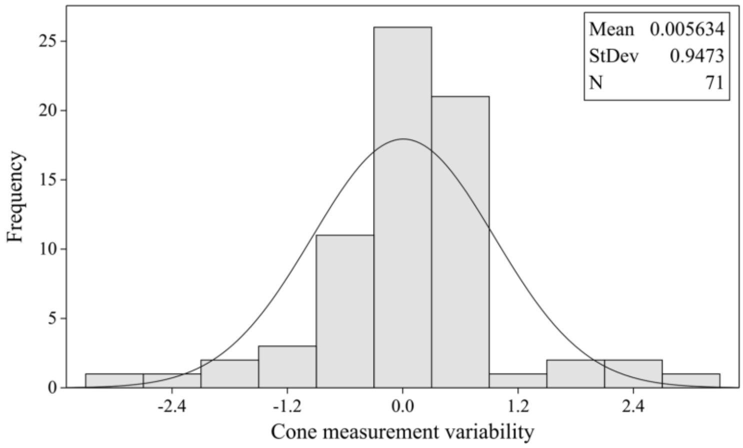


Figure 3.24: Variation in cone expansion measurements, taken from measurements over four axes around the cone (for various increments).

Taking a greater number of measurements around the cone, at various heights, would help improve precision and the ability to identify convex/concave flow behaviour. However, this may not be practical given the time constraints in a commercial test environment. Further, measuring expansion with height presents challenges due to cone height reduction during a test.

3.5.4 Effect of Number of Drops (Knocks) of the Flow Table

The IMSBC Code currently prescribes that fifty knocks be applied on the flow table. To determine if this requirement is adequate, and to assess the significance of this parameter, the relationship between cone expansion and the number of knocks was explored. At moistures just beyond the turning point, Redhill 110 cone expansion was measured to increase almost linearly with number of knocks on the flow table. This is shown in Figure 3.25 (overleaf).

Unsurprisingly, the gradient of the $\Delta w/\Delta d$ curve also increased almost linearly with the number of knocks, as shown in Figure 3.26 (overleaf)[i]. This relationship has implications for

[i]This linearity will diminish as the number of drops increases and beyond a certain level of saturation.

the TML results obtained by the two common measurement methods;[i] as these both apply flow criteria that depends on this gradient. More specifically, if the number of knocks is increased then the FMP determined from the IMSBC Code Expansion Method will increase (the gradient will increase and thus the intersection will occur at a higher moisture content). Conversely, the FMP determined from the Threshold Expansion Method will decrease, as the threshold will be reached at a lower moisture content.

Observation of the moisture content (w) versus cone diameter (d) *curve* shown in Figure 3.26 indicates that *the moisture content at which the turning point occurs does not vary with number of knocks*. In other words, if sample moisture is sufficient then the cone will lose strength and begin to expand, regardless of the number of cycles of applied force. It follows that the turning point moisture directly reflects the cone's strength behaviour and, unlike the other two common measurement methods, does not depend on this arbitrary number-of-knocks criteria.[ii] It may

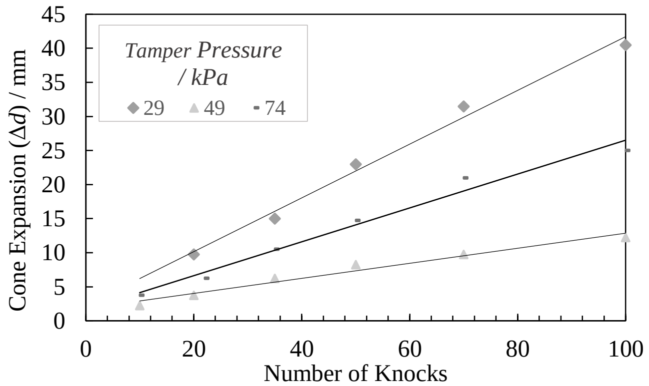


Figure 3.25: Increasing the number of knocks has a linear impact on cone expansion, at moistures above the FMP.

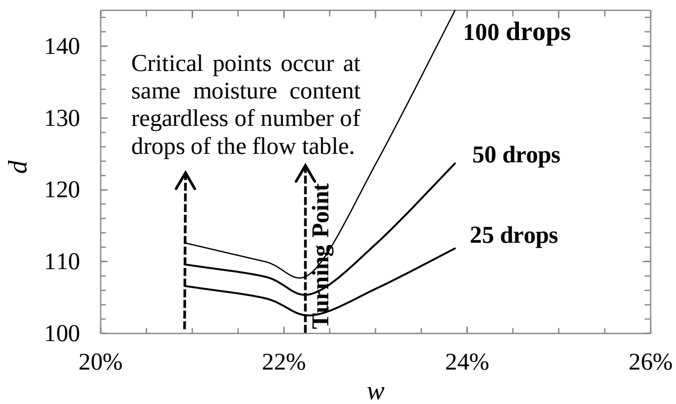


Figure 3.26: Measured cone behaviour by number of drops.

[i]Presented previously in *Section 3.5.2*, pp. 63, namely the: (*i*) IMSBC Code Intersection Method; and (*ii*) Threshold Expansion Method.

[ii]Unlike the other measurement methods, the turning point will not change by varying of number of knocks. The turning point may be influenced by other arbitrary criteria including knock-height and the tamper-pressure. The former is controlled by apparatus constraints, whilst controls for the latter have been suggested in Section 3.5.2.

therefore be a more suitable flow determination criteria. This relationship between number of knocks and the turning-point for Redhill 110 is consistent with graphical FTT results presented by Norwegian researchers to IMO, for several types of concentrate cargoes (IMO BCXIV/4, 1972; IMO BCXV, 1974).

Note that these relationships also imply that the samples flow potential is primarily dependent on the energy applied per cycle (*i.e.* drop height), rather than the number of cycles. The cone expansion for each knock ($\Delta d / number\ of\ drops$) depends on the physical characteristics of the sample before the test (including compaction characteristics) and the initial moisture content (ultimately the initial degree of saturation achieved at the given compaction energy).

3.5.4.1 Recommendation

Visual observation of flow becomes clearer with increasing number of knocks. In this regard, the 50-knocks parameter currently specified within the IMSBC Code appears reasonable. However, the FMP obtained from the two commonly used measurement methods varies depending on the rate of cone expansion ($\Delta d/\Delta w$), and on the arbitrary 'number-of-knocks' test parameter ($\Delta d/number\ of\ knocks$). To negate this dependence *the IMSBC Code measurement method should consider the turning point moisture content as the criteria for flow* (*i.e.* the FMP). This is an improvement on the existing measurement methods on several counts:

(a) The turning point moisture appears to be independent of the rate of expansion and number of applied cycles, as shown in Figure 3.26.

(b) A FMP obtained from the turning point moisture directly reflects the relationship between moisture content and the conical samples strength characteristics on the FTT (*i.e.* the turning point corresponds directly to measured expansion behaviour);

(c) The turning point moisture is likely to be a better representation of the moisture content at which dangerous cargo liquefaction and loss of strength occurs, as only beyond this moisture does the cone of material lose significant shear resistance and begin to rapidly expand.

Redhill 110's turning point occurs at around 22.2-22.4 % moisture (shown in Figure 3.26). The FMP from the proposed method would therefore be 22.2-22.4% (a TML of 19.9-20.2%). For iron ore fines, cone expansion increased with further moisture additions immediately post-crumbling, as shown previously in Figure 3.17. Therefore, it exhibits no turning point moisture (*i.e.* the curve has no local minimum) and FMP would be taken as first point where flow was recorded, or FMP/TML of 12.6/11.3% (*i.e.* the same as by observation).

3.5.5 Apparatus Considerations

The setup of the flow-table apparatus may vary significantly amongst laboratories. The IMSBC Code prescribes that the flow-table is mounted according to ASTM C230-68, which specifies that it be fixed to a concrete block. However, contrary to this requirement, site observations have shown that some laboratories mount the flow-table on a wooden bench. This is either due to unawareness of the contents of the separate ASTM standard (the IMSBC Code does not directly specify the mounting requirements) or because the installation of the permanent cement mounting may be inconvenient or impractical. A higher FMP/TML result may be obtained from a wooden bench due to the damping characteristics of the bench that lead to decreased sample compaction. This effect may be accentuated if the flow-table is not fixed rigidly to the surface, whether it be cement or wood.

Additionally, if the flow-table is not level, the sample may rotate and 'hop' across the surface of the flow table through the test, during the application of cyclic force. The tests on Redhill 110 and iron ore fines have shown this can result in uneven expansion, due to variations in amplitude/direction of applied energy through the sample.

3.5.5.1 Recommendation

To obtain reproducible results amongst different TML testing laboratories, the IMSBC Code must incorporate prescription that ensures consistency in apparatus use. It is suggested that the IMSBC Code incorporates prescription of the apparatus mounting *within the method* (not separately), and includes commentary of its significance. More specifically, it should incorporate a requirement that the flow table be fixed rigidly to a cement base, to minimise damping of the energy. It must also specify that the surface of table is levelled, to within a fixed tolerance.

3.6 PROCTOR/FAGERBERG TEST (PFT) VARIABILITY AND ISSUES

An in-depth assessment of the PFT methodology was undertaken, comprising of laboratory test-work, a review of the literature, and interactions with other researchers familiar with the test. In some cases, the results reported by other laboratories were re-calculated and reinterpreted. A number of issues with the methodology were identified that lead to TML variability, bias and/or an unrepresentative sample being tested. More specifically:

(a) The 70% saturation intersection condition that Fagerberg reported does not hold true to all products and is essentially arbitrary.

(b) The results from the PFT are highly sensitive to specific gravity (G_s) determination and this introduces unacceptable variability.

(c) An unrepresentative compaction energy is applied through the PFT compaction hammer. This results in densities in the Proctor mould being different to those measured in a hold.

(d) Drying a sample prior to moisture addition may affect sample mineralogy or remove naturally inherent moisture from the grains micro-pores. This moisture cannot be replaced by subsequent moisture additions and prevents the ‘as-shipped’ moisture state from being attained.

(e) The IMSBC Code does not specify the maximum height to which the sample should be compressed within the extension piece, introducing possible variation in the compaction conditions at the top of the levelled mould.

3.6.1 TML Determination: 70% Saturation and the Specific Gravity

Whereas the TML obtained from the FTT is based on a subjective interpretation of flow, the TML determined from the PFT is based only on measurements and calculations. It is therefore widely considered the more objective TML Test Method (Fagerberg, 1965a; Fagerberg, 1965b; 1988; Kruszewski, 1991; IMO DSC18/INF.10, 2013, IMO DSC18/INF.12, 2013). However, despite this objectivity, considerable error may still arise due to the assumption that *70% saturation* represents the TML. In addition, because the calculations that underpin this assumption depend on the *specific gravity,* the TML results are highly sensitive to the accuracy and precision of its determination. These issues appear to have been overlooked by both regulators and researchers.

3.6.1.1 The 70% Intersection Condition

Fagerberg found that for tests carried out on concentrates of Scandinavian ore, the minimum void ratio occurred between saturations of 70 to 75%. Assuming that the minimum void ratio represented the moisture content beyond which liquefaction is likely to occur, 70% saturation was taken as the safe moisture condition, *i.e.* the TML (Fagerberg, 1965a; Fagerberg, 1965b; IMO BC29/INF.3).[i] However, it appears Fagerberg's findings are not applicable to all cargoes:

(a) *For some cargoes, the minimum void ratio occurs at moisture contents less than 70% saturation*. For these cargoes, the TML from the PFT may be too high, introducing a safety risk. Polish and Japanese researchers found that the minimum void ratio for coals and galena concentrates occurred at 50-60% saturation[ii] (IMO BCXXII/5/12, 1981; IMO BC30/5/2, 1990).

(b) *For some cargoes, the minimum void ratio occurs at moisture contents significantly higher than 70% saturation*, meaning that the PFT will likely yield conservative TML values for these cargoes[iii]. Canadian researchers (IMO BCXX/INF.9, 1979) found the minimum void ratio occurred at 85% saturation for some cargo samples. More recently, research by iron ore fines producers reported that the minimum void ratio of iron ore fines cargoes occurred at 90-95% saturation. This is shown in Figure 3.27, on the following page (IMO DSC18/INF.12, 2012).

The findings for iron ore fines illustrated in Figure 3.27 informed the basis of a new 'modified PFT'—adopted by IMO in 2013 for iron ore fines only. In this test, the TML criteria has been raised from 70% up to 80% saturation, so that it gives less conservative results for these cargoes, *i.e.* the TML more closely aligns to the minimum void ratio. However, *this modification appears to be an ineffective way to address the issue,* as it still applies an arbitrary degree of saturation criteria to determine the TML, *i.e.* the margin of safety varies for different cargoes, depending on where the minimum void ratio lies in comparison to the saturation intersection. Further, this TML criteria leads to TML results highly sensitive to specific gravity (as detailed in the following section). See page 81 for commentary on the expected merits of the modified test.

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[i]This methodology was only prepared for inclusion within the BC Code during the late 1980's and early 1990's, much later than when it was developed (1960's). It is likely that the intent of Fagerberg's original findings and intentions were lost within the discussions at this later time-period.

[ii]Thought to be due to the volumetric changes that result from a collapse/degradation of particles, due to repeated stress from the compaction hammer.

[iii]Swedish domestic regulation accounted for this possible conservatism by also considering ship design. The cargo carriage criteria for 'general cargo vessels' (*i.e.* not designed for bulk solids) was S < 70%; for specially fitted general cargo vessels was S < 75%; and for specially constructed bulk carriers was S>75% (IMO BC30/5/2, 1990). This regulation was not recognised internationally.

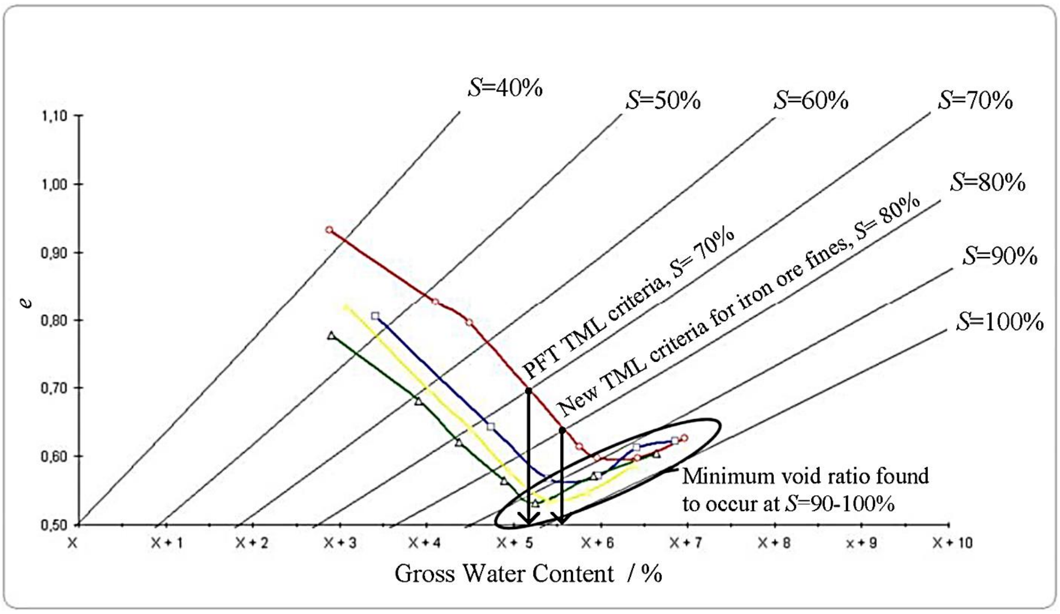


Figure 3.27: Results reported for Brazilian and Australian iron ore fines material showed that the minimum void ratio occurred between 90-95% saturation, whereas Fagerberg's found this occurred at 70-75% saturation. From these findings, a new PFT test for iron ore fines was developed, where the TML is derived at 80% saturation (IMO DSC1/Circ.71, 2013). This plot was adapted from IMO DSC18/INF.12 (2013).

3.6.1.2 Sensitivity to Specific Gravity (G_S)

TML results from the PFT are highly sensitive to the value of specific gravity (G_s). This is demonstrated in the sensitivity analysis shown in Figure 3.28. For Redhill 110 and iron ore fines tested, varying the G_s by only 0.05 resulted in significant absolute errors of around 0.7% and 0.2%, respectively.

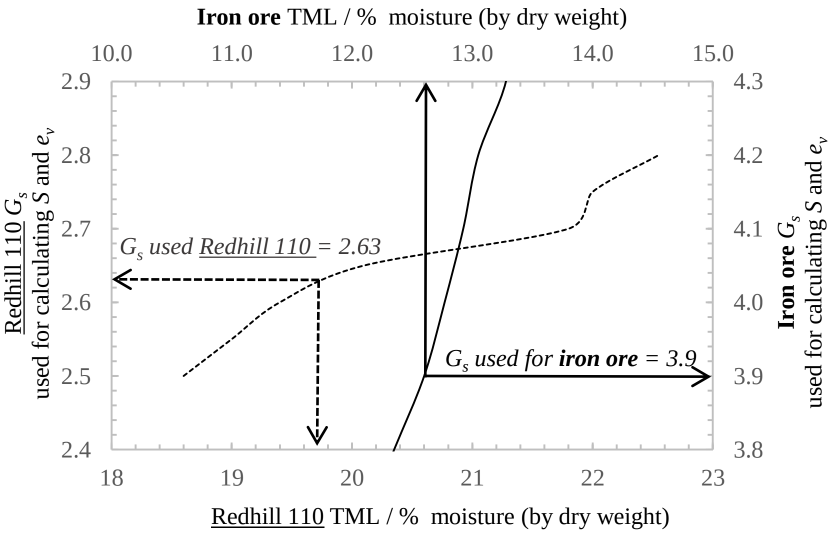


Figure 3.28: Sensitivity of TML to the specific gravity, for Redhill 110 and iron ore fines.

The TML's sensitivity to G_s is a calculation-derived error, whereby varying G_s alters the intersection of the compaction curve and the 70% saturation line from which the TML is based.

More specifically, changing G_s will linearly change the *gradient* of the degree of saturation (S) line, calculated from the void ratio (e) and moisture content (m), whereby:

$$\frac{d(w)}{d(e)} = \frac{G_s}{S} = \frac{G_s}{0.7} \tag{3.2}$$

For the compaction curve, changing G_s will *scale* the void ratio:

$$e = \frac{G_s}{\rho_{dry}} - 1 \tag{3.3}$$

These errors will be unique for a given compaction curve and are greater for flatter, wider curves such as that exhibited by Redhill 110 (a poorly graded material). Of concern, there has been no known commentary in the literature on this specific gravity issue, and it appears largely unconsidered by laboratories performing the PFT.

Specific gravity measurement methods can vary significantly—some can be particularly unreliable for porous material such as some unprocessed cargoes. These will typically underestimate G_s and result in a TML bias. This raises doubts on the validity of the new modified PFT for iron ore fines[i] (described previously on p. 79), in which the TML criteria has been raised from 70 to 80% saturation. It is possible that the findings that informed these modifications (namely, that the minimum void ratio occurs at 90-95% saturation for iron ore fines) was actually the result of a *systematic underestimation of* G_s perhaps due to measurement error.[ii] Figure 3.29 (overleaf) shows how the PFT curve for the iron ore fines material tested varies with specific gravity input. If a specific gravity of 3.9 is used, results similar to those reported by the iron ore fines producers is obtained, where the minimum void ratio occurs at 90-95% saturation. However, if the specific gravity is increased to 4.4, the results resemble those observed by Fagerberg for concentrates (minimum void ratio at 70-75%).

Note that the TML results obtained for the different assumptions shown in Figure 3.29 varies significantly: *(i) for a* G_s *of 4.4*: the TML is 13.3% (PFT, S=70%) or 15.20% (modified PFT, S=80%); and *(ii) for a* G_s *of 3.9* the TML is 12.6% (PFT, S=70%) or 13.2% (modified PFT, S=80%). Regardless of the merits of this modified test, this highlights the inconsistencies in results that can be obtained from applying the arbitrary degree of saturation TML criteria.

[i] *i.e.* they found that the OMC consistently occurred at 90-95% saturation and this formed the basis of a modified test in which the TML is taken at 80% saturation.

[ii] For example, it is unlikely that the pycnometer test suggested in the IMSBC Code allows adequate water absorption into the pores through the duration of a typical test, and G_s would be underestimated by this method.

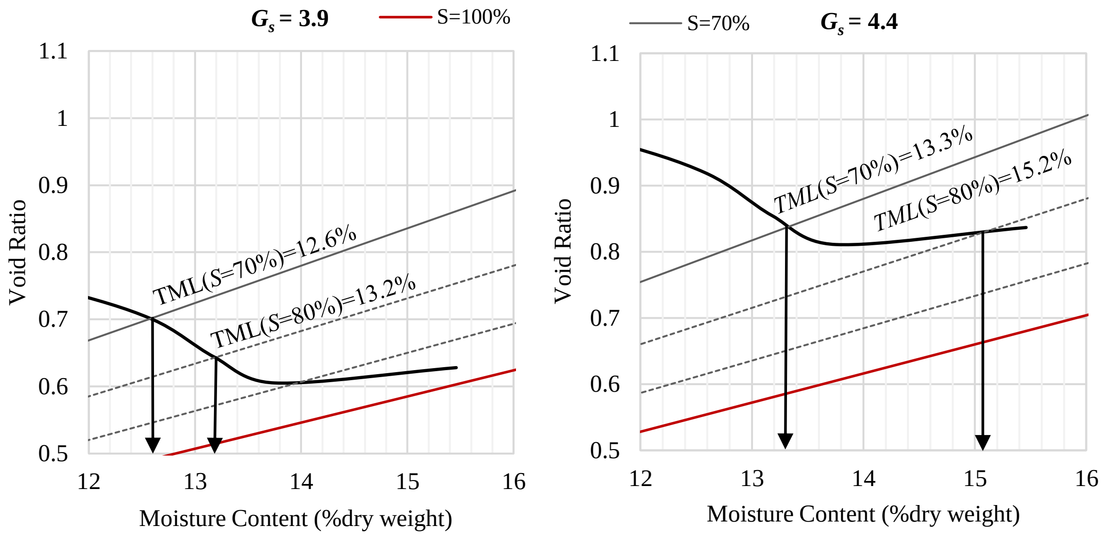


Figure 3.29: PFT plots of the iron ore fines tested as part of the present work, using different G_s values in the calculation. It is possible that the minimum void ratio reported by other iron ore producers to occur at 85-95% saturation *(left),* which formed the basis of a new methodology incorporated into the IMSBC Code for iron ore fines, is the result of an underestimation of the G_s. If a higher G_s,is used *(right)* then results similar to those of Fagerberg can be obtained, with a minimum void ratio between 70-80% saturation.

Inspection of a range of PFT curves, presented by a number of different laboratories, has indicated that G_s sensitivity commonly leads to an erroneous TML result being presented, even for official results for use in the Shipper's Declaration. For example, a number of laboratories have presented PFT plots within the certificate of analysis that shows a compaction curve exceeding the 100% saturation/zero-air-void lines. Figure 3.30(a) (overleaf) provides an example. This solution is not technically possible and clearly indicative of erroneous specific gravity measurement that is too low—given the magnitude of the error, it is unlikely that it arose from issues with bulk density and moisture measurement. This error would result in a particularly conservative TML. Ensuring that laboratory operators possess a basic knowledge of soil mechanics may help recognise these errors. However, graphical identification of G_s errors may not be possible if they are less significant and the 100% saturation line is not been surpassed, or if the test is only performed at moistures up to 70% saturation (see Figure 3.30(b) for an example).

Error identification by considering the actual G_s value used within the PFT calculations is also often not possible, as this value is typically not presented within a certificate of laboratory analysis or the Shipper's Declaration. This is not a requirement of the IMSBC Code (*i.e.* it only requires presentation of the TML, not the PFT plot or the G_s used in calculations).

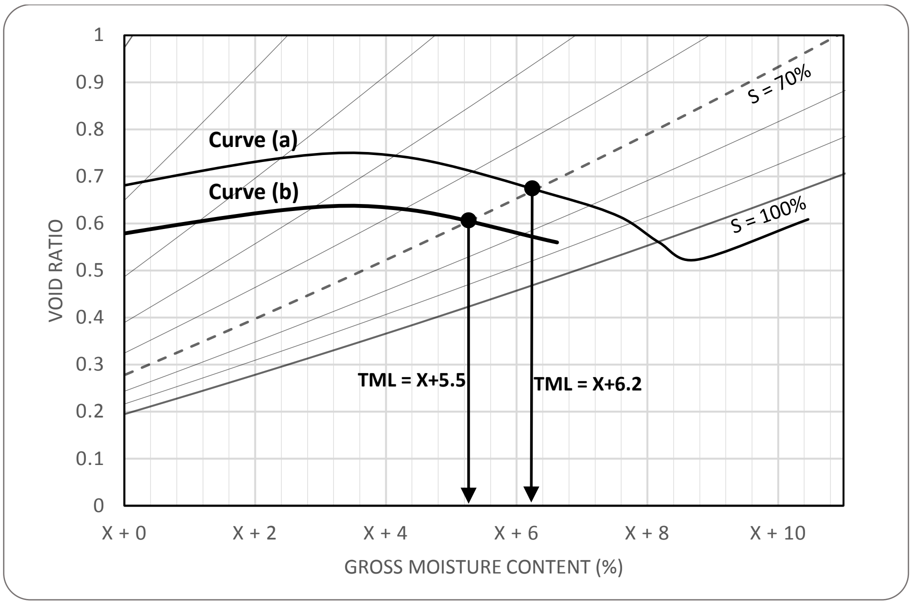


Figure 3.30: Curve (a) illustrates the erroneous PFT curve that experience has shown TML testing laboratories commonly present. Note how the compaction curve extends significantly beyond *S*=100%, likely the result of a *Gs* input that is too low within the calculations. Ultimately, this leads to an incorrect TML being obtained. As illustrated in curve (b), many laboratories will only test to moistures just beyond *S*=70%. This can inhibit the detection of G_s errors.

3.6.1.3 Recommendations

TML determination from the PFT is based on an arbitrary 70% saturation endpoint that is dependent on the calculation of S and e_v. This results in a test that is *highly sensitive to specific gravity.* Furthermore, it *ignores the minimum void ratio* that formed the basis of Fagerberg's original assumption.

The IMSBC Code could address this sensitivity to G_s by prescribing consistent, accurate measurement practices (for example, specifying internationally recognised determination methods be used). Further, to facilitate identification of G_s errors (such as those in Figure 3.30), the IMSBC Code could incorporate a reporting provision that requires the Shipper to present the PFT plot and G_s (used to derive the TML) within the Shipper's Declaration. Then, by incorporating a commentary describing how these errors can be identified, erroneous results can be recognised and managed accordingly.

However, it is proposed that a much more effective method would be to *derive the safe moisture content (TML) directly from the optimum moisture content* (*OMC*), which occurs at an equivalent moisture to the minimum void ratio. The OMC therefore represents the moisture content that formed the premise behind Fagerberg's original methodology. This proposed method would have the following advantages over the PFT:

- As demonstrated in Figure 3.31, the OMC does not depend on the specific gravity. It will *therefore negate the TML's dependence on specific gravity*, altogether removing the need to measure the specific gravity or calculate *S* and e_V. This will improve test reproducibility, as the TML will only be sensitive to errors associated with density and moisture measurement;
- It will *address the issues related to the arbitrary 70% saturation condition* and therefore make the test more appropriate to a wider range of cargoes;
- It will significantly *simplify the methodology* (*i.e.* fewer measurements, calculations, no need to plot degree of saturation lines), making it faster and easier to perform and errors easier to detect. Only the moisture content, bulk density and changes in density need be considered; and

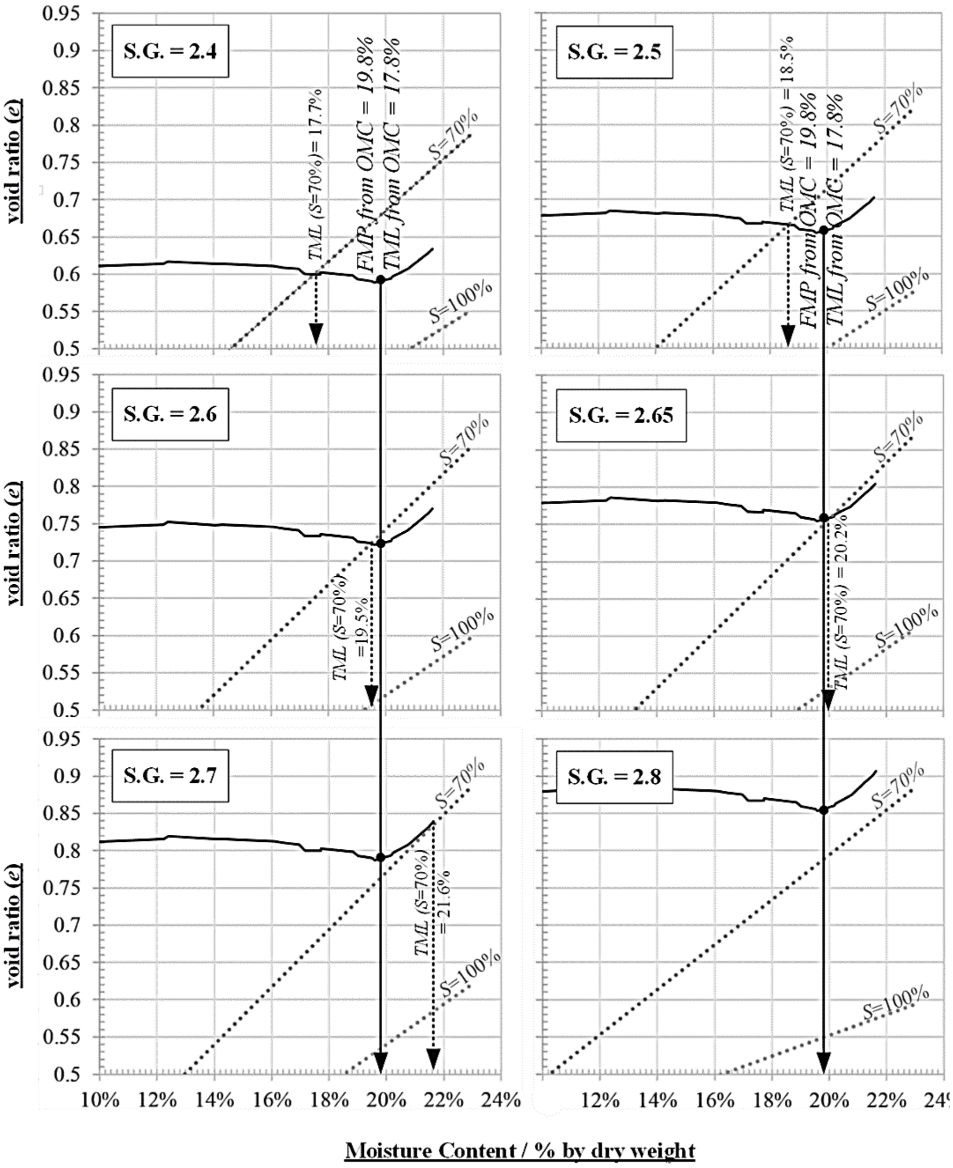


Figure 3.31: Shows the significant effect that G_s has on the TML obtained from the 70% intersection condition (dotted arrow), for Redhill 110. By considering the OMC (black arrow) as the FMP, this sensitivity to G_s is removed.

- It is more *technically appropriate*, as the OMC and minimum void ratio align more closely to the true compaction behaviour of the material than the arbitrary saturation condition. Therefore, it likely better represents the material's liquefaction behaviour.

In order to incorporate *a factor of safety* into this proposed method, the OMC could be considered analogous to the FMP, and the TML could then be obtained by incorporating a safety factor (say, 10% as for the FTT and PTT). This is superior to the arbitrary factor of safety that is currently applied within the IMSBC Code PFT, which changes for different cargo types (depending on the degree of saturation at which the OMC occurs).

A possible way to substantiate this proposed method[i] is to determine the OMC/TML for a range of cargoes and then compare these results to those obtained by the other TML Test Methods. The results from a comparison of this type are shown in Figure 3.32, developed as part of this thesis. This compares the TML obtained from the OMC (incorporating a 10% factor of safety), with the TML obtained from the IMSBC Code FTT and PFT (TML taken from 70% intersection). It can be observed that in most cases, the TML results from the proposed method are more closely aligned to those obtained from the FTT than for the IMSBC Code PFT method. This is likely because *the proposed TML is not dependent on the arbitrary intersection condition but instead reflects the true compaction, and thus the strength characteristics of the material.*[ii]

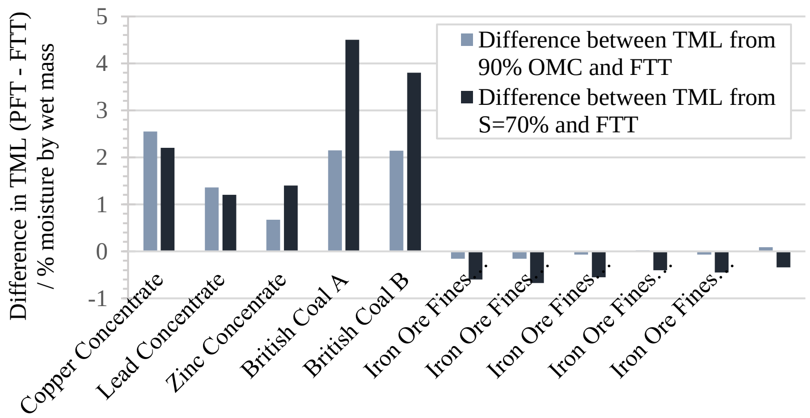


Figure 3.32: Shows the absolute difference in TML obtained from the proposed method (*i.e.* TML = 90%xOMC) and the PFT (TML at *S*=70%), with reference to the FTT result. Interpreted from data presented in BCXX/ INF.9 (1979) (five on left-hand-side) and from within TML test certificates for iron ore fines (six on right-hand-side).

[i]By "substantiate", the Author means within the context of it being an accepted method within IMO. As the FTT is seen by many within the maritime industry as the as the 'standard' (or benchmark) method, any new test would most likely need to be compared to the FTT to gain acceptance. This differs from true validation in which the OMC would need to represent the liquefaction potential of a cargo (discussed in Chapter 4).

[ii]Sample strength in the FTT is reflected visually by the onset of expansion/plastic behaviour.

Note that this analysis was performed ad-hoc using results and data reported from other PFT/FTT testing regimes (where the reported PFT curves obtained by other laboratories have been visually assessed for use within this study). There was limited data publicly available, and thus the range of data was limited to eleven cargoes. Some of these materials were tested in different laboratories, which makes conclusive comparisons challenging (*i.e.* there is likely TML bias amongst the different laboratories). Future work should focus on a robust validation of the proposed method. This would require further testing of samples by the FTT, PFT and the proposed method. Testing should be performed within a single laboratory (to reduce bias), and on a wide range of cargoes (to ensure it is generally applicable within the IMSBC Code).

3.6.2 Compaction Energy Does Not Represent Cargo Conditions

If the compaction curve obtained by the PFT is to be representative of the cargo, then a material's bulk density within the PFT mould should be representative of that within the hold. However, the wet densities the iron ore fines tested within the mould (see Proctor plot in Figure 3.19) were significantly greater than bulk densities reported in a hold for a similar iron ore fines materials (IMO DSC18/INF.13, 2013) (2.3-2.8 tm^{-3} compared to 1.9-2.3 t/m^3, respectively). This is consistent with findings by other investigators (IMO DSC18/INF.13, 2013) and also appears to hold true for other cargoes—Kruszewski (1988) reported that a concentrate's density was 3.04 to 3.37 t/m^3 within the PFT mould compared to around 2.87 t/m^3 within a hold.

Higher densities in the proctor mould will result in a conservative TML being be obtained (*i.e.* lower than actual). This is because this state of tighter particle packing results in a lower void ratio, with less moisture being required to fill these voids. Figure 3.33 (overleaf) shows the impact of the compaction energy on the OMC and the maximum dry density, ρ_{dry} (or dry unit weight, γ_{dry}).

3.6.2.1 Recommendations

Bulk density is a commonly known property of cargo consignment. It would therefore be simple to consider this within the PFT methodology, without needing to perform an additional assessment of bulk-density. The PFT methodology should be *modified to include a calibration step that aims to align the proctor mould density with cargo bulk density.* This could be achieved by adjusting the energy applied *through the compaction hammer, for each cargo.*

To adjust compaction energy (*E*), consideration may be given to the following equation (in terms of energy per unit volume): (Das, 2009)

$$E = \frac{\left(\begin{matrix} Number\ of\ blows \\ per\ layer \end{matrix}\right)\left(\begin{matrix} Number\ of \\ layers \end{matrix}\right)\left(\begin{matrix} Weight\ of \\ Hammer \end{matrix}\right)\left(\begin{matrix} Height\ of\ drop \\ of\ Hammer \end{matrix}\right)}{Volume\ of\ Mold} \qquad (3.4)$$

Of these variables, adjustment of number of blows or layers can be done without modification to the existing compaction apparatus. However, decreasing these significantly may impact homogeneity of the compaction/density in the mould, affecting test repeatability[i]. It is therefore suggested that the *compaction energy be adjusted by changing to hammer drop height*—although this would require minor redesign/modification of the Proctor compaction hammer. On this basis, simple *iterative adjustments would then need to be made to drop height to obtain a wet density within the proctor mould that corresponds to the cargo density*. These adjustments should be performed on an as-received sample, of equivalent moisture content of the cargo.

A cargo's bulk density varies throughout a voyage and with changes in moisture content (discussed further in Chapter 4). Thus, to ensure safe results are obtained, the worst-case (greatest) expected cargo bulk density should be targeted.

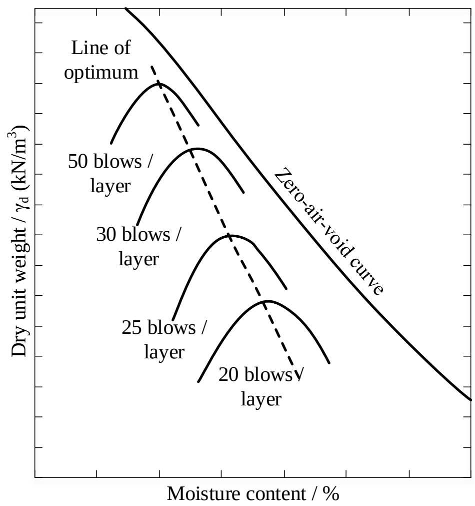


Figure 3.33: Example of the effect of compaction energy on the compaction curve.

3.6.3 Drying of sample before moisture addition

The IMSBC Code specifies that a PFT sample should first be dried prior to moisture addition. However, this may result in the loss of naturally inherent moisture from the test sample that

[i]For example, applying only 10 drops per layer, rather than 35, is unlikely to result in a sample of consistent density characteristics through the mould.

cannot be replaced by conventional water addition. More specifically: (*i*) porous materials may encounter resistance to water re-absorption into the micropores; and (*ii*) some materials may permanently lose moisture bonded intrinsically within the soil structure. It follows that drying may result in a test sample that is unrepresentative of an equivalently moist cargo. This will lead to a conservative TML (*i.e.* is too low).

3.6.3.1 <u>Recommendations</u>

PFT testing aims to assess how a sample compacts around moistures at which liquefaction is likely to occur. There is therefore no need to perform tests on a dry sample. To ensure that the test sample is representative of the cargo, *a sample should never be oven dried prior to testing*. If an as-received test sample contains moisture above the FMP (meaning that its moisture content must be reduced to below its FMP prior to testing), then this sample should be dried at room temperature.

3.6.4 Filling of the Mould

The IMSBC Code fails to specify the height that the sample is to be filled and compacted within the detachable extension piece of the Proctor mould. At high moistures approaching saturation, this may introduce errors in moisture and density measurement—particularly for permeable materials such as Redhill 110. At moisture contents above approximately 20%, Redhill 110 exhibited a wet surface layer at the upper 3-5 cm of the mould (or extension piece). This surface layer contained higher moisture and lower dry sample mass than the underlying material in the remainder of the mould. If this inhomogeneous surface layer is captured within the test portion of the mould (because the sample is not filled up sufficiently beyond the levelled brim into the extension piece) then this will result in an underestimation of sample density. This will introduce variability to density measurements and therefore to the TML result. For iron ore, which exhibited slower drainage characteristics, this issue appeared less significant.

3.6.4.1 <u>Recommendations</u>

For permeable cargoes, the IMSBC Code should specify that *the sample is to be filled to the top of the removable extension piece prior to levelling of the mould.* This will reduce variability of TML results by ensuring homogeneity of moisture/density in the test portion of the mould.

3.7 GENERAL VARIABILITY AND ISSUES

In addition to the aforementioned issues with the PFT and FTT, this work has identified a number of general issues and/or ambiguities with the IMSBC Code methodologies that lead to variability in the TML results obtained, regardless of the method. In addition, some parts of the IMSBC Code facilitate incorrect sample preparation procedures that may lead to a non-representative sample being tested. More specifically, these issues include:

(a) Moisture addition procedures can affect sample representivity and TML precision.

(b) Moisture determination approaches can vary significantly amongst laboratories and these directly influence the measured TML, leading to variable results.

(c) Following a test, sample re-use and further addition of moisture during testing may result in sample conditioning and impact the TML results, for some materials.

(d) Screening of a sample prior to testing may result in a sample of different strength properties than that of the cargo.

(e) Moisture loss before, during or after the test will result in TML bias and variability.

3.7.1 Moisture Addition

There are several factors related to the addition of water that contribute to variable TML results, namely: *(i)* the resolution of the moisture increments around the flow point (which allow the TML to be targeted); (*ii*) the manner in which moisture is added (soaking time may be required); and (*iii*) sample mixing (which promotes moisture homogeneity). The IMSBC Code methodologies do not address these factors appropriately.

3.7.1.1 Moisture Addition Increment Size

To obtain precise TML results, the moistures of the tested increments should be targeted around the point of interest[i]. The IMSBC Code methodologies are inadequate in this regard.

For the FTT, the FMP is usually determined from the average of the two increments before and after when flow is observed. The IMSBC specifies that moisture be added in less than 0.5% increments. At this resolution it is possible for 0.25% absolute error in the TML result (relative error of around 2.5% for Redhill 110 and 5% for the iron ore fines). First hand observations and

[ii]*i.e.* for the FTT the point of interest is the point when plastic behaviour is observed (the FMP). For the PFT it is at 70% saturation (or the OMC for method proposed previously).

descriptions of other laboratory practices (IMO BCVI/WP.6, 1968) indicate that greater increments of up to 1% are sometimes used, increasing the possible error.

For the PFT, the TML is identified from the curve that fits between two samples at moisture contents above and below 70% saturation. The IMSBC Code specifies that the test be performed at five to ten different moisture increments ranging from dry to almost saturated. However, this may result in a low resolution curve around 70% saturation (up to 1 or 2% for the material tested) and lead to errors in identifying the intersection.

3.7.1.1.1 Recommendations

To facilitate precision of TML results, sample moisture should be *adjusted within 0.2% increments*[i] *around the point of interest from which flow is determined*. For the FTT, this is the moisture content when plastic deformation starts to occur. For the PFT, only moistures around 70% saturation (or the OMC) are of interest when determining the TML, and therefore *contrary to the IMSBC Code, it is unnecessary to perform tests at moisture contents significantly below or above these moisture contents*.

3.7.1.2 Equilibration/Settling Time Following Moisture Addition

As previously discussed, some cargoes such as many unprocessed ores may contain a proportion of grains that readily absorb water. For these cargoes, a test sample may need time to equilibrate following moisture addition. This allows the water to be absorbed into the grains, ensuring that the moisture conditions of the test sample are representative of an equivalently moist cargo. For a given volume of water added, an equilibrated sample will therefore contain less water within the inter-particle voids, decreasing its flow potential (*i.e.* unequilibrated samples may give conservative results, for porous materials).

3.7.1.2.1 Recommendations

To ensure that testing is performed on a sample that represents the as-loaded moisture state of a cargo, the sample should be allowed to *equilibrate for at least 15-30 minutes following water addition* (exact times can be determined by targeted testing on individual cargoes). It is likely that this is only necessary for cargoes containing a portion of porous grains.

3.7.1.3 Mixing

Following moisture addition, mixing helps to ensure homogenous distribution of water

[i]For example a minimum of 2000 g of sample with maximum of 4 g water additions.

throughout the test sample—yet the IMSBC Code gives no guidance. To assess how optimum mixing could be achieved, three samples of equal mass were prepared (~1000 g) and to each of these, an equal amount of water was added. These were then mixed by *(i)* a mechanical mixer; *(ii)* a scoop; and *(iii)* by hand, and subject to different mixing times. Then, to assess homogeneity, a number of ~100 g subsamples were taken from the mixed portion and these were each subject to oven moisture determination.

Mixing by hand (by 'kneading' the sample) was found to be more effective than mixing by a scoop, as greater homogeneity could be obtain within a shorter period of time. By hand, a mixing time of 60 seconds was sufficient to obtain acceptable homogeneity (less than 0.1% absolute variation in the moisture content for five 100 g lots within the 1000 g sample). Under the same conditions, mixing by a scoop resulted in around 0.2% variability. Mixing of the granular material using the mechanical mixer presented difficulties, and the mass of material that could be mixed simultaneously by this method was limited by bowl size.

3.7.1.3.1 Recommendations

To ensure water is evenly distributed through the test sample, the IMSBC Code should prescribe that mixing be performed *by hand for at least 60 seconds*, although longer mixing times of up to 2-3 minutes may be beneficial for inhomogeneous samples.

3.7.2 Moisture Determination and Moisture Loss

A TML result can only ever be as accurate and precise as the moisture determination step. Most laboratories determine sample moisture by drying the entire portion of the test sample immediately after a test (the *'oven method'*). However, if significant moisture loss occurs between testing and drying of a sample, then the oven method may underestimate the moisture content of the sample during testing—and therefore the TML result will be too low.

In addition, this Author is aware of some laboratories that determine moisture from the volume of water added to a sample of known moisture content (*'volume added method'*). If significant moisture loss occurs after moisture addition and prior to testing (say, from mixing or evaporation), then the volume added method likely overestimate the moisture in the sample during testing—and the TML result will be too high.

To assess the validity of the different moisture determination practices, a comprehensive

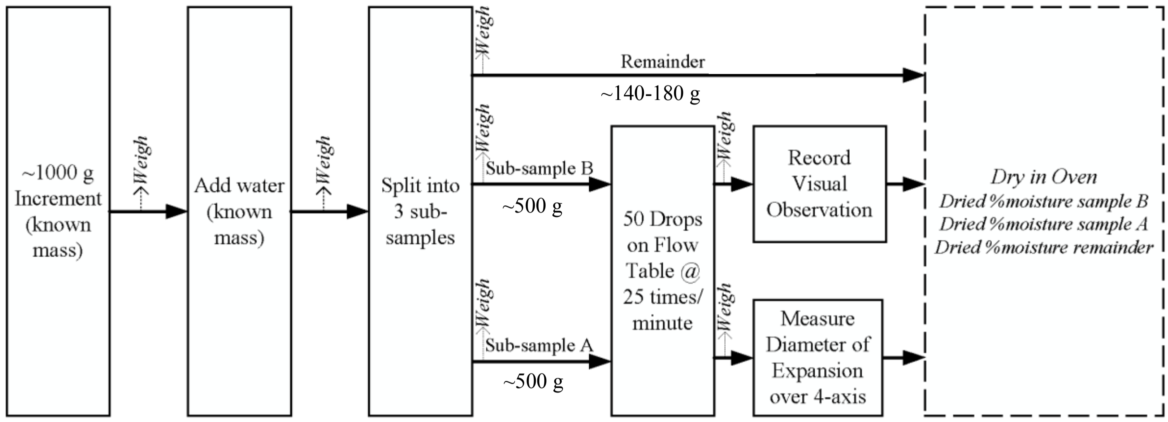


Figure 3.34: Sample preparation of the three samples taken within the bias assessment scheme. Mass was measured between each step to assess moisture loss.

assessment of moisture loss was undertaken, as illustrated in Figure 3.34. A number of 1000 g samples were prepared and a known mass of water added. From this, two ~500 g sub-lots were taken (A and B samples) and each was subject to testing on the FTT and to oven moisture determination, sequentially. After performing both tests, the 'remainder' mass (~140-180 g) was then subject to oven moisture determination. Stepwise mass measurements were taken at eight different stages through to the test to assess moisture loss. These revealed that:

(a) Significant moisture loss occurred before the test and therefore *the volume added method introduces a bias and overestimates the TML* (shown in Figure 3.35 *(left)*, overleaf). The mixing step was measured to be the greatest contributor to moisture loss, whereby moisture decreased significantly by 0.5% absolute; 2.98% relative after 240 seconds of mixing. Sample adherence to the gloves or mixing implement further distorted moisture results. Moisture loss to the environment was measured at a rate of approximately 0.35 g every ten minutes for an exposed sample (greater than 0.1 % relative error for a 500 g sample exposed for 15 minutes, although this value is unique to a laboratory's environmental conditions).

(b) Minimal reduction of moisture occurred during or following the test itself, and therefore *the moisture content obtained from oven determination post-testing is likely to provide an accurate representation of the material subject to testing*. As shown in Figure 3.35 *(left)*, the moisture loss was the same for the samples subject to the flow table (A and B), as for the sample that was not tested (remainder). This indicates that minimal moisture was lost on the flow table during the test (actually, slightly greater moisture was lost from the remainder as it was subject to oven determination 3-5 minutes after A and B testing). Note that testing on Redhill 110 indicated that measurement error increased for samples of lower mass, primarily due to balance errors and the greater effect of moisture loss, as shown in Figure 3.35 *(right)*.

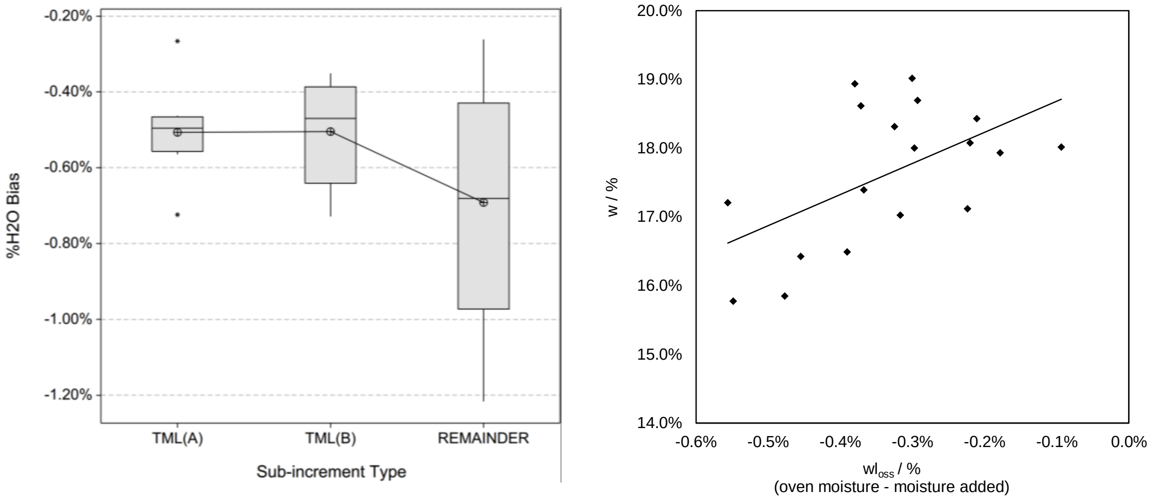


Figure 3.35: *(a)* The samples that underwent testing, TML(A) and TML(B), lost no more moisture than the sample not subject to testing ('REMAINDER'), indicating that little moisture loss occurred during the test and that over moisture determination is likely representative of the moisture of the sample during testing (*left*); and *(b)* Significant moisture loss occurred during mixing and prior to testing, indicating that moisture determination from considering the moisture added will result in biased results. Moisture bias increases at lower moisture contents because moisture loss from evaporation is greater as a percent of the whole (*right*).

3.7.2.1.1 Recommendations

The bias between the volume added method and a tested, dried sample was significant (0.2-0.8%, see Figure 3.35). Therefore, the IMSBC Code must include prescription that ensures that *official TML results*[i] *use only oven moisture determination. More specifically, the moisture content should be determined by drying of the entire test portion immediately after it has undergone testing*. Minimal reduction in moisture content was measured to occur during the test and oven moisture content is likely accurate to within ±0.15% absolute.

Notwithstanding this, oven moisture determination post-testing can still be subject to a systematic underestimation of sample moisture and the FMP, due to: *(i)* moisture loss during the testing process (for example, through streaking or leaking for more permeable samples); *(ii)* environmental exposure post-testing and pre-oven resulting in evaporation; and (*iii*) general measurement errors associated with oven moisture determination. Care must be taken to minimise these errors.

Measurement errors associated with oven moisture determination can be significant (IMO BCXIX/6/1, 1976; IMO BCXVIII/6/1, 1976) and must be prevented and/or controlled. For example, observations at different TML facilities has indicated that some laboratories may

[i] *i.e.* that used to determine a cargo's transportability.

perform drying at an inappropriately high temperature and this may result in chemical changes to the sample, for example from oxidation (IMO BCXIX/6/1, 1978; IMO BCXVIII/6/1, 1978). As a result, the TML will over-represent the cargo (be too high). It has been observed and reported (IMO BCXIX/6/1, 1978) many laboratories dry to constant time, rather than constant mass. If drying times are insufficient then this may result in a conservative TML. To ensure that correct oven determination practices are followed, the IMSBC Code must ensure that *moisture determination should be performed to international standards (specific to that cargo)*—these typically require that a sample be dried to an appropriate temperature and to a constant mass.

Note that whilst the volume added method may not be suitable for TML results presented within a Shipper's Declaration, it may yield satisfactory results for some research requirements. The tests on Redhill 110 (Figure 3.36) showed that although there was a significant bias between this method and the oven method (around 0.5%), the variability (approximately ±0.3%) may be acceptable for investigating large-scale trends and where long drying times are impractical.

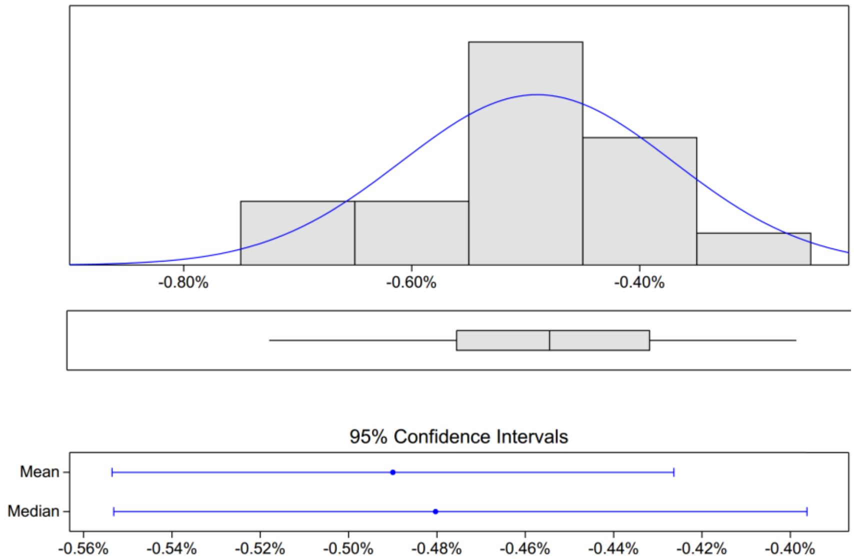


Figure 3.36: Analysis of the difference between moisture added and oven moisture shows that moisture loss can be predicted and a bias can be applied with reasonable confidence.

3.7.3 Sample Conditioning from Reuse

The FTT methodology within the IMSBC Code Appendix 2 (Section 1.1.4.3) implies that a sample should be returned to the bowl for further moisture addition, before being subject to a further test at the next moisture increment. Similarly, it has been reported that some operators attempt to target the TML once the FMP has been exceed, by adding dry material back into a sample that has already undergone testing (IMO BCXIX/6/1, 1978). These practices can affect

TML results, due to soil conditioning that changes the material's behaviour in subsequent tests.

The impact of sample re-use on TML is likely more significant for cargoes containing a portion of porous grains (for example, iron ore fines which contain some 'chalk-like' particles). In these cargoes, the micropores may fill with water during a test. Then, if this sample is re-used in a further test, the micropores may have a diminished capacity for moisture absorption. As such, less water is required to fill the inter-granular voids, lowering the FMP/TML. This explanation is supported by reports from an inter-laboratory study that found that sample re-use (to save sample mass) resulted in a lower TML (IMO BCXVIII/6/1, 1977), although they offered no explanation as to the cause.

3.7.3.1 Recommendations

To facilitate precision and prevent bias, *the IMSBC Code methodologies should be amended to prevent a sample from being subject to re-testing*. Instead, separate sub-samples of the material should be tested, and these each adjusted to different moistures. A similar methodology is presented within the international standard ISO 12742:2007. However, this method is often not used and according to Cook (2012), it does not strictly comply with the requirements of the IMSBC Code methodology (Dr P. Cook, personal communication, February, 2012).

3.7.4 Sample PSD and Screening

Increasingly, there is a trend for cargoes with large top-sizes to be considered as Group A cargoes within the IMSBC Code (for example, a coal with topsize of 50 *mm* is currently being considered for inclusion as a Group A cargo (IMO CCC/1/5/8, 2014)). However, current test methods do not facilitate the testing of these types of materials. *The FTT* has a limited particle topsize due to the relatively small cone volume that affects sampling precision. Furthermore, it is susceptible to crumbling when large particles are present. *The PFT* has a limited topsize due to the relatively small 1000 cm^3 proctor mould volume that affects sampling precision. Furthermore, PFT density measurements can be subject to errors due to difficulties associated with levelling the mould in the presence of large particles. Whilst *the PTT* can test larger material up to 25 mm topsize, the apparatus is inaccessible to many Shipper's (for practical reasons, as presented previously).

To address the top-size limitations of the TML Test Methods and comply with the top-size restrictions prescribed within the IMSBC Code, many laboratories may screen a test sample. However, *modification of a samples PSD will also change its compaction characteristics, liquefaction potential and the TML result*. In addition, it may also alter the distribution of physical and chemical properties through the test sample (*i.e.* different size fractions often possess different mineralogy, specific gravity, porosity characteristics, moisture contents, etc.). Narrowing of the PSD by screening has usually been reported to *increase* the measured TML (Kruszewski, 1986; Popek, 2013; IMO DSC18/INF.10). This is likely because the omitted larger particles contain less inherent moisture, by mass.

As an additional concern, the samples PSD may also be affected by particle degradation before or during a test. Practices such as incorrect mixing techniques or excessive compaction energies may cause particle degradation. Recent investigations have found that this may be significant if mechanical mixers are used on soft granular material (IMO DSC17/INF.10, 2012).

3.7.4.1 Recommendations

All TML testing should be performed on material with a PSD that is representative of the cargo loaded into a ship. The IMSBC Code therefore needs to highlight the importance of the PSD on the TML and should specify: (*i*) that a TML sample should *not be screened* prior to testing; and (*ii*) recommended *mixing techniques* to prevent practices that promote particle degradation (mixing by hand is recommended). To check if particle degradation has occurred from mixing and/ or compaction, repeated PSD tests should be performed (*i.e.* sieving).

Given the size limitations of the PFT and FTT and the aforementioned practical challenges associated with the PTT, there is a need to *develop a new TML test.* This test must be designed to accommodate cargoes that contain large particles (7-50 mm), whilst also being cheap, simple and fast (so as to be viable within a commercial shipping laboratory environment).

3.7.5 Drying of Sample Prior to Testing

Section 3.6.3 (p. 87) described the impact of drying a sample in relation to its effect on the sample and on the TML obtained by the PFT—recommending that *a sample should not be dried prior to testing* (contrary to the PFT method within the IMSBC Code). This recommendation is also applicable to all TML testing practices, including for the FTT.

3.8 RELIABILITY OF THE TML: OTHER ISSUES

The recommendations presented in Sections 3.5-3.7, if implemented, will ensure that the PFT and FTT each give less variable and more representative TML results when testing a given cargo sample. However, for these results to be effective when identifying an at-risk cargo, then the cargo sample tested (and the TML result presented within the Shipper's Declaration) must be representative of that particular consignment. The IMSBC Code attempts to address this by incorporating provisions on sampling, handling and reporting. However, an assessment of the regulation, including experience with bulk shipping operations, discussions with a range of Shippers and laboratories and a review of the literature, has shown that in practice these provisions are deficient on several counts:

(a) TML testing is not required for every shipment,[i] but is usually performed on a cargo only occasionally (around every six months). It is unlikely that a single reported value accurately represents the TML of each shipment during this period.

(b) In practice, many Shipper's report cargo moisture as an average over the shipment, rather than per hold. This may lead to a ship commencing passage with some holds above the FMP.

(c) The TML and moisture analysis are usually conducted in different laboratories and any variation in practices between these laboratories may lead to results that do not compare. The IMSBC Code does not adequately facilitate common practice amongst laboratories.

(d) The IMSBC Code requires that a Shipper know the moisture content of a cargo prior to loading (within seven days) but this may not be possible in some bulk shipping operations that have not been designed to meet these requirements.

(e) During a precipitation event the IMSBC Code applies restrictions on cargo handling, but in some cases this subjects the Shipper to unnecessary delays.

Consequently, the Master will typically receive a Shipper's Declaration that contains a single moisture content obtained from multiple samples of the individual shipment, and a single TML value obtained from a single cargo sample that was subject to testing up to six months prior. This raises questions as to the comparability of the two independently measured values—from different samples, at different times. Yet, a cargo's transportability depends on this comparison.

[i]The intention of TML testing is to ascertain a safe moisture limit at which the cargo can be shipped, not whether a given cargo consignment is safe for shipment.

Samples for TML and moisture analysis may be taken from a number of different locations, including: *(i)* as it leaves the mine; *(ii)* as it arrives at the port; *(iii)* from a port stockpile; or *(iv)* as it is loaded onto a ship (refer to Figure 3.37). A sample's representivity of a given cargo consignment depends on where the sample is taken, and on the sampling techniques/scheme. However, the IMSBC Code provides little guidance.

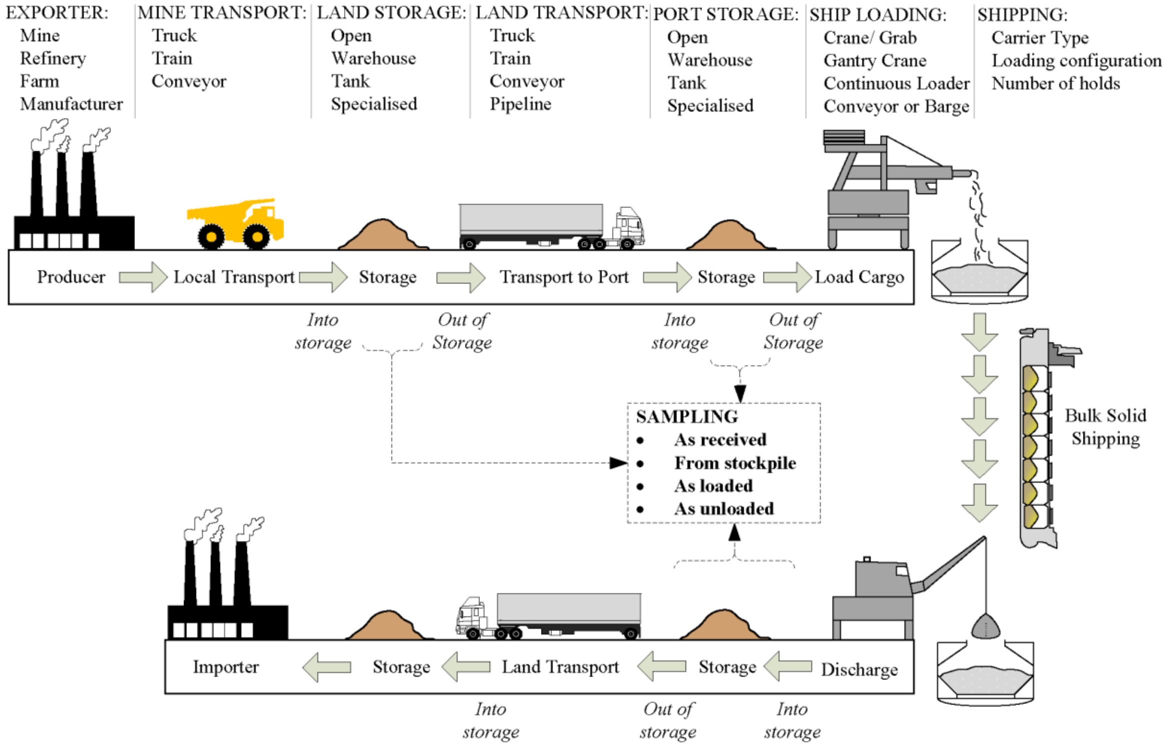


Figure 3.37: Possible sampling locations within a typical dry bulk shipping supply chain. Supply chain representation adapted from Stopford (2009).

3.8.1 TML Sampling and Reporting within the IMSBC Code

The IMSBC Code sampling requirements are non-specific. Consequently, the Shipper must subjectively decide when to test for TML and what sample to test.

Firstly, the IMSBC Code requires that the TML presented within the Shipper's Declaration is *"updated every six months, or if there is a significant change in the material shipped"*. A commodity producer may consider a large chemical change as significant, yet it is the physical changes that influence TML. Most bulk commodity operations are designed to produce a product of consistent grade, however minor changes to the physical characteristics of an ore, such as PSD, may go unacknowledged (this variation is likely to be more pronounced for unprocessed ores, as discussed previously in Section 2.2.2). Because the IMSBC Code does not require a Shipper to perform TML testing on the cargo to detect if changes in the TML occur over time, significant variability in the TML from shipment to shipment may also go unacknowledged. Experience has shown that on this basis, the TML may be updated only once over the six-month period (in other words, only a single TML value is reported for all shipments over that period). Note that the current requirement is also in some ways contradictory—a Shipper can only detect significant change in liquefaction potential by TML testing, yet they are not required to re-test for TML unless there has been a significant change.

Secondly, the IMSBC Code requires that the TML presented within the Shipper's Declaration is *"representative"* of the cargo, whereby testing is performed on a cargo sample obtained by internationally or domestically accepted standard sampling procedures. In practice, this non-specific requirement is highly subjective—especially given that a cargo's TML may vary significantly within the different holds of a ship or between shipments. Figure 3.38 provides an example, showing how the TML obtained from sixty-five different samples of the same copper concentrate cargo (taken during loading of four shipments) varied from 7.25-9.05%.

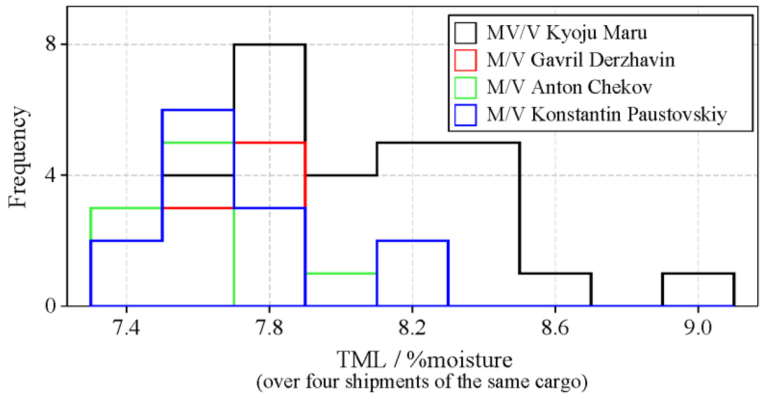


Figure 3.38: The variation in TML from sixty-five different sample lots taken during loading of four 'Class A' copper concentrate consignments (adapted from data presented by the U.S.A. in BCXX/ Inf. 10 (1979))

Yet, the IMSBC Code (and the sampling standards) give no guidance on how to select the TML result to report within the Shipper's Declaration. A declared TML value could be based on:

- a single TML test on a *single sample of a cargo* (for the example shown in Figure 3.38, this means that a Shipper may obtain and report a TML result anywhere between 7.25-9.05%);
- a single TML test on a composite sample of a single cargo consignment;
- a single TML test on a composite sample of multiple consignments; or
- an *average of multiple TML test results* obtained from any combination of the above sampling schemes (for the example shown in Figure 3.38, this means that a Shipper may obtain and report a TML based on the average of some, or all of the TML results shown).

Clearly, the declared TML result will vary depending on the Shipper's chosen sampling and testing approach. If the Shipper from Figure 3.38 reported a TML of 7.25%, then this would be particularly conservative as a cargo could be loaded a few percent above this moisture and still be unlikely to liquefy during transport (*i.e.* most cargo material has a significantly higher TML)—thus the Shipper may be subject to unnecessary cargo moisture restrictions. Conversely, if 9.05% was the reported value then this may introduce a safety risk, as a wet vessel could commence passage with a significant portion of its cargo above the TML/FMP and at risk of liquefaction. Of concern, a Shipper may be more likely to declare the higher TML value that presents a lower commercial risk. Yet, the IMSBC Code does not require a Shipper to report their reasons for selecting a declared TML, or from what (combination of) tests/samples it was derived.

As an additional issue, the internationally recognised standards that the IMSBC Code requires to be used for TML sampling were typically developed to assess a cargo's chemical and moisture properties, for individual cargo consignments (so that the Shipper knows the grade/ quality of a given shipment). However, these standard sampling methodologies are unlikely to be suitable for TML sampling, which is not performed on a per-shipment basis and is a function of physical properties rather than chemical or moisture properties. According to Dr R. Holmes, the sampling methodologies required to obtain a representative sample for TML testing are likely to be very different to the requirements for obtaining a representative sample for chemical and/or moisture analysis (R. Holmes, personal communication, March, 2012)[i].

3.8.1.1 <u>Recommendations</u>

A cargo's chemical properties may remain relatively consistent amongst holds and shipments over a period, yet evidence indicates that the TML may vary. For these cargoes, a single declared TML is unlikely to be representative of all shipments over a period of months. To address this, the following is proposed:

(a) The non-specific, ambiguous wording within the IMSBC Code must be amended to ensure that a significant change is informed by changes to a cargo's physical properties or more effectively, to changes in its TML (*i.e.* not to its chemical properties or otherwise).

[i]Dr. R. Holmes has been Chair of the ISO committee on Sampling of Iron Ore and Reduced Products (ISO/TC 102/SC 1) and Convener of ISO committee on Sampling of Copper, Lead and Zinc Ores and Concentrates (ISO/TC 183/WG 9). He has also presented to IMO on behalf of ISO in relation to cargo liquefaction (*i.e.* to the BC Sub-Committee (BC32/INF.6, 1992)) and played an active role in developing the ISO standard for TML determination by the flow table test (ISO12742, 2012).

(b) The IMSBC Code must include provisions that require the Shipper to demonstrate consistent and predictable TML results over each hold and for each shipment, over time. If TML repeatability is not demonstrated, then TML test frequency should be increased for this cargo. Higher variability operations require more frequent TML testing and reporting.

(c) It is proposed that complementary provision be added that require the Shipper to also re-test for TML based on a number of shipments (or loaded tonnes). That way, a Shipper that loads hundreds of ships and millions of tonnes, within the time-period from (b), will sample for TML more frequently than those Shippers that only ship occasionally.

(d) The IMSBC Code must improve prescription around what constitutes a "*representative sample*." It should provide guidance on how the Shipper should select the individual TML result presented within the Shipper's Declaration. Given the proposed testing frequency (in points (a) to (c)), it is then suggested that multiple TML tests are performed on *(i)* a statistically relevant number of randomised samples (higher variability operations will require more samples); and *(ii)* at mass based increments (based on a hold's mass capacity, for example around 20,000 tonnes for a typical Capesize Carrier).

(e) To ensure a safe value is declared, the TML should be taken as the lowest of all results over a hold (or at the lower range of a defined confidence interval). An average result should not be reported (this could lead to a vessel sailing with some material above the TML or FMP).

(f) For most bulk commodities, there exists internationally recognised sampling standards for chemical and moisture sampling. However, evidence shows that TML sampling requirements are different and standards should be developed to reflect this (whether within the IMSBC Code or by a recognised body such as ISO).

(g) The IMSBC Code must require a Shipper to justify their reasons for selecting a TML value used within the Shipper's Declaration (probably in the form of a report, as part of (f)).

(h) For a truly representative indication of liquefaction potential, the TML should be determined for each hold of each shipment. However, this is not practical for the current TML tests as by the time testing has been complete, the vessel may have sailed. The Can Test (see p. 41) is designed to provide an approximate indication of flow of an individual consignments, but this should not be used as a conclusive indicator of a cargo's transportability (there also appears to be little basis behind the prescribed test parameters and these are not well controlled). There is therefore an opportunity to develop a quick (<30 minutes), simple, portable, controlled procedure that can be used to determine the liquefaction potential of each shipment. This procedure should be designed to give a rapid, definitive indication of a cargo's transportability.

3.8.2 Moisture Reporting Practices: Per Consignment or Per Hold

As for the TML, cargo moisture may also vary significantly between shipments and within a given shipment. This is demonstrated in Figure 3.39, which shows how the moisture content varied over sixty-five sample lots taken during loading of four separate shipments of the same copper concentrate cargo, taken during loading (adapted from data presented by the U.S.A. to the BC Sub-Committee (IMO BCXX/INF.10, 1979)).

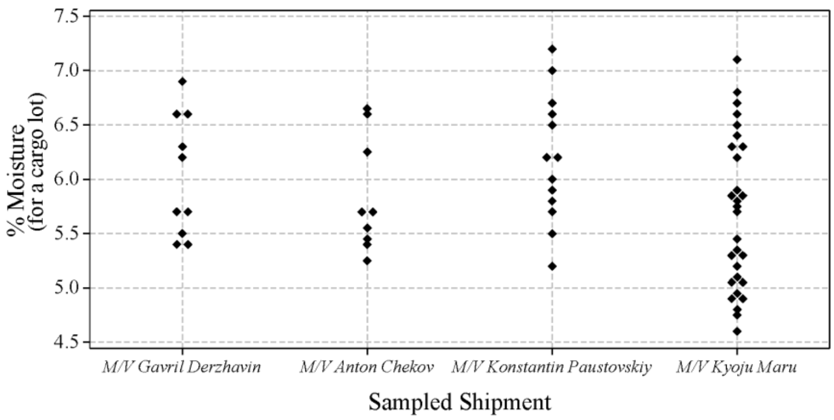


Figure 3.39: Moisture content of sixty-five different lots taken from four different "Class A" copper concentrate consignments. Adapted from data presented by the U.S.A. in BCXX/ Inf. 10 (1979).

To address this, the IMSBC Code specifies the following moisture reporting requirements:

(a) a cargo's moisture content should be reported for each hold; unless

(b) recognised standard sampling procedures[i] indicate that the moisture content is consistently uniform through consignments, in which case only an average moisture content is required.

Experience has shown (and others have reported (Jonas, 2014)) that in practice a Shipper will commonly report the moisture of a cargo consignment as a *single average value of the shipment* (*i.e.* over all of the holds) rather than for each hold. However, this approach to reporting could lead to a vessel being loaded and allowed to commence passage with some holds containing moisture in excess of the flow point (FMP) and potentially at risk of liquefaction. This is demonstrated in an example in Figure 3.40 (overleaf). Although such a situation, where only some holds contain liquefied cargo, does not necessarily compromise stability, there have been reports of incidents from shift within a single hold (IMO BC/Conc/8, 1964).

[i]For example, ISO 3082:2009 Iron ores: Sampling and Sample Preparation.

(1) VALUES PRESENTED TO MASTER IN SHIPPER'S DECLARATION

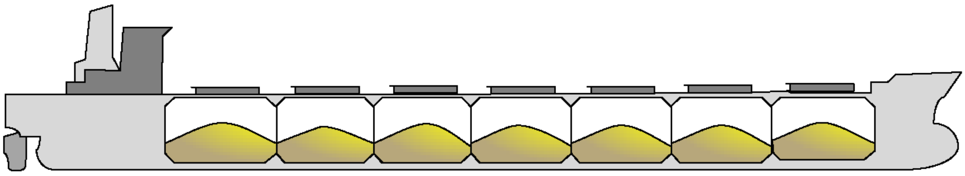
a) TML and FMP values presented
Cargo FMP = 10%
Cargo TML = 9%

b) Cargo consignment moisture content presented to Master
Moisture Content = 8.95%

(2) CAN THE VESSEL SAIL?

Yes. According to the certificates presented to the Master, the cargo moisture content is below the TML

(3) ACTUAL MOISTURE OF CARGO CONSIGNMENT WITHIN EACH CARGO HOLD



HOLD NO.	1	2	3	4	5	6	7	**Average**
MOISTURE %	*10.2%*	8.3%	*10%*	7.9%	8.5%	*10.1%*	7.7%	**8.95%**
BELOW FMP?	*No*	Yes	*No*	Yes	Yes	*No*	Yes	**Yes**
BELOW TML?	*No*	Yes	*No*	Yes	Yes	*No*	Yes	**Yes**

(4) IS THE CARGO SAFE FOR CARRIAGE?

Probably Not. Three of the seven cargo holds contain cargo with moisture above the FMP (above 10%). These may be susceptible to liquefaction and cargo shift during passage

Figure 3.40: Provides an example of how average moisture could be reported, allowing a ship to be loaded with multiple holds above the FMP and at risk of liquefaction.

The situation in Figure 3.40 is unlikely to occur within larger mining operations, where short-term moisture variability is minimised due to high tonnage throughputs (a 200,000 tonne ship may be loaded in 15 hours) and rigorous stockpile blending. On the other hand, moisture variability may be significant for smaller mining operations that are characterised by lower throughput and long periods between shipments. In these operations, it is possible that two stockpiles of significantly different age and moisture contents are loaded into alternate holds.

3.8.2.1 Recommendations

To prevent a vessel commencing passage with some holds containing Group A cargo at risk of liquefaction, the IMSBC Code should *incorporate a requirement for the Shipper to understand per-hold moisture variability*. This may involve taking a number of samples of each hold, over a number of shipments—most operations are set up with sampling systems that facilitate a reasonable estimation of moisture content on a per hold basis.

It is proposed that the IMSBC Code applies a situational approach to reporting, whereby the need to report per-hold or per shipment is based upon *(a)* moisture variability, and *(b)* the cargo's average moisture with respect to the TML. More specifically:

(a) If a Shipper can demonstrate low moisture variability amongst holds, reporting per-hold is not required *unless* the average moisture for a shipment is close to the TML. By way of example, consider a cargo (TML=10%) in which per-hold cargo moisture variation is consistently less than 1%. In this situation, cargo moisture could be reported as an *average* over the entire ship up to a moisture content of around 10%, with confidence that the moisture in each individual hold is below the moisture at which liquefaction can occur (*i.e.* FMP =11.1%).

(b) Where variability is greater *and* the average moisture content for the shipment is significantly below TML, only an average moisture needs to be reported for the shipment.

(c) For more variable operations *and* where the average cargo moisture is close to the TML, per-hold moisture reporting should be required.

(d) Operations with lower moisture variability per hold can ship at cargo moistures closer to the TML without having to report on a per-hold basis.

(e) The requirement to report on a per-hold or average basis can (and should) be quantified by consideration of the relationship between moisture variability and product moisture for a given shipment, in comparison to the TML (*i.e. TML–mc*). This should be captured within the IMSBC Code.

(f) A Shipper's moisture variability may change over time. To ensure that this is captured, the IMSBC Code should require the Shipper to re-assess the variability within a fixed period (say, each six months). If variability measurements cannot be demonstrated for any reason, then *per-hold moisture reporting should be mandatory.*

The proposed situational approach to sampling and reporting, as recommended above, has a number of advantages over the current provisions in the IMSBC Code. In high variability operations, it prevents liquefiable cargo being unknowingly loaded into individual holds (improving safety). For low variability operations or where cargo moisture is low, it negates the requirement for per-hold reporting (reducing the Shipper's reporting and testing requirements).

3.8.3 Comparison of the Moisture and TML Results

Typically, cargo moisture and TML measurements are performed in independent laboratories. Any differences in the moisture determination methods used at the two laboratories may result in an erroneous comparison between the cargo moisture and TML results presented within the Shipper's Declaration. The IMSBC Code does not adequately specify uniform procedures for the two different analyses, and in practice moisture measurement techniques can vary significantly.

More specifically, a cargo's *moisture content* is measured per shipment, within a port-based laboratory that is experienced in testing the cargo material. This is typically performed to internationally or domestically accepted standards (for example, ISO standards), due to its commercial importance[i]. By contrast, *TML testing* is performed less frequently, whereby the Shipper will occasionally send off a composite sample to be tested (around every six-months is common, see Section 3.8.1). This is performed in an independent laboratory from where per-shipment moisture analysis was performed and often within a laboratory that is inexperienced in handling that cargo. Observation of a range of TML testing laboratories has indicated that the moisture analysis in these laboratories is often not performed to internationally recognised standards (the IMSBC Code does not require this). The different moisture determination techniques employed at these two laboratories may lead to non-comparative TML and moisture results being declared.

3.8.3.1 Recommendations

To ensure that comparable results are presented within the Shipper's Declaration, the IMSBC Code must contain specific prescription that ensures both *the TML and moisture analysis are obtained by the same moisture determination method.* Recommended approaches have been presented in Section 3.7.2 of this thesis.

3.8.4 Moisture Sampling Requirements in the IMSBC Code

Although the BC Code and IMSBC Code has been updated at regular intervals since 1965, there appears to contain many outdated provisions that are detached from the practical realities of a bulk commodity shipping operation. Modern bulk shipping operations are often very different

[i]The Shipper is normally remunerated only for the shipped commodity, not for shipped water.

from those that existed when many of these provisions were introduced, yet the assessment of the regulation's development within the IMO archives (London) has indicated that many remain essentially unchanged. There has been a clear tendency to add new provisions, but not to amend the old ones. Furthermore, many of these provisions do not accurately capture the risks of shipping a Group A cargo.

The requirements for moisture sampling provide a good example. The IMSBC Code requires that the Shipper perform sample and test a cargo consignment within *"seven days"* of loading. This may appear reasonable as it prevents a liquefiable material being loaded into a cargo hold. However, in practice, this is not viable in many modern high throughput operations designed to perform moisture sampling *during* loading (samples are often taken by cross-stream cutters fitted within the conveyor network).[i] In these operations, the moisture content of the cargo is not known until after loading is complete—although it is usually known before the vessel commences passage. The Shipper is therefore unable to comply with the IMSBC Code and to change these sampling practices would require large, probably unrealistic, capital investment in port infrastructure.

However, the sampling systems typically used within these operations allow moisture content to be determined with high precision and accuracy. In addition, their high throughput (for example, in excess of 200,000 tonnes per day for some iron ore mining operations), compliance with internationally accepted standards (for example, ISO standards) and ore blending processes, allow moisture prediction with reasonable accuracy. Moisture prediction can facilitate the detection of excessively moist cargoes prior to loading.[ii]

On the other hand, many smaller operations will know cargo moisture before loading and thus meet the requirements of the IMSBC Code. Yet, the moisture results presented are often obtained from stockpile samples of poor accuracy and precision. In borderline operations, *i.e.* where typical cargo moisture is close to the TML, this sampling may be unsatisfactory to guarantee safety. This sampling approach presents a greater risk that the as-loaded sampling regime, yet the IMSBC Code requirements are met.

[i]For example, iron ore fines was not until recently classified a Group A cargo. There was therefore no requirement to know cargo moisture prior to loading (discussed in Section 2.1).

[ii]It has recently been demonstrated that for predictable, large scale, bulk operations cargo moisture content can be predicted based on previous shipments of the same cargo, with a reasonable degree of accuracy using an autoregressive moving average (Everett et al., 2013). Whilst this tool can provide an indication as to whether a future shipment is likely to exceed the TML, it cannot detect future anomalies and therefore does not negate the requirement for moisture determination within individual cargo consignments.

3.8.4.1 Recommendations

The IMSBC Code therefore contains restrictive provisions regarding sampling that do not appropriately account for risk. The provisions within *the IMSBC Code must be updated to reflect (and allow) now common and more accurate sampling practices such as-loading sampling*. It must also *consider the precision and accuracy of the wide range of sampling practices and account for this accordingly*—these impact the risk of carrying the cargo. This could be achieved is by varying the 'margin of safety' between the FMP/TML, whereby the safety margin could be reduced/increased for lower/higher variability sampling systems.

3.8.5 Treatment of Precipitation in the IMSBC Code

If precipitation occurs after a cargo is sampled for moisture content, then it is possible for this to raise the cargo moisture content in excess of the TML/FMP, despite the certificate presented to the Master indicating otherwise. There have been recorded cases of liquefaction and cargo shift following precipitation (IMO BCI/WP.3, 1964). Tropical regions such as South East Asia may be particularly susceptible (Isacson, 2010).

To address this, the IMSBC Code contains provisions that aim to control the handling and sampling of a cargo during/after precipitation. These may subject the Shipper to non-specific handling restrictions, for example:

(a) The cargo "shall not be handled during precipitation" unless "the actual moisture content of the cargo is sufficiently less than its TML."
(b) If precipitation occurs then a Master may have rights to cease loading during rainfall, subjecting the Shipper to delays and/or throughput reduction.

These apply blanket regulations that disregard the impact of precipitation on cargo moisture, which will vary depending on *(i)* rainfall characteristics (rainfall volume and duration) and *(ii)* operational attributes (exposed surface area, stockpile tonnages and/or throughout rates). It possible for a significant precipitation event to have only a minimal impact on total cargo moisture content, in which case the above handling restrictions are unnecessary.

By way of example, it is estimated that a significant 50 mm rainfall event before and/or during loading of a 200,000 tonne Capesize vessel (at a rate of 10,000 tonnes per hour) would result in around 300 to 800 tonnes of additional moisture over the ship's holds.[i]. If initial cargo moisture was 11%, then this precipitation event would increase overall cargo moisture to 11.67%. Even if this precipitation event led to the ship sailing at moistures above its TML, its moisture would still be lower than the FMP, and therefore liquefaction is unlikely. Restrictions on loading would probably not be warranted in this situation. Yet, for this iron ore operation, any restrictions applied may cost the producer around $700,000 to $1.5 million per hour (per shiploader).

Several amendments and improvements to the precipitation provisions have been suggested, but few of these have attempted to apply a situational based approach when considering precipitation. For example, the USSR suggested that for precipitation events exceeding 50 mm, the cargo moisture content be increased depending only on the port stockpile height[ii] (IMO BCXII/7/1, 1971). However, this adjustment neglected to take into account the effect of a given rainfall volume on the exposed surface area.

3.8.5.1 Recommendations

In order to prevent unnecessary cessation of loading during or following a precipitation event, the IMSBC Code should consider *the impact of a precipitation event on cargo moisture*. More specifically, it should incorporate a calculation that considers *(i)* precipitation volume, and *(ii)* exposed cargo area (*i.e.* area of hatches, stockpiles, conveyors), with regard to their impact on overall cargo moisture. If these calculations indicate that the precipitation event has negligible impact on cargo moisture (*i.e.* introduces no risk of exceeding the TML and/or FMP) then *the restrictive handling and loading requirements should not apply*.

[i]The calculation's assumptions were developed from experience in a bulk commodity operation, whereby a 200,000 tonne vessel is loaded at 10,000 tonnes per hour over approximately a day. Assumptions were also made regarding the exposed surface area of the cargo (stockpiles, conveyors and nine open cargo hatches on a Capesize bulk carrier). An iron ore price of US$70-150 per tonne is assumed (based on approx. 2011-2014 price ranges).

[ii]The U.S.S.R. suggested that reported cargo moisture be increased by 0.5%, 0.3% and 0.2% for stockpile heights of 2, 4 and 6 meters, respectively (BCXII/7/1, 1971).

3.9 PROPOSED BEST PRACTICE METHODOLOGY

In consideration of the information presented within Sections 3.5-3.8, a summary of the main sources of variability and points of difference for the FTT and PFT are shown in Table 3.4. This is presented in terms of *repeatability* (*i.e.* for a given operator in the same laboratory) and *reproducibility* (for different operators). A flow diagram, outlining a proposed methodology for both the FTT and PFT, is presented as a simplified schematic in Figure 3.41 (p. 111) and Figure 3.42 (p. 112), respectively. These findings are also summarised in Appendix 5.

Table 3.4: Main considerations and points of difference for the PFT and FTT.

	THE FLOW TABLE TEST (FTT)	THE PROCTOR/FAGERBERG TEST (PFT)
Apparatus	(*i*) Flow table is standardised, easy to obtain; cheap and easy to setup; (*ii*) FTT must be mounted appropriately (mustn't dampen the energy applied when applying knocks on the flow table); (*iii*) Tamper is usually unique for given laboratory (*i.e.* not standardised).	(*i*) Apparatus is standardised, easy to obtain, cheap and easy to setup; (*ii*) Leakage can be problematic in materials that exhibit some drainage. An operator must ensure that the apparatus is sealed to prevent drainage at moistures approaching saturation (this will result in errors).
Test Material	(*i*) Large particles may affect slumping characteristics of the cone; (*ii*) Small mould volume limits particle size and sampling precision—therefore greater variability is likely to be experienced with larger topsize material; (*iii*) Some materials may be susceptible to adhesion when removing the mould; (*iv*) Requires up to 5 kg of material.	(*i*) 1000 cm^3 mould volume sufficient to facilitate sufficient sampling reasonable precision within the allowable range; (*ii*) A shallow compaction curve is obtained for well-draining, fine material and this may make interpretation more difficult; (*iii*)Requires up to 10kg of sample to perform a series of tests.
Operator Requirements	Little experience is required, although this can affect the subjective observation of flow (see below).	Calculation for void ratio and degree of saturation and error identification may require some basic maths and civil engineering understanding (the curve is easily misinterpreted).
Repeatability for a single operator.	Can be repeatable for a single operator (±0.4% for Redhill 110) but is subject to errors associated with: (*i*) moisture determination; (*ii*) consistent identification of flow (particularly by	Repeatable by a single operator (±0.3%) but is subject to errors associated with: (*i*) moisture determination; (*ii*) variations in compaction; (*iii*) levelling the mould

	THE FLOW TABLE TEST (FTT)	THE PROCTOR/FAGERBERG TEST (PFT)
	observation); (*iii*) variability in tamping pressure (say, through kneading effects); (*iv*) moisture loss; and (*v*) measurement precision.	(particularly for materials with large particles); (*iv*) moisture loss to environment and by leakage; and (*v*) measurement errors.
Reproducibility for multiple operators.	As for above, but additional variability/biases may be introduced due to: (*i*) differences in interpreting of flow; (*ii*) different/incorrect tamper pressure settings; and/or (*iii*) sample preparation variation (for example, drying the sample).	As for above, but additional variability/biases may be introduced due to variation of: (*i*) sample levelling techniques; (*ii*) compaction techniques and/or (*iii*) sample preparation variation (for example, drying the sample).
Reproducibility amongst Different Laboratories	As for above, but variation may be more pronounced amongst laboratories (up to 1.1% has been recently reported (Allen, 2012)) due to the introduction of additional variability/biases from different: (*i*) sample re-use practices; (*ii*) interpretations of observed flow; (*iv*) methods of interpretation by measurement (IMSBC code/threshold); (*v*) measurement errors; (*vi*) moisture determination methods (*i.e.* added versus dried); *(vii)* oven determination techniques (drying temperature/time); (*viii*) mixing and moisture addition techniques (impacting moisture absorption, particle degradation); (*ix*) different tamper apparatus/settings; and/or *(x)* applying a different number of drops;	As for above, but additional variability/biases may be introduced due to differences in: (*i*) G_s determination method (helium, pycnometer?); (*ii*) sample preparation (drying of a sample before testing?); (*iii*) calculation errors; (*iv*) measurement precision; and (*v*) differences in moisture determination techniques. The PFT contains less ambiguities and thus in terms of its measurements is less variable than the FTT, but errors arise from its TML criteria (the arbitrary 70% saturation condition, sensitivity to G_s) and other inherent issues (requirement to dry a sample before testing).
Method Accuracy	Unknown with respect to the ship. FTT gives up to 10% relative lower results than the PFT. See Chapter 4 for further discussion on accuracy.	Unknown with respect to the ship. PFT gives consistently higher TML result than other methods. Ssee Chapter 4 for further discussion on accuracy.

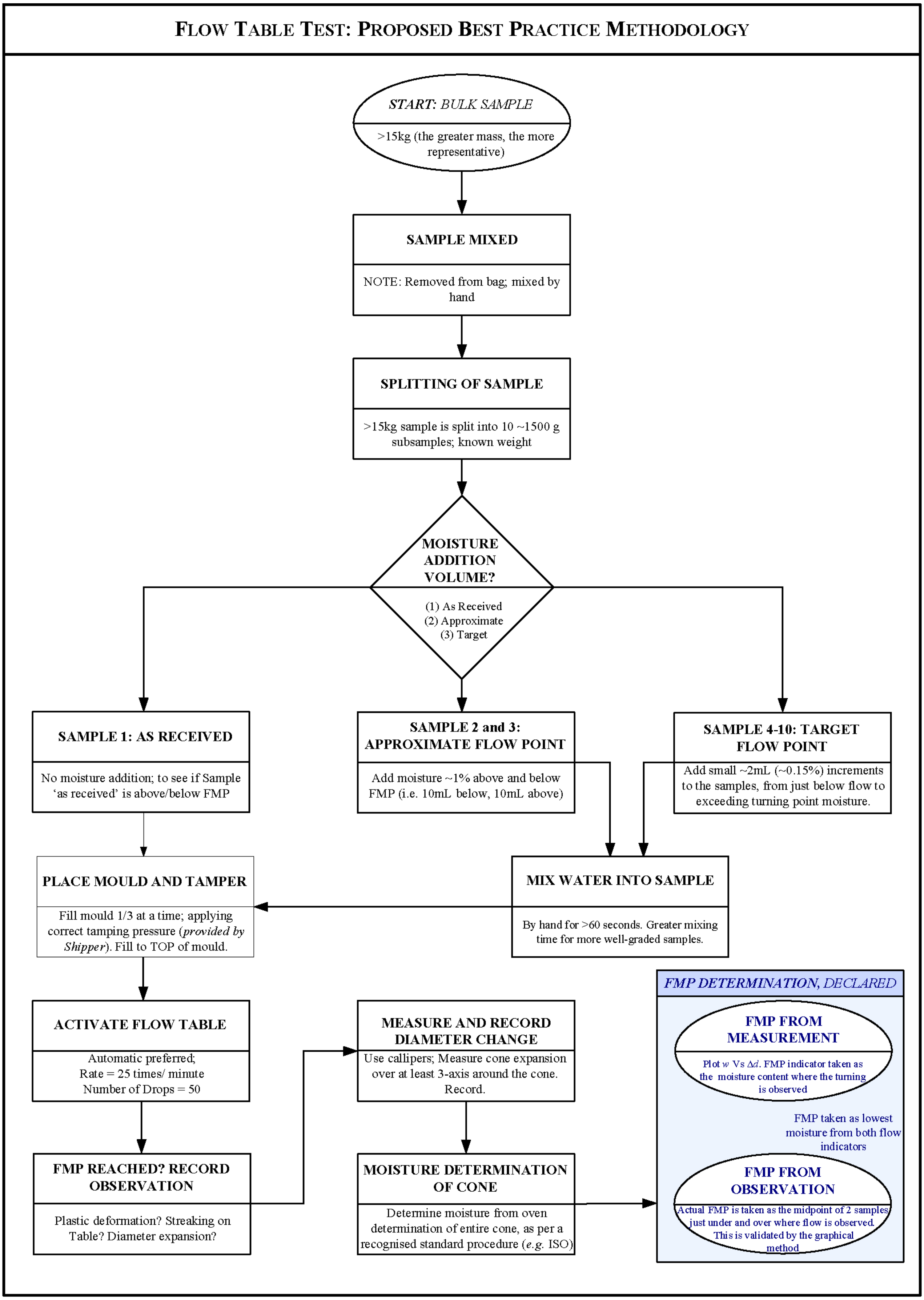


Figure 3.41: A representation of the proposed FTT methodology

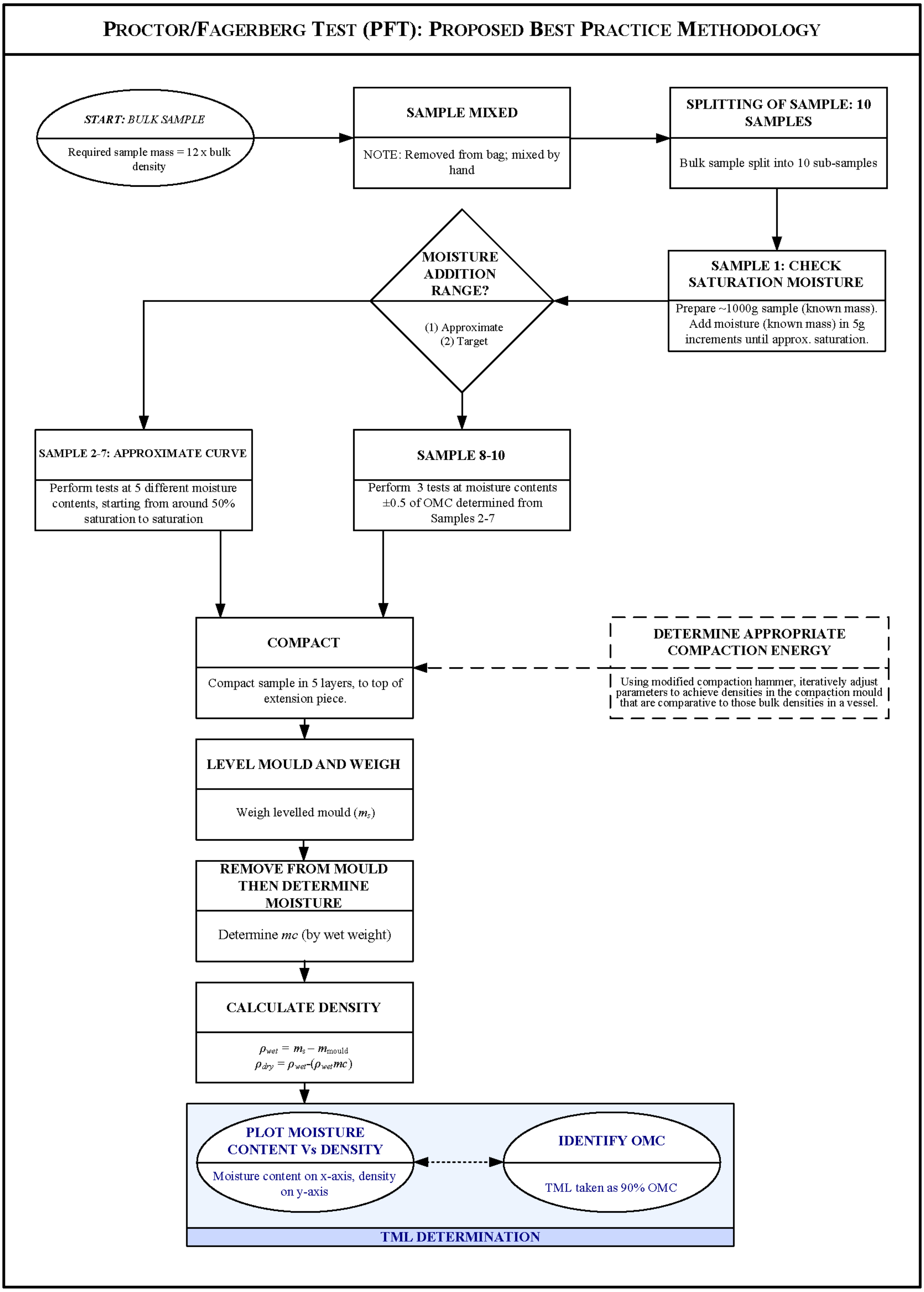


Figure 3.42: A representation of the proposed PFT methodology.

3.10 THE BIAS BETWEEN THE TML TEST METHODS

In principle, there should be only a single safe shipping moisture content (and FMP/TML) for a given cargo consignment, on a given journey. However, it has been reported that the different TML test methods *may each give a different results.* This was found for the Redhill 110 and iron ore fines tested, shown in Table 3.5. The higher TML results obtained from the PFT are consistent with research findings reported by Kirby (1982), Kruszewski (1985), Popek et al (2001) and for Brazilian iron ore (DSC17/INF.10, 2013). As discussed in Section 3.1.1, this not only raises questions as to the suitability of these methods, but also has commercial implications.

Table 3.5: A comparison of the TML results from the PFT and FTT

	FLOW TABLE TEST	PROCTOR/FAGERBERG TEST
Redhill 110	18.6 %	19.6 %
Iron Ore Fines	11.3%	12.6%

3.10.1 A Basis for the Bias between TML Test Methods

Each of the TML Test Methods has been designed with the intention of determining the moisture content at which cargo strength is likely to be lost due to liquefaction. However, the assumption of when this occurs is different for each TML Test Method:

(a) For the FTT, it corresponds to the moisture content when cone strength is lost and plastic deformation is first observed on the flow table (*i.e.* fixed number of knocks and drop height).
(b) For the PFT, it corresponds to the moisture content at 70% saturation (or for the alternative method proposed in Section 3.6.1.3, the OMC); and
(c) For the PTT, it corresponds to the moisture content at which significant penetration can occur in the sample under vibration (1g for 6 minutes, fixed penetration mass).

In addition to these *"interpreted flow parameters*" the strength and liquefaction outcome is also influenced by a number of inherent test parameters that affect the samples measured behaviour ("*primary test parameters*"). These include: *(i)* the manufactured material properties of the test material (for example the samples initial density); and for the PFT and FTT *(ii)* the amplitude of any applied cyclic forces, and to a lesser extent frequency.

As these parameters vary for each of the TML Test Methods, it is not surprising that they each give different results.

3.10.1.1 The FTT and PFT Primary Test Parameters

Measured material behaviour in the FTT and PFT depends on the *density* of the test sample, as manufactured by the act of tamping (for the FTT), or by dropping of the compaction hammer (for the PFT). In addition, for the FTT, measured material behaviour also depends on the energy applied by the repeated *cyclic knocking of the flow table* and the *number of cycles* applied. Variation of these parameters will influence the TML result.

The sample densities for all tests should match the as-shipped condition. Yet, if a sample is compacted to an incorrect density in one of the tests then this may contribute to the FTT/PFT TML bias. As discussed in Section 3.6.2 (p. 86), densities in the **PFT** compaction mould are already greater than that on a vessel. Lowering these densities to represent the as-shipped condition will result in a higher TML result from the PFT, and further increase the bias between the two methods, *i.e.* the PFT already gives significantly higher TML results. For the **FTT**, each cargo sample is subject to tamping energies intended to represent those experienced by a cargo at the base of a hold (sample density is not directly considered). As discussed in Section 3.5.2, FTT tamping may be subject to errors. However, the tests on Redhill 110 and results from other researchers (IMO DSC18/INF.10, 2012) indicate that incorrect FTT tamping pressures are unlikely to account for the entire TML bias between the FTT and PFT methods. This is because significant variations in tamping led to maximum TML variation of less than 0.8% relative—significantly less than the TML bias between the PFT and FTT (1-1.5% relative). Additionally, accounting for the bias using the tamper pressure would present challenges due to its non-linearity (see Section 3.5.2).

The cyclic forces applied in the FTT could also explain the TML bias between the different methods. Cyclic forces should simulate those applied by a ship, although in practice this is difficult to achieve (as discussed further in Chapter 4). This current work indicated that the TML from the FTT was dependent on the *energy applied per knock of the flow table,* whereby raising/lowering the height of each drop of the flow table would likely decrease/increase the TML (see Section 3.5.4[i]). It is likely that this parameter contributes to the PFT and FTT bias. If the drop-height (currently fixed at 50 mm) was lowered then this will increase the TML result

[i]Section 3.5.4 explained that the moisture content at which a significant loss of shear strength begins to occurs, *i.e.* the turning point on a plot of moisture against cone expansion, does not vary with the number of cycles (knocks) of the flow table but is instead is a function of the energy per drop.

obtained for a given sample, taking it closer to the TML given by the PFT. However, adjusting this parameter would require significant apparatus modification and is therefore is an unpractical way to address the bias. Note that varying the *number of knocks* will change cone expansion but does not change the moisture content at which flow occurs—this does not account for the bias.

Although incorrect density and cyclic energy settings lead to variations in measured material behaviour and contribute to the TML bias, these cannot be reasonably adjusted to account wholly for the bias.

3.10.1.2 The PFT and FTT Interpreted Flow Parameters

The primary test parameters affect measured material behaviour. Then, for a given set of measurements, the TML result depends on the interpretation of liquefaction. By way of example, *for the FTT*, the bias between the PFT can be accounted for by:

(a) Adjustment of the 10% FMP/TML safety margin (*i.e.* increasing the safety margin will decrease the TML). For Redhill 110, the PFT TML of 19.65% can be obtained by reducing the FTT safety margin to 5%.

(b) Adjustment of the arbitrary threshold cut-off expansion as determined by measurement (*i.e.* raising this threshold will raise the FMP/TML). As illustrated in Figure 4.43, increasing the cut-off may increase the TML significantly, but only minimal downward adjustments to the TML are possible (*i.e.* for Redhill 110, the minimum possible FMP is 21%).

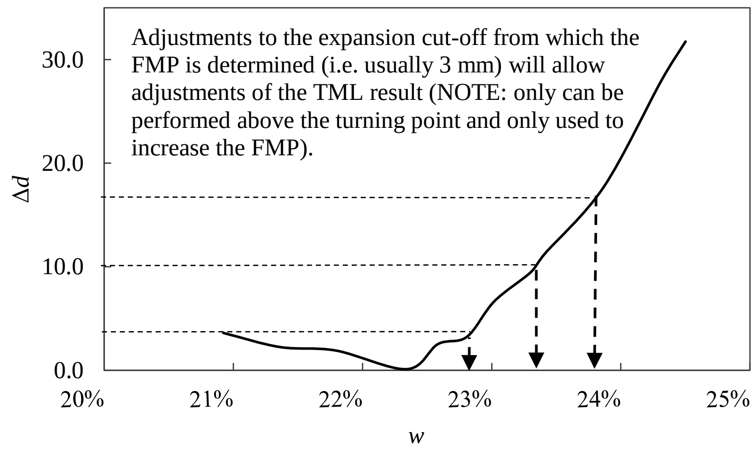


Figure 3.43: Demonstrates how FMP can be adjusted by varying the threshold measured expansion. Note that this adjustment is arbitrary and ignores where the strength behaviour of the sample.

For the PFT, the TML depends on graphical interpretation. For example, using the current IMSBC Code criteria, alignment of the PFT and FTT results could be achieved by:

(a) adjustment of the degree of saturation condition (*i.e.* instead of TML being determined from S=70%, this could be raised/lowered to increase/decrease TML). For example, for Redhill 110 alignment with the FTT TML (18.7% from IMSBC Code method) could be achieved by taking the TML at 67% saturation;

(b) adjustment of the specific gravity input (increasing G_s increases the TML—although this would be technically inappropriate); or

(c) for the method proposed in Section 3.6.1.3 where the TML is derived from the OMC and incorporates a safety margin, adjustment of the safety margin (incorporating a 4.1% safety margin on the OMC of Redhill 110 would align with the FTT result).

Although possible, accounting for the PFT and FTT bias by these criteria for flow is however, not a satisfactory approach. They both apply different arbitrary criteria to arrive at the TML and these do not directly reflect the strength behaviour of the tested material. Furthermore, different cargo material would likely require a different adjustment.

3.10.2 FTT and PFT Calibration: Aligning the TML Results

In consideration of the above, the IMSBC Code TML results from the PFT and FTT are both derived from different arbitrary interpretations of flow, more specifically: (*i*) the FTT incorporates a 10% safety factor from the point where strength loss occurs, and (*ii*) the PFT uses a 70% saturation to arrive at the TML (which has little relationship with strength). *For the current IMSBC Code methodologies, it is therefore impossible to draw a meaningful comparison between the results on the basis of their TML.*

Given that apparatus restrictions prevent adjustments on the basis of the primary parameters (Section 3.10.1.1), the only legitimate way to calibrate the TML obtained by the PFT and FTT is to adjust the interpretation of the TML. To achieve this, the flow interpretation criteria for both tests (say, the 'Flow Moisture Point') must be comparable and predictable.

In order to draw comparison between the behaviour of a given sample in the PFT and the FTT, the TML must be ignored and instead only the measured properties considered. These measured properties are shown in Figure 4.44 and Figure 4.45 for Redhill 110 (overleaf). These plots indicate a relationship between the moisture and measured behaviour:

(a) At around 20.8% moisture (just after the OMC in the Proctor/Fagerberg curve) the FTT ceases crumbling and begins to gain strength; and

(b) At moisture contents greater than 22.5 %, saturation is approached in the PFT (shown as scatter in Figure 4.44), whilst the FTT cone began to rapidly lose strength with further additions of water (measured as an increase of cone expansion).

Further tests would be necessary, on a range of cargo materials, to draw any wider conclusions regarding this relationship observed for Redhill 110. However, if comparable TML results are to be obtained between the two tests methods, then it is these types of behavioural relationships that must be examined and upon which the TML should be based. Note that for iron ore fines, insufficient FTT measurements were obtained to meaningfully compare measured behaviour from both TML Test Methods.

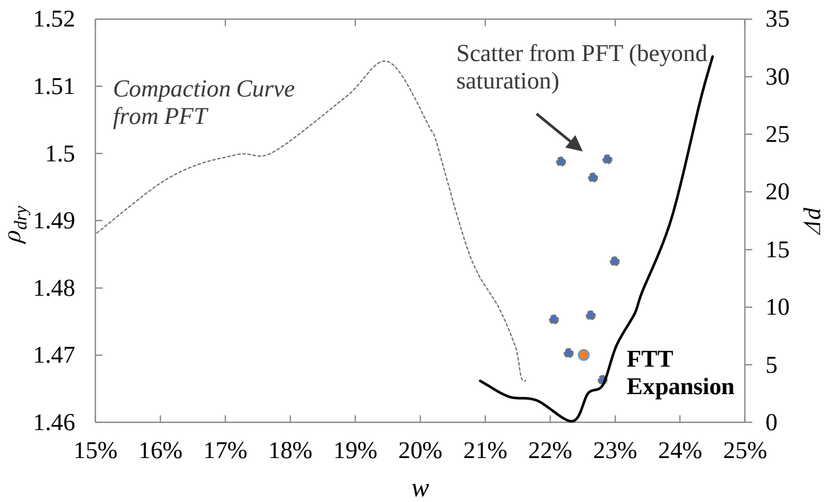


Figure 3.44: A comparison between FTT cone expansion measurements (Δd) and the Proctor compaction curve ρ_{dry}. A relationship between the behaviour of the material in the two tests can be observed.

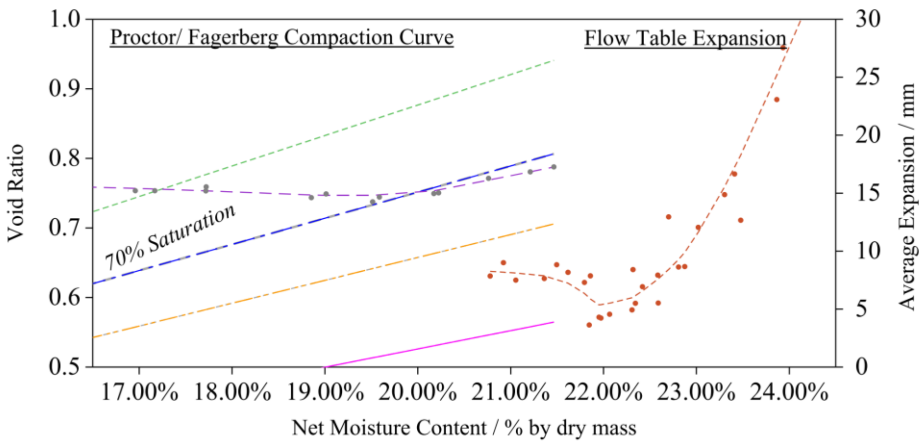


Figure 3.45: A comparison between FTT cone expansion measurements (Δd) and the PFT curve for Redhill 110 (*i.e.* void ratio, not density).

4. ACCURACY OF THE TML TEST METHODS

Although the findings on variability of the TML test methods presented within Chapter 3 will, if implemented, improve the reliability of TML results obtained within and amongst TML testing laboratories, there is little evidence available to indicate their accuracy. That is, *the ability of these methods to accurately predict the likelihood for a cargo to liquefy during a voyage is not quantified*. As discussed previously in Section 3.1.1(p. 42), an incorrect TML may have significant financial and safety implications. It is therefore important to assess whether they are fit for purpose.

The current approach to cargo stability assumes that for a given cargo there is a critical moisture content, the FMP, above which a Group A solid bulk cargo could liquefy and so become unstable, but below which the cargo is stable. A simplified analogy between the TML test methods and cargo behaviour is represented in Figure 4.1. In reality, assessing the potential for cargo liquefaction and dangerous cargo shift is much more complex than shown, due to the many dynamic variables that influence actual cargo behaviour, but which are not captured within TML testing.

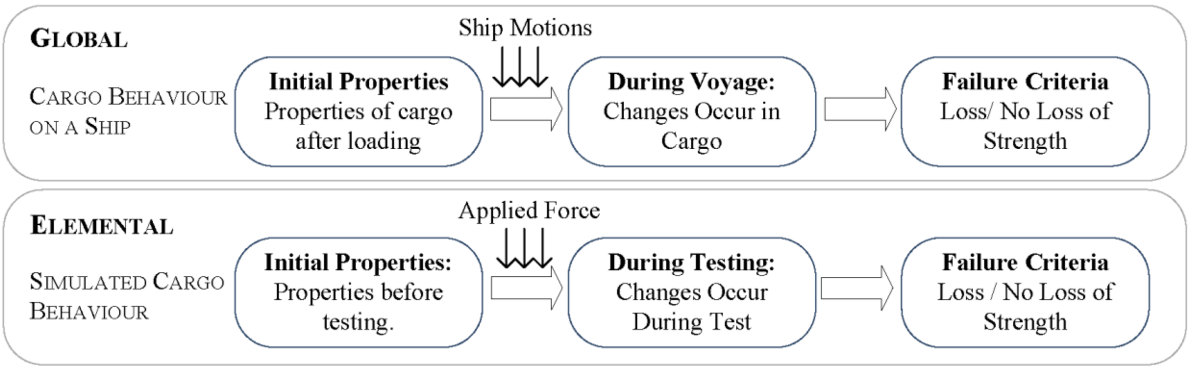


Figure 4.1: Simple analogy between cargo shift and small scale testing.

This section explores these variables in relation to the TML Test Methods and summarises previous work that has aimed to assess cargo behaviour. It then suggests a possible approach for assessing the changes in material properties in a cargo during shipping, based in part on testing of Redhill 110.

4.1 IDENTIFICATION OF THE VARIABLES THAT CAUSE CARGO SHIFT

In order to assess whether the results obtained from elemental test-work accurately represent the global cargo behaviour, it is necessary to give consideration to those variables that cause cargo compaction, a loss of strength and in the worst-case, significant shift. This section extends on the overview of cargo shift that has been developed and presented in Chapter 1 (Figure 1.3, p. 3), to examine those variables and mechanisms that lead to dangerous cargo shift. The work is presented is a in a series of flow diagrams, following the style in Figure 4.2.

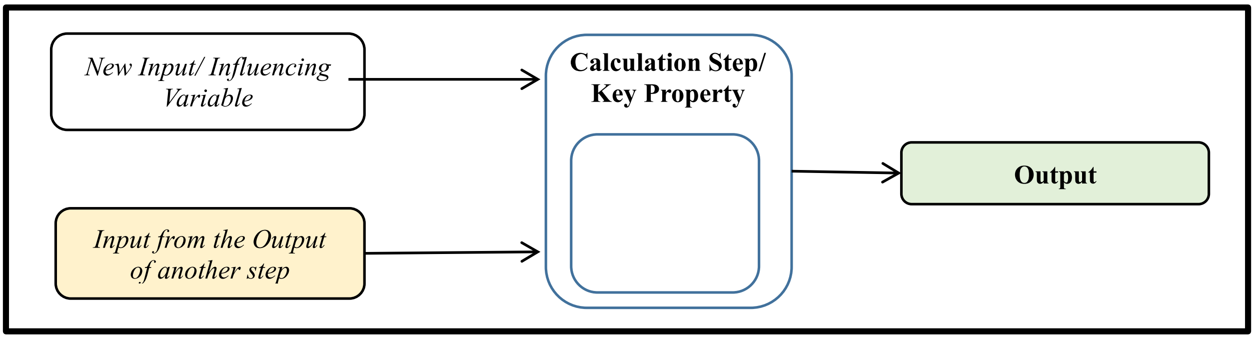


Figure 4.2: Notation for the flow diagrams presented within this section

4.1.1 Properties of the Cargo before a Journey: The Initial State

Prior to loading, a cargo is characterised by unique *granular properties* (such as the PSD, granular porosity, water holding properties, specific gravity) and *moisture content*. The act of ship loading causes compaction of the material that leads to an *initial state* within the hold. In this state, the cargo may be considered as approximately homogenous and is characterised by material properties such as *bulk density* (ρ), initial *degree of saturation* (S), in addition to the *geometry*. Each of these factors, which are unique for a given cargo consignment, influence the strength of the material and its resistance to shift during passage.

Major considerations in an assessment of the cargo's initial state are illustrated in Figure 4.3. This shows the interactions, in terms of the *input drivers* (including physical properties and shiploading practices) that influence the initial state of a cargo in a hold, as characterised by the *outputs* shown in Figure 4.3. Any numerical or elemental assessment of test method accuracy must simulate the cargo's initial state by considering these inputs and outputs.

Key findings from other studies relating to the cargo's initial state are shown in Table 4.1, as developed from a complete review of the literature. Any new assessment of cargo liquefaction should consider and/or incorporate findings from previous work.

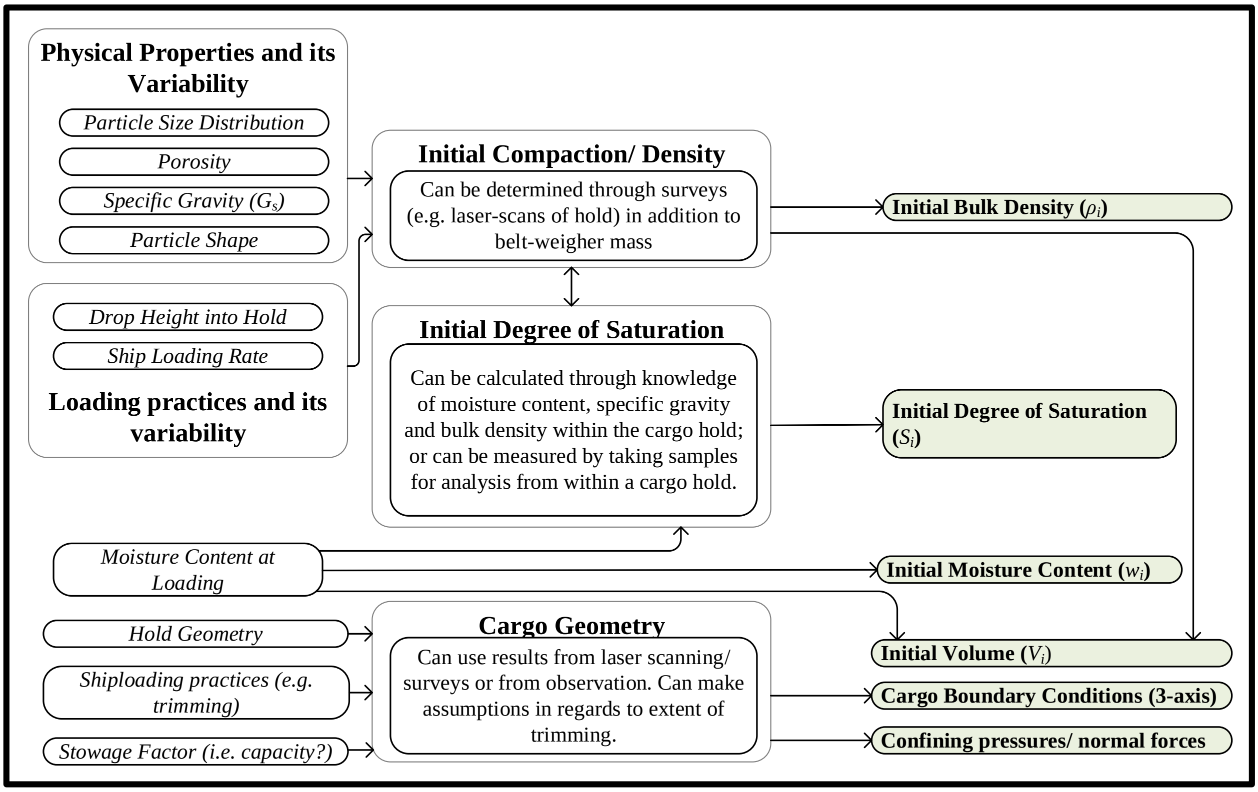


Figure 4.3: Key variables associated with the cargo's initial state, in addition to their influencing parameters and calculation steps.

Table 4.1: Significant findings from other research with regard to the initial state of a cargo.

CONSIDERATION	FINDINGS/OBSERVATIONS
Initial Compaction Characteristics: Effect of Shiploading	The loading process is the critical step in determining initial cargo density. The initial bulk density within a hold will increase as a function of drop height and flow rate, although at a certain threshold, a greater bulk density will not be achieved. (Macrae et. Al., 1961; Lo Presti et al., 1998; Zhang et al., 2001; IMO DSC18/INF.13, 2013) For a Capesize vessel, with a hold depth of ~9-10 m, it is not unusual for the ore to be loaded from around 15 – 20 *m* drop height from the hold. At this height, the density achieved will be the maximum possible density achieved by gravity. Some cargoes dropped below this critical height may be in a loose state in the hold, and these are likely more susceptible to compaction by the forces from the ship's motions.
Initial Compaction Characteristics: Compaction and Density Variation through Hold	Various measurements of density with depth in a cargo hold (cone penetrometer and core samples) have indicated no clear relationship (it varies sporadically through the hold) (IMO BC33/INF.8, 1994; IMO DSC18/INF.13, 2012). However, in one study, cone tip resistance has been found to increase 20-30% with depth (IMO DSC18/INF.13, 2012).
Effect of PSD on the potential to liquefy	Although there is a relationship between the potential for a cargo to liquefy and PSD (*i.e.* due to its effect on void ratio), this has not been defined for bulk cargoes.
Initial cargo geometry	Trimming a cargo reduces the slope angle and the confining pressures at the edges of the pile with lower resistance to shear. The hold design is also an important consideration in preventing cargo shift (*i.e.* self-trimming holds).
Effect of S.G. and unit weight	Heavier materials such as iron and nickel ores will consume less space in the hold and experience greater accelerations for a given volume at a given location within the hold. The normal confining forces at the base of the cargo may be greater these for low density cargoes; and confining pressure will vary more with a given change in height.

4.1.2 The Ship's Motions

Upon commencement of a voyage, the imposed cyclic forces will cause gradual settlement and/or consolidation of the cargo, in turn influencing its strength properties. The degree to which this occurs depends on the magnitude of the ship's **(a)** *rigid body motions*; and/or **(b)** its *vibrations*.

Assessment of **(a)** may be performed by numerical modelling or measurement of the *sea-state* over which the ship travels. This is typically described in terms of significant wave height, frequency and directional energy spread. For a conservative assessment of cargo behaviour, worst-case sea-state conditions should be assumed—these are unlikely to be captured by on-board measurements (although these can validate numerical models). Once sea-state conditions have been established, numerical analysis can then be used to determine a probabilistic account of the ship response through a voyage in terms of its linear and rotational motions (roll, pitch, and yaw)[i]. This response will be unique for a given voyage and will depend on variables including its *heading in relation to the waves*, *loading condition*, and the *vessel size/type/design*.

In regards to assessing **(b)**, it is commonly thought that ship vibrations from the engines and/or propellers may create the conditions necessary for cargo liquefaction (Jonas, 2010; Britannia, 2010). However, on-board measurements have indicated that engine vibrations of a bulk carrier are insignificant in comparison to those from the sea-state—accelerations from ship's vibrations have been measured as less than 0.65 ms^{-2} (at maximum engine revolutions) in comparison to measured accelerations of up to 5 ms^{-2} from vessel roll (during a typical voyage) (IMO BCI/Conc, 1964; IMO DSC18/INF11, 2013). Therefore, it appears reasonable to ignore engine vibrations in an analysis of cargo shift.

Major considerations in an assessment of sea-sate and ship's vibrations, and subsequently the ship's rigid-body motions, are shown in Figure 4.4 and Figure 4.5, respectively. Again, these are given in terms of input/influencing variables, determination methods and required outputs for the cargo shift problem.

Once the time dependent motions of a ship around the three axes (6-DOF) have been determined for a voyage, it is possible to analyse the accelerations at different locations around the ship and within the hold in terms of: (*i*) *amplitude;*(*ii*) *direction*; (*iii*); *frequency/period*; and (*iv*) *number*

[i]See Figure 2.10, pp. 16, for a description of these motions.

of cycles. These values will vary depending on the *location* in reference to the centre of rigid body motion and therefore on the *hold/cargo geometry*.

A numerical or elemental assessment of cargo shift must consider the above interactions. In particular, it must consider the accelerations acting on the cargo material through a voyage, as characterised by the outputs shown in Figure 4.6. Findings from previous cargo shift studies with regards to bulk carrier design, and its impact on motions, have been compiled and shown in Table 4.2.

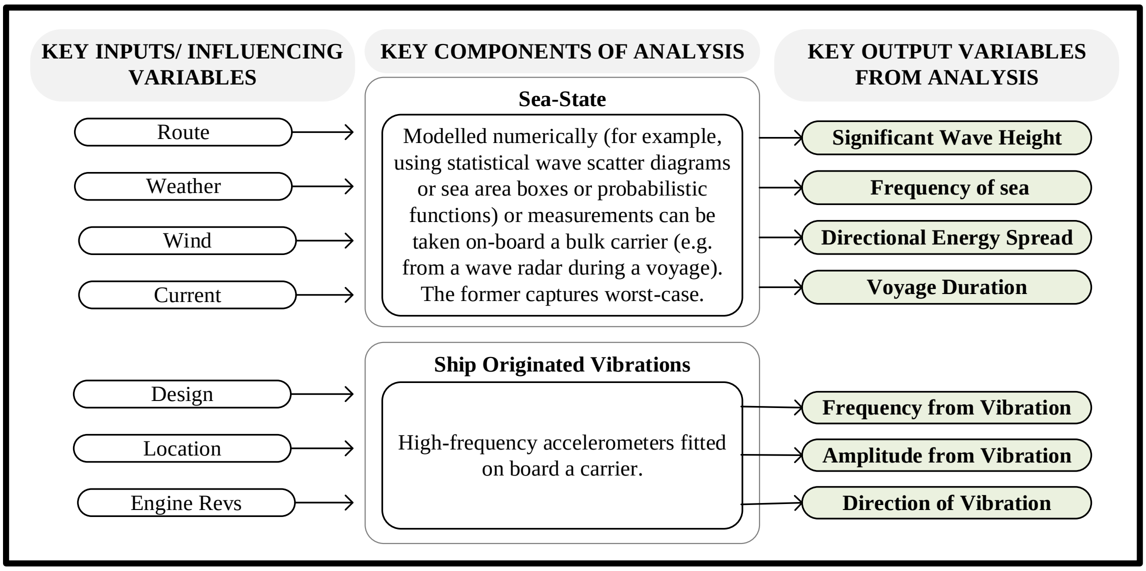


Figure 4.4: Key variables for the assessment of the sea-state and ship's vibrations, in terms of input, output and determination requirements.

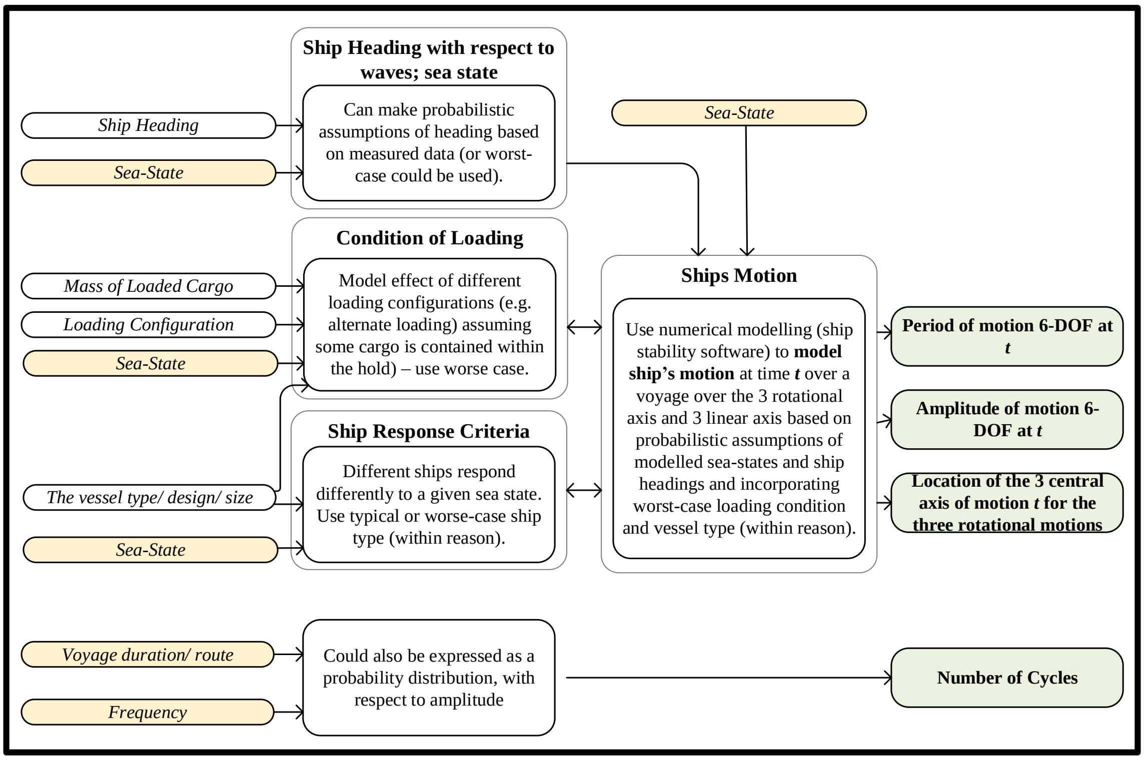


Figure 4.5: Key considerations and influencing variables for an assessment of overall ship's rigid body motions, in terms of input, output and determination requirements.

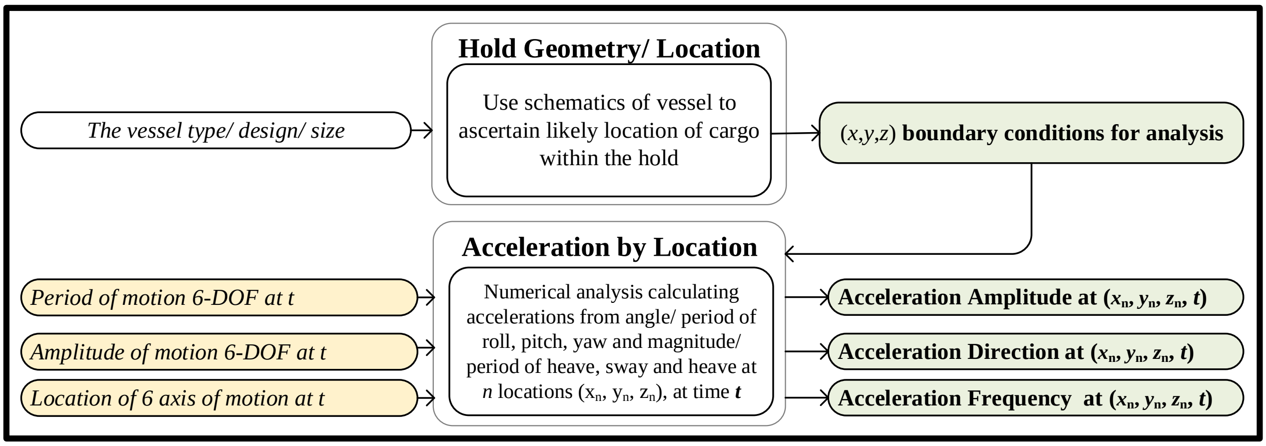


Figure 4.6: Key considerations for the assessment of a ship's motion over a ship and on a cargo, in terms of input, output and determination requirements.

Table 4.2: Overview of significant findings from other studies, with regard to vessel motions and cargo shift.

VARIABLE	FINDINGS
Ship Heading with Respect to the Waves	Roll angle is highly dependent on ship heading. A ninety degree change in course from travelling head on to the waves, to travelling perpendicular, was calculated to result in a 15 degree increase in roll. Changing vessel size had minimal effect on this relationship (IMO DSC18/INF11, 2013).
Location of greatest accelerations on a ship	The edge of the foremost hold of ship has been found to experience the greatest overall acceleration—higher vertical accelerations are experienced here, from vessel pitch and slamming effects (*i.e.* the furthest locations from the axis of rotation). Transverse accelerations from roll tend to be similar for all holds (IMO DSC18/INF11, 2013).
Most significant motions	The accelerations in the transverse (*i.e.* roll) and vertical (*i.e.* pitch) axes are most significant (DSC18/INF11, 2013).
Effect of ship size.	Measurements and numerical modelling indicated that vertical accelerations were approximately 20% greater on a Handysize than on a Capesize carrier (IMO DSC18/INF11, 2013). *Smaller bulk carriers are likely to experience greater rigid body accelerations for a given sea state.*
Ship's Vibrations in comparison to Rigid Body Motions	Accelerations from ship's vibrations have found to be insignificant in comparison to those from rigid body motions (IMO BCI/Conc, 1964; IMO DSC18/INF11, 2013).
Condition of Load	A bulk carrier is designed so that it possesses high transverse stability whilst carrying heavy solid bulk materials and whilst this leads to a more stable vessel, it can also lead to greater accelerations at the deck level (CHB, 2014), although this effect on the bulk cargo is unlikely to appropriately considered in ship design
Frequency/Period of Motion	Frequency of accelerations from vessel vibration are typically (0.5Hz to 1.5 Hz for the engines and 5-10 Hz from the propeller blade) whilst those from rigid body motions occur at natural frequencies of approximately 0.1, 0.056 and 0.52 Hz for roll, heave and pitch respectively (for a Capesize carrier) (IMO DSC18/INF11, 2013).

4.1.3 A Loss of Cargo Strength and Cargo Shift

The effect of the ship's motions on a cargo's behaviour are twofold. Firstly, they cause cargo compaction that either: (*i*) facilitates the development of pore-water pressure, reduction of effective stress and reduction in strength (wet cargoes); or (*ii*) increases cargo strength due to increased relative density and particle inter-locking, leading to more dilation on shearing (dry or wet cargoes). Secondly, given this adopted state of cargo compaction/strength, it is the ship's transverse motions (roll) that cause dangerous displacement to the outer edges of the hold and leads to a list. More specifically, these transverse motions impart shearing forces on the cargo (from gravity when tilting the pile to the horizontal, or from the ship's accelerations) and these may overcome the material's resistance to shear.

Therefore, a cargo's strength will depend on both the initial state and the physical changes of the cargo resulting from ship's accelerations/cyclic forces, whilst those forces which act to disrupt this strength and cause shift also depend on the accelerations/cyclic forces.

Figure 4.7 (overleaf) illustrates how the outputs from the interactions shown diagrammatically in Figure 4.3 to Figure 4.6 then act as input variables in an elemental assessment of cargo shift—the output in this case being the physical changes that occur to the cargo through a voyage, and ultimately cargo strength and cargo displacement. This diagram differentiates between those changes that can be considered to occur over the whole cargo (*i.e. compaction* and the *moisture content/drainage* of the granular material), and those changes that occur at an *elemental* level (*i.e.* pore-water pressure build-up, loss of effective stress within only a small region of the cargo)—although these are interrelated.

Table 4.3 (p. 126) then presents significant findings from other studies, with regards to the changes that occur in the cargo through the voyage.

4.1.4 Loss of Ship Stability

Cargo shift/liquefaction is accompanied by a shift in the global centre of gravity of the ship. This does not necessarily result in a dangerous situation if the impact of the shifted mass on vessel stability is negligible. Main considerations include: (*i*) the stability response of the ship (this will vary for different bulk carrier designs); (*ii*) the overall change in the centre of gravity (which will depend on the total mass displaced and its location in relation to the roll axis); (*iii*) the design of a ship (*i.e.* narrow holds or shifting boards fitted within the hold my prevent significant changes in centre of gravity); and (*iv*) the behaviour of the shifted mass (*i.e.* whether it acts as a free surface like a liquid, or whether it stays displaced to the side of a ship).

Maritime engineering principles can then be used to assess the impact of the displaced mass.

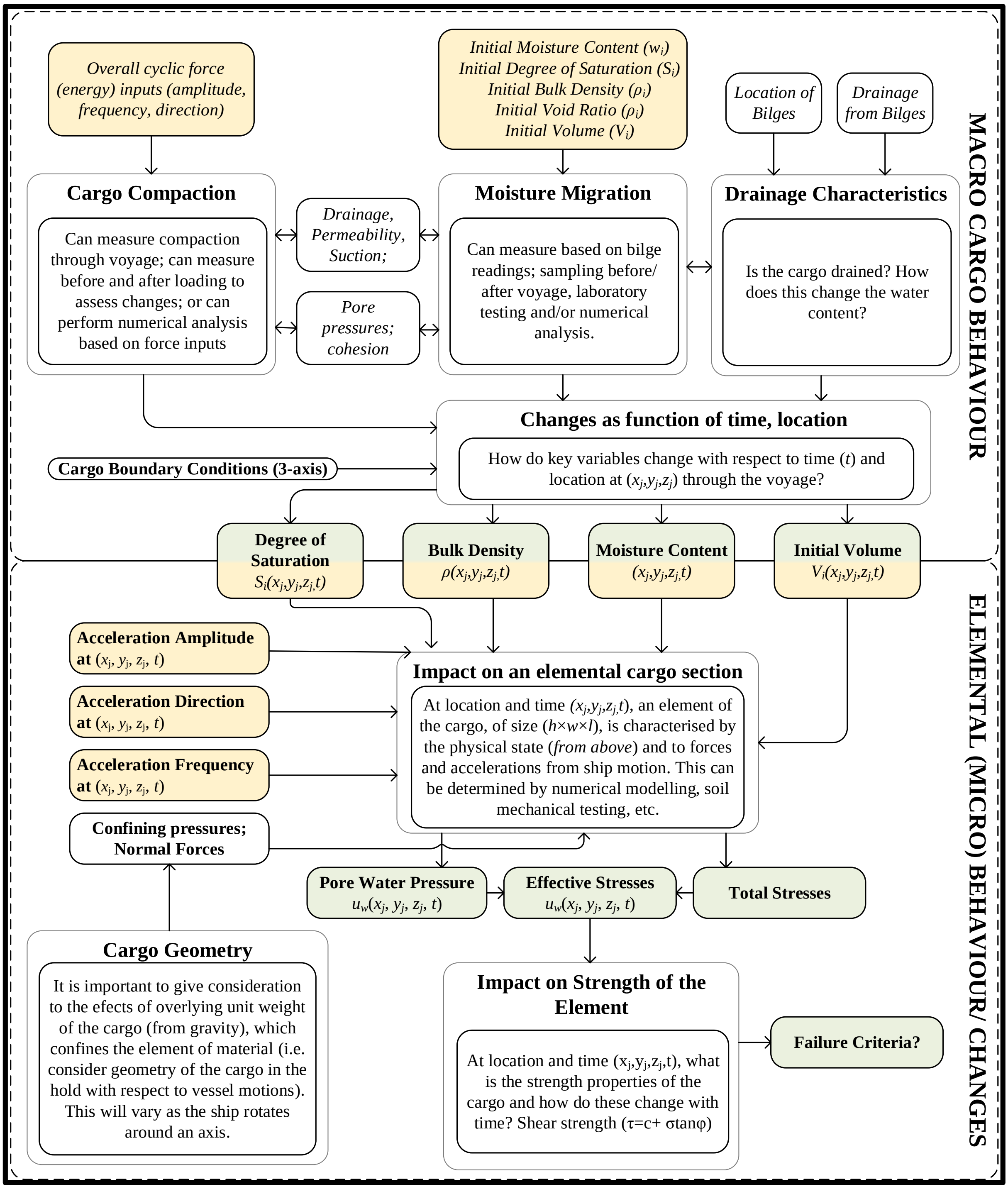


Figure 4.7: The interactions between the inputs, outputs and calculation steps to be considered for an analysis of an element of cargo material.

Table 4.3: Considerations from other cargo shift research, with regards to the changes that occur in the cargo through the voyage

CONSIDERATION	FINDINGS/OBSERVATIONS
Formation of a Saturated Base	Although a cargo may be loaded at a moisture content which is well below the point at which it will flow, the drainage of water through some cargoes may lead to the formation of a saturated bottom layer (Kruszewski, 1988; Kruszewski, 1991; Kruszewski, 1993; Atkinson and Taylor, 1988).
Development of a free surface	Free surface water has been observed to occur for some cargoes (IMO BCIX/12/1, 1970; IMO BC28/INF.4, 1987; IMO DSC18/INF.13, 2013).
Impact of Vibration on Moisture Migration	Vibration appears to have no effect on drainage properties (at the laboratory scale) (Kruszewski, 1988).
Moisture Migration	Moisture migration will usually occur, but will vary for different cargo types.
Effectiveness of the Bilges	There have been concerns expressed regarding the effectiveness of bilges on bulk carriers. Bilges are known to become blocked during passage, by fine cargo material (IMO BC32/INF.10, 1992; IMO DSC17/INF.9, 1992). Secondly, there are often only two of them, and this may be insufficient to facilitate efficient drainage.
Water Holding Ability	Some ores possess a stronger ability to hold water than others; which may impact the likelihood of rapid pore pressure build-up.
The Effect of Compaction on Permeability	As compaction occurs during the journey, the space between voids will decrease and so too will the permeability of the material.
Use of Additives to Absorb Moisture	Polymer materials may prevent drainage of the water from the ore particle's pores. Popek (2012) found that addition of 0.25% of superabsorbent increased the FMP from 21.3% up to approximately 26.3% moisture. However, this is likely impractical.
Fines Migration	There was no measurable evidence of fines migration accompanying water flow through Carol Lake Iron Ore Concentrate (Kruszewski, 1985).
Cargo Compaction	Measured cargo settlement varies for different cargoes, although it almost always occurs (for Carol Lake Concentrate, it was reported between 0.5-1 m, although settlement from 1-2m or greater was reported in over a third of the cargoes) (Kruszewski, 1985). Canada measured a reduction in pile height from 7.5 m to 6.4 m and an expansion around the base in the transverse axis from 18 m to over 18.5 m (IMO BC33/INF.8, 1994). Australian producers reported that cargo volume compaction was typically 1 to 4%, and material in the hold at the front of the ship compacted more than the hold at the back of the ship (IMO DSC18/INF.11)

4.2 THE LIKELY ACCURACY OF THE PFT AND FTT

Section 4.1 showed that a cargo's liquefaction potential, as understood by the FMP, depends on the complex interaction of many dynamic factors. Yet, the TML Test Methods give only a single FMP for a given cargo sample. They are therefore deficient on several counts:

(a) *Vessel motions* and *vibration* will vary at sea, yet are fixed during TML testing;

(b) *Initial material density* and *confinement* conditions are unique for a given voyage, yet constant in TML testing;

(c) *Cargo geometry within the hold* (*i.e.* surrounding cargo material) imparts the necessary forces which cause cargo displacement, yet these are not considered in TML testing; and

(d) *Moisture migration* results in gradual changes in the degree of saturation during a voyage, yet this occurs rapidly at an elemental level in TML testing.

Considering the above, **for the FTT**, on **(a)**: the dropping of the flow table introduces forces to the sample that induces compaction and shear, a build-up of pore-water pressure and subsequent plastic deformation (for a sufficiently wet sample). However there is little evidence to suggest that the forces or frequency of the repeated knocks of the table (15 mm drop height, 25 drops per minute, 50 times) accurately represent those forces experienced on a vessel. On **(b)**: The tamper pressure is adjusted so that it approximately represents the pressures experienced by the cargo material at the base of a hold. However, it is unlikely that the density of the cone—and therefore the volume of voids between particles—truly reflects that in a cargo. On **(c)**: In the FTT, it is unlikely that the unconfined conditions of the cone on the flow table represent an element of material within the surrounds of the cargo. There are possibly thousands of tonnes of surrounding mass confining an element of actual cargo material and this will interact with the element and affect the likelihood of displacement. Any pore pressures that develop in an actual cargo will likely transfer to the surrounding cargo material.

For the PFT, on **(a)**: The PFT is a static test (the sample is not subject to dynamic conditions). However, the manufactured density conditions should represent those on the cargo. So long as this is accurate, the moisture at which the minimum void ratio occurs is likely to represent the point beyond which dangerous pore-water pressures may develop. However, this is unlikely representative of an actual cargo, because of **(b)**: The compaction conditions are fixed in the PFT yet dynamic in an actual cargo. It is unlikely that fixed density achieved by hammer compaction (or thus void ratio) accurately represents that at the *high-risk area* of an actual cargo, which vary over the cargo and during passage. Fagerberg's testing found that the prescribed compaction energy created a void ratio representative of the concentrate cargoes he tested. However, in reality the void ratio of a material within the hold will vary depending on a cargo's physical characteristics, applied vibration and cargo geometry (and therefore on the cargo's initial state within the hold, as discussed in the previous section). Therefore, the compaction energy needs to be adjusted to achieve this representative minimum void ratio. Furthermore, whilst the OMC may represent the point at which the void ratio is minimum, it does not necessarily represent the strength behaviour of actual cargo. For example, it is possible that a wet cargo exhibits reduced strength before or significantly after, the OMC. On **(c)**: For the PFT, the confining forces of surrounding/overlying material are unaccounted for, although if the void ratio and compaction density within the mould are representative of the at-risk areas of the cargo then it should provide an indication of the material's strength.

As an additional consideration, dynamic changes occur during the voyage, such as time-dependent moisture migration and compaction, **(d)**. Neither the PFT nor FTT account for these intermediary states at different locations in the cargo.[i] Prior to testing by the FTT, a material may be only partially saturated. The vertical dropping of the table then causes rapid compaction, which is accompanied by a rapid increase in saturation and pore pressure development that induces plastic behaviour in the test sample (if initial moisture content is sufficient). This is very different mechanism to that in an actual cargo, where compaction and drainage occur only gradually—a saturated region may take many days to develop, if at all. Ultimately, pore pressure development on the FTT is unlikely to accurately reflect that in an actual cargo. In the PFT, the slope of the compaction curve is not considered (*i.e.* the material's relative compressibility)—those materials with a steep compaction curve may compact very rapidly with only minor increases in moisture, and therefore may be more susceptible to shift due to moisture migration. Therefore, a material's response to the dynamic changes such as moisture migration and compaction are ignored in the PFT.

It is clear that both the FTT and PFT do not yield TML results that accurately reflect cargo behaviour. This is especially concerning for the FTT, given that it is by many seen as the 'standard' method for TML determination. When the FTT was being considered for adoption in

[i]In the interest of considering the worst-case liquefaction potential, an element of test material should be subject to the conditions of this high-risk section of the cargo.

the first version of the BC Code it was acknowledged that it was not known if the test provided a *"completely safe [TML] value"* (IMO BCI/5, 1965). Sixty years later this seems to remain the case, yet the TML results from this method are commonly used as a benchmark to compared the TML results given by other methods. For example, during the development of the PTT methodology, applied vibrations were 'calibrated' to give results that match the FTT (IMO BC/5/1, 1990).

4.3 PREVIOUS ASSESSMENT OF CARGO BEHAVIOUR

A range of research efforts have aimed to understand to the behaviour of a cargo at sea. Most testing has been on concentrate cargoes (IMO BC26/5/11; IMO BC26/INF.2; IMO BC28/INF.4; IMO BC32/INF.11; IMO BC32/INF.12; Kirby, 1983; Kruszewski, 1985, 1988; Atkinson and Taylor, 1988, 1994), although coals (Kruszewski, 1985; IMO BC30/5/2, 1990; IMO CCC/1/5/8, 2014, nickel ores (IMO BC33/3/16, 1992; IMO BC33/3/2, 1994) and iron ore fines (IMO DSC18/INF.11, 2012;IMO DSC18/INF.13, 2012) have also been assessed. Testing regimes include soil mechanics testing (such as shear box, triaxial and/or cyclic triaxial), scale modelling (for example, in shipping simulators, scale models and within a centrifuge), on-board measurements and/or numerical analysis (for example, finite element techniques assessing strength drainage). The assumptions and inputs that have formed the basis of any findings have varied significantly amongst the studies, which in many instances makes comparison between these findings challenging and of limited value. To date, no research has been able to adequately capture cargo behaviour or conclusively propose a criteria for assessing cargo shift. Figure 4.8, on page 134, provides an overview of major bodies of work and a brief description of some of these assessments (further detail of these studies are included in table form in Appendix 6). This has been included to provide a point of reference for future cargo shift research.

Broadly, past work has focussed on soil mechanics assessment using either (a) cyclic; or (b) static approaches.

4.3.1 The Cyclic Approach

It is widely accepted that a rise in pore-water pressure develops from cargo compaction that occurs due to the ship's cyclic motion. As a result, recent investigations have focussed on assessing cargo shift through consideration of a cargo's cyclic behaviour by cyclic triaxial tests (DSC18/INF.13, 2013). The approach has been analogous to soil liquefaction during an earthquake, whereby tests are performed in undrained conditions. Failure criteria have included:

(a) *pore-water pressure* (for example, >95% confining pressure [IMO DSC18/INF.13, 2013])

(b) *axial strain*, which could indicate excess shear stress rather than liquefaction (for example >5% [IMO DSC18/INF.13, 2013] or >10% [Ura, 1983a, 1983b, 1983c, 1983d]); or

(c) *cycles survived*.

Recent investigations conducted jointly by Australia and Brazil (2013) have assessed the liquefaction potential of several iron ore fines cargoes during a voyage. In this study, finite element analysis on a model cargo hold was used to determine the induced cyclic shear stress ratio through a cargo during a voyage. This was then compared to the cyclic shear resistance (CSR) obtained by cyclic triaxial testing at varying degrees of saturation. Here, the test sample was initially loaded in unsaturated conditions and then saturated conditions were reached during the test, due to compaction and a reduction of void ratio from the applied cyclic stresses (IMO DSC18/INF.13, 2013). The investigators found that the measured CSR exceeded the modelled induced cyclic shear stress ratio, at all degrees of saturation. From this, it was concluded that liquefaction could not occur for these iron ore fines in a worst-case sea-state (DSC18/INF.12). More details on the outcome of this cyclic study is included in Appendix 7.

However, there are many differences between cargo failure that causes shift, and failure within an earthquake or seabed, namely:

(a) The *accelerations* generated by vessel motions may differ considerably to those generally experienced by a soil, whereby (cyclic) loads are applied by both vibrations from the ship's engines and by the linear and rotational motions from ship rigid body motions (in six-degrees of freedom).

(b) *A cargo is typically unsaturated following loading*, with time dependent moisture migration occurring through a journey. In earthquake engineering, soils are typically considered saturated. In a cargo, only a small base layer may be saturated, if any at all.

(c) *Loading frequency* from earthquakes is much higher than from the ocean (around 0.1 Hz for roll compared to >1 Hz), yet there are *far more cycles* in a storm. Consequently, any generated *pore pressure may dissipate* by drainage before the next loading cycle and *considering the undrained strength may not be appropriate*.

(d) Significant *inhomogeneity in material properties may develop through a voyage*, whereas in earthquake engineering this may be less significant;

(e) Accelerations are of interest in earthquakes, where there is little differential movement in the soil. For a cargo, it is likely the *displacements* with respect to gravity, which are of interest. For example, the shearing/normal forces due to gravity will vary during ship's motions such as roll (accelerations aside from gravity are reasonably minor, ship's vertical accelerations may rise up 1g in a storm but are typically less than 2 ms^{-2} during a common voyage).

(f) There is significant *inhomogeneity of strain and differential movement within a cargo*, compared to in a soil during an earthquake.

The Author therefore believes that the behaviour of an element of cargo material, under low frequency undrained cyclic loading gives an unrealistic account of the dynamic cargo behaviour as whole.

4.3.2 The Static Approach

A few studies have taken a static approach to assessing cargo shift, whereby a cargo's static strength properties (friction angle, cohesion) have been assessed by soil mechanics testing (shear box or triaxial testing), often at a range of moisture contents. In some studies, static test results are input into analysis of slope failure within a cargo, using simplified hold and cargo geometries for different angles of applied heel and/or roll (Atkinson and Taylor, 1988, 1994; IMO BC32/INF.11, 1992; IMO BC32/INF.12, 1992; IMO BC33/3/2, 1994). However, these studies also likely under-represent cargo behaviour due to limitations associated with applying static soil mechanics to highly dynamic conditions. Further limitations are as follows: (*i*) focus has been primarily on static shear strength, widespread liquefaction is typically ignored; (*ii*) the material properties have been assumed to be generally uniform throughout the cargo (for example density, moisture and degree of saturation) as cyclic time dependent changes aren't considered; and (*iii*) the static strength failure criterion is applied globally over the cargo (*i.e.* failure of the element represents failure of the cargo). Appendix 8 presents the outcome of one static study on iron ore concentrate.

4.3.3 Scale Modelling

The behaviour of a cargo has also been assessed by applying cyclic loads to scale models of a ship's holds (IMO BC28/INF.5, 1987; IMO BC32/INF.12, 1992; Koromila et al. 2013; IMO DSC18/INF.12, 2013), drainage columns (Kruszewski, 1985, 1988, 1991; Kruszewski et al. 1993), and in centrifuges (Atkinson and Taylor, 1988; 1994; Atkinson et. al, 1991)—the latter attempting to address scaling laws with regards to moisture migration. In these studies, focus has been on characterising the behaviour of the test material with respect to changes in moisture content and sometimes accelerations. However, no scale test-work appears to have accurately captured cargo behaviour. In most cases, this appears to be due to the difficulties associated with applying scaling laws to the problem (including scaling of accelerations, particle size, relative densities, moisture migration and confining pressures). For example, one investigation reported observing standing waves in a wet cargo upon applying accelerations at a frequency of 1Hz to a very wet material (Kaloumenos, 2013; Spandonidis, 2013). However, it is unlikely that this would occur in an actual cargo where the roll period is only around 0.1 Hz and inertial forces are only minor.

4.3.4 Other Issues with Previous Approaches

Previous research in the area of cargo shift has often been initiated in response to a major accident(s) or potentially disruptive regulatory change. It appears, from an in-depth assessment of the development of international shipping regulation since 1965 that this is because

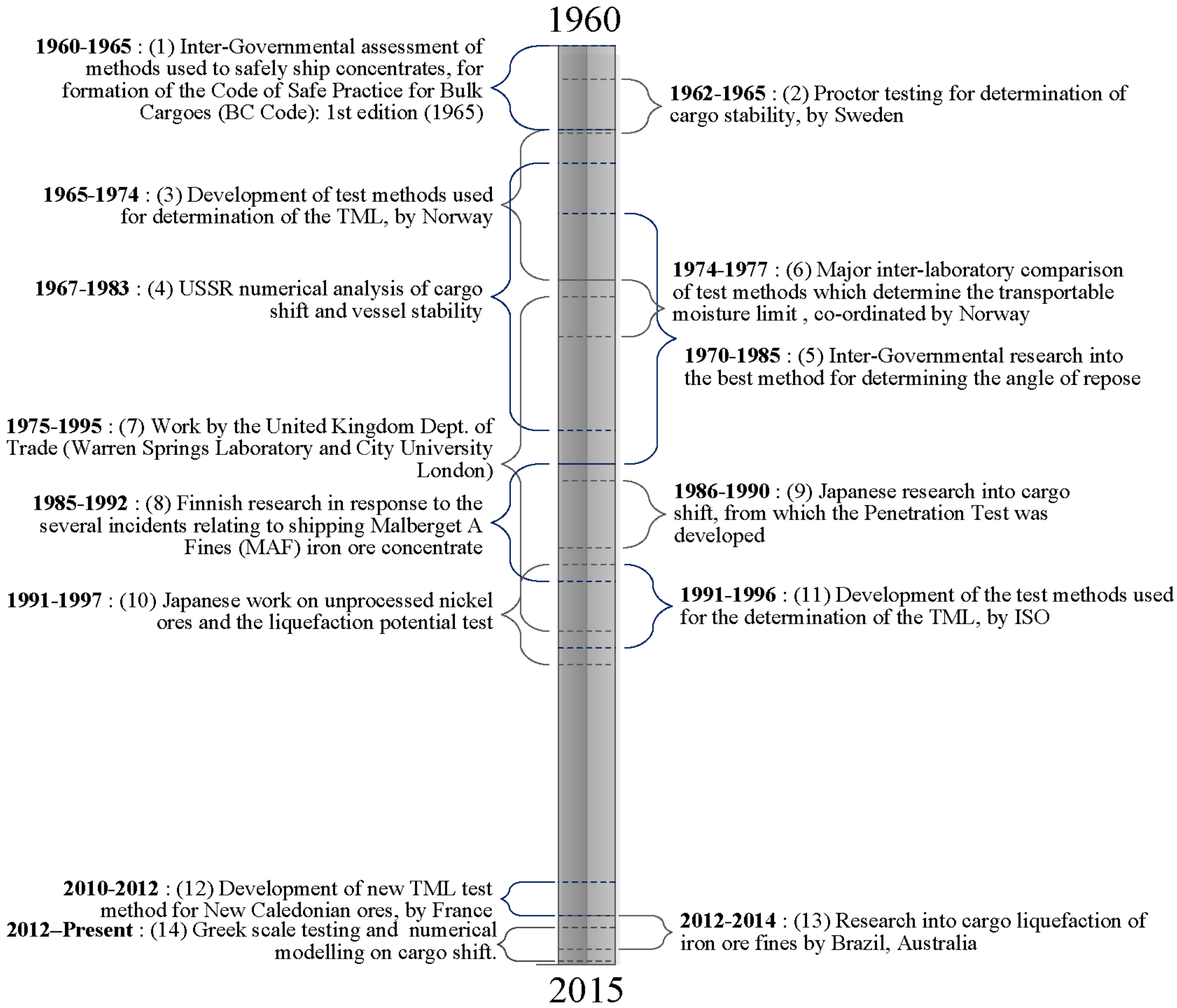
(a) research has often been initiated in reaction to a particular incident, often with a *vested interest*;

(b) most approaches have *focussed on a single discipline* (usually maritime, soil-mechanical or regulatory) and therefore only a small part of the broad problem is addressed and holistic interactions are not captured, resulting in conclusions that are not fit-for-purpose;

(c) target stakeholders within IMO (for example, ex-Master's or legal representatives) typically do not have the expertise to interpret the technical research results;

(d) only *limited cargo types have been assessed* and the findings have not been applied more widely for a range of cargoes; and

(e) there have been many *repeated research efforts* because the results and findings from most of this research are not available to the general public (*i.e.* prior to 1998 it only exists in hardcopy only available within the IMO archives). Therefore some areas have been comprehensively explored (for example, moisture migration) whilst many have significant gaps (for example, the accuracy of the test methods).



No.	REFERENCE(S)
1	BCI/Conc xxx
2	BC(II)/Conc/12; BC29/INF.3; BC29/5/7; BC29/WP.3; BC30/5/2;' BC32/3/17; BC27/WP.1
3	BCXIV/4; BCXV/Inf.3
4	BCXII/7/1; BCXIV/4/1; BCXV/(b)'; BCXV/4(a)/3; BC30/5/10; BCXIX/6(d)/2; BCXX/5/3; BCXXII/5/6; BC23/5/16; BC24/5/15
5	BCVXIII/6; BCVXIII/6/1; BCVXIII INF papers I, J, K and L; BCXIX/6; BCXX/INF.5 ; BCXXII/5/12; BC26/INF.2; BC23/INF.4; BC25/INF.7./Rev.1; BCXVII/3(d)/1; BCXVIII/6/2; BCXIX/6/1
6	BCXVI/WP.2; BCVII/3(b); BCXVII/3(b)/Add.1; BCXVII/WP.6; BCXIX/6/1; BCXIX/6/1/ Add. 1
7	BCVI/4(e)/1; BCVXIII/Inf.2; BC25/5/6; BC.29/INF.7; BC31/INF.2; BC31/INF.3; BC32/WP.2; BC32/INF.3; BC32/INF.7
8	BC32/INF.11
9	BC28/INF.5; BC29/5/11; BC30/5/1; BC31/INF.4; BC31/INF.5; BC32/3/16;
10	BC32/3/16; BC32/WP.2; DSC2/12/1; DSC3/11/2 ,DSC2/12/1; DSC3/11/5; DSC4/5/4; DSC4/5/5; DSC6/5/3'; DSC 6/WP.4;
11	BC32/INF.6; ISO 12742:2007: Copper, lead, and zinc sulfide concentrates: Determination of TML by the Flow Table Method
12	DSC 16/4/10, DSC 17/4/2 ; E&T 17/5/1; DSC 17/4/41
13	DSC 16/INF.4 ; E&T17/ 2/2; E&T/Inf.2; DSC 17/4/24; DSC 17/4/34; DSC 17/Inf.2; DSC17/Inf.9/ DSC17/Inf.10; DSC17/INF11; DSC17/INF15; E&T18/2/1; E&T18/Inf.2; DSC18/6/13; DSC18/6/14; DSC18/6/27;DSC18/6/28; DSC18/6/29; DSC18/Inf.9; DSC18/Inf.10; DSC18/Inf.10/Corr.1; DSC18/Inf.11; DSC18/11/ Corr.1; DSC18/Inf.12; DSC18/Inf.12/Corr.1;DSC18/Inf.13;DSC18/13/Corr.1
14	(; I.A. Koromila, C.C. Spandonidis, K.J. Spyrou ., 2013), (Christos C. Spandonidis and Kostas J. Spyrou , 2013),(Christos C. Spandonidis & Kostas J. Spyrou, 2012)

Figure 4.8: Some of the major bodies of work that have been performed in regards to assessing cargo shift and cargo liquefaction.

4.4 A PROPOSED APPROACH

As demonstrated in the previous sections, the ship's motion leads to cargo compaction during a voyage. These macro changes to the cargo arise from *changes at an elemental level*, whereby the applied forces cause inter-granular response and particle rearrangement—whether it be only slight rearrangement (causing compaction) or drastic (causing cargo shift). Similarly, the overall drainage that occurs through the cargo is dependent on elemental behaviour such as the space between voids (ultimately a function of compaction), the suction that impedes drainage (a function of compaction and initial moisture content) and therefore the permeability of the material.

In cyclic triaxial testing, the sample is typically prepared at a given degree of saturation, moisture content or void ratio and then the cyclic forces (which are intended to be representative of those within a cargo) result in gradual compaction of the test material, a decrease in void volume and increase in saturation. Eventually, for saturated materials a critical void ratio may be reached whereby a rise in pore-water pressure will result in a loss of effective stress and failure of the material. For partially saturated materials, pore pressures may not change much, but the sample may fail axially. Whilst this may in principle be equivalent to the overall global mechanism that causes liquefaction within a cargo, it is not evident that this phenomena is represented by testing an element of material under undrained, fully saturated or partially saturated cyclic triaxial conditions.

More specifically, further to the general issues outlined given in the previous section, previous cyclic assessment of a cargo is deficient on several counts:

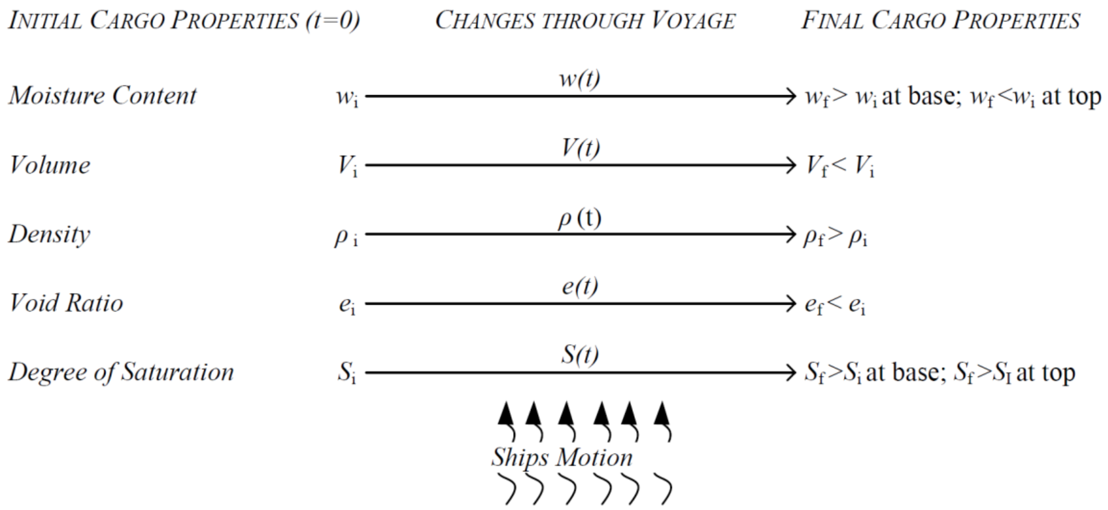
(a) As this testing is performed in undrained conditions, moisture variation through the cargo (arising from moisture migration) is ignored. In a vessel this will result in some sections of the cargo increasing in moisture content and degree of saturation, whilst others will become drier. Some sections may lose strength, whilst others may gain strength;

(b) In a cargo, cohesion/suction from surrounding material will increase its strength relative to that observed within undrained element testing; and

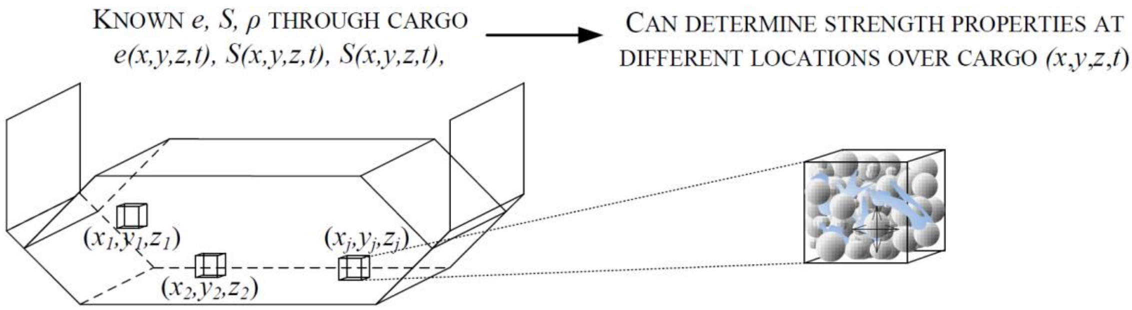
Notwithstanding its relevance, it is proposed that the complex cyclic ship motions and inter-particle interactions that cause compaction in an element of cargo are initially considered separate to an assessment of the changes in material properties through a cargo (*i.e.* S, ρ, etc.), and instead the easily measured *overall* cargo changes be considered. These can be easily obtained by measurement of, by example, total volume, moisture content and mass before and after a voyage. Then, by approximating how these properties may change during the voyage (for example, from knowledge of compaction and moisture migration), a profile of the likely material properties can be assumed throughout a cargo and from this static or cyclic soil mechanics tests can then be used to ascertain the likely strength properties at targeted points over the entire cargo mass, during a voyage.

More specifically, it is proposed that cargo strength be ascertained by a staged assessment as follows:

(1) *Characterising the large scale material changes that occur in the cargo due to a ship's motion, based on easily obtainable data and from these, approximate how these values change with time (see w(t), V(t), ρ(t), e(t), S(t) in diagram below) at different locations within the cargo:*

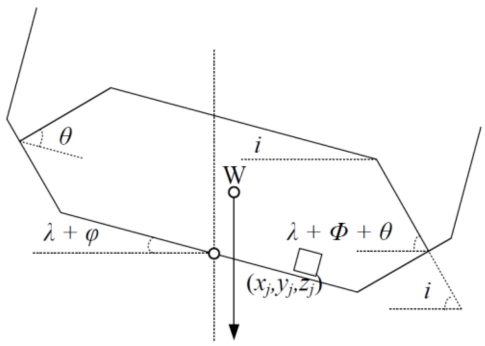


(2) *Determining the likely strength properties of the cargo at different cargo locations from soil mechanics testing:*



(3) *Then, given these strength characteristics through the cargo and the cargo geometry, an assessment can then be performed to ascertain whether the ship's transverse motions are sufficient to cause cargo displacement:*

GIVEN THE STRENGTH PROPERTIES AT DIFFERENT LOCATIONS OVER CARGO *(x,y,z,t)*, CAN THE IMPACT OF THE SURROUNDING CARGO MASS AND FORCES FROM SHIPS MOTIONS (ROLL) LEAD TO DISPLACEMENT?



φ = angle of roll
λ = assumed heel/ list
θ = angle of repose/ trimmed slope
W = Weight from gravity and ship motion
i = slope angle at a given roll list angle of the ship

For sliding en masse
$i = \lambda + \theta$
For slope failure
$i = \lambda + \Phi + \theta$

(4) *From application of the above assessment, it is possible to determine if displacement is possible. Then, its overall effect on the centre of gravity can be then be ascertained by consideration of ship stability information. A failure criteria can then be established for dangerous shift.*

This assessment differs from previous approaches because of Step 1, where time dependent changes in material properties are considered, through a macro assessment.

Note: The endpoint of any test criteria for practical application must be derived from the *as-loaded moisture content, bulk density, specific gravity and/or particle size distribution*, as only these variables are known for every cargo consignment and therefore only these variables can be used to ascertain whether this cargo may liquefy (*i.e.* currently moisture content [TML] is considered).

4.4.1 Exploring the Cargo's Physical Changes during a Voyage

Whilst the phenomena of cargo compaction and moisture migration may be understood by considering changes at the elemental scale, in practice it is very difficult to measure these small scale changes that occur during a voyage. Conversely, the overall physical changes that occur over the cargo—characterised by variation in the bulk density (ρ) (or unit weight (γ)), volume (V) and moisture content (w) can be easily obtained by measuring these before and after a voyage; these are documented for some different cargoes.

This section presents a method by which elemental scale changes in the cargo's dynamic compaction and moisture migration characteristics can be deduced from easily measurable large scale changes; incorporating the findings using Redhill 110 and also the measurements and observations taken by other researchers. Once these cargo characteristics are deduced, they can then serve as inputs into elemental soil mechanics test-work, again considering the elemental response separate to macro influences. Key outputs for this work are:

(a) Density at a given element in the hold;

(b) Moisture content of a given element in the hold; and therefore

(c) Degree of saturation of a given element in the hold.

4.4.2 Assumptions

4.4.2.1 Cargo Geometry

Figure 4.9 shows possible notation for an analysis of a cargo element in a cargo hold. Note that for analysis over multiple ship holds, these axes may be defined over the entire ship, with multiple boundary conditions (as ship accelerations will vary for different holds).

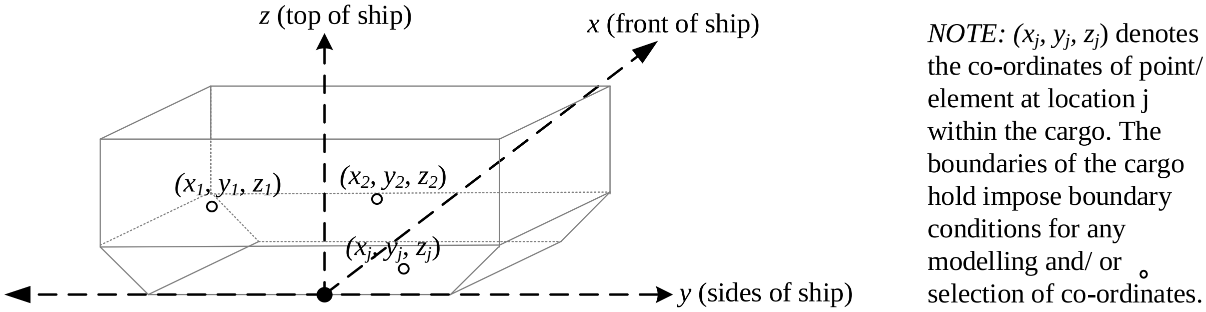


Figure 4.9: Schematic which shows the possible axes notation and the boundary conditions

In the following analysis, only a single dimension is considered (cargo depth), with respect to time (due to time and resource restrictions) However, for greater accuracy, multi-dimensional analysis should also be performed.

4.4.2.2 Initial Cargo Properties

In the cargo's *initial state* (denoted as subscript *i*), immediately prior to loading (t=0), the entire cargo within a hold may be characterised by its average initial moisture content (w_i [% by dry mass]), total mass ($m_i\left[\text{kg}\right]$), initial bulk density ($\rho_i\left[\text{kgm}^{-3}\right]$) and specific gravity ($G_s$). Typically, reasonable homogeneity could be assumed through the cargo in each hold, and therefore at given location (x_j, y_j, z_j) within the cargo (Figure 4.9). The key material properties will be the approximately the *same at both the macro and elemental level*:

$$\begin{aligned} \rho_i(x_j, y_j, z_j) &\approx \rho_i \\ G_s(x_j, y_j, z_j) &\approx G_s \\ w_i(x_j, y_j, z_j) &\approx w_i \end{aligned} \tag{4.1}$$

From these variables alone, it is then also possible to determine other important cargo variables through the cargo including the initial volume ($V_{i,}$), dry bulk density ($\rho_{i,dry}$), average void ratio (e_i) and therefore initial degree of saturation (S_i), whereby:

$$V_i\left[m^3\right] = \frac{m_i\left[\text{kg}\right]}{\rho_i\left[\text{kgm}^{-3}\right]} \tag{4.2}$$

$$\rho_{i,dry} = \frac{\rho_i}{1 + w_i} \tag{4.3}$$

$$e_i = \frac{G_s}{\rho_{i,dry}} - 1 \tag{4.4}$$

$$S_i = \frac{w_i G_s}{e_i} = \frac{w_i G_s \rho_{i,dry}}{G_s - \rho_{i,dry}} = \frac{w_i G_s \left(\rho_i \middle/ (1 + w_i) \right)}{G_s - \left(\rho_i \middle/ (1 + w_i) \right)} \tag{4.5}$$

Note that other researchers have often used S_i as the starting moisture for test-work (*i.e.* the test sample is often prepared/compared to this moisture in TML or soil mechanics test work). However, as demonstrated below, this is incorrect—*S* (and therefore moisture content) will over the voyage and this will affect the cargo's strength properties.

4.4.2.3 Overall Changes in Moisture over a Voyage

If a ship's bilges are operating effectively then the volume of water (V_{water}) in the cargo will decrease and thus the **final average moisture content** of the entire cargo (w_f [%by dry mass]) will be lower than at loading. This can therefore be expressed in terms of the volume of bilge-water pumped out (V_{bilge}) and the known initial moisture content (w_i) and loaded mass (m_i) by:

$$w_f = \frac{\left(m_{water,i} - m_{\text{bilge}}\right)}{\left(m_{dry,\text{i}}\right)} = \frac{\left(\frac{m_i w_i}{1+\ w_i} - V_{\text{bilge}}\right)}{\frac{m_i}{1+\ w_i}} = w_i - \frac{V_{\text{bilge}}(1+\ w_i)}{m_i} \tag{4.6}$$

However, as doubts have been expressed about the effectiveness of operating bilges (IMO BC32/INF.10, 1992), if no drainage occurs and evaporation is considered negligible then it can be assumed that w_f=w_i (*i.e.* all mass is conserved). Note that the moisture content may still vary through the cargo, as explained below.

Moisture migration/drainage characteristics of a cargo can be predicted or measured (for example, by element tests such as a drainage column, numerical analysis or from measurements within a cargo) and these curves will be unique for different materials, at different degrees of compaction and initial moisture contents (*i.e.* permeability is a function of these). A typical one-dimensional curve of moisture drainage behaviour through a cargo is shown in Figure 4.10 (note how these differ for different initial moisture contents). For a given cargo, under a given set of loading conditions, there is likely to be a minimum moisture content (w_{min}), corresponding to a moisture where no drainage occurs due to suction, and a maximum moisture content (w_{max}), where saturation is reached and water completely fills the voids between particles.

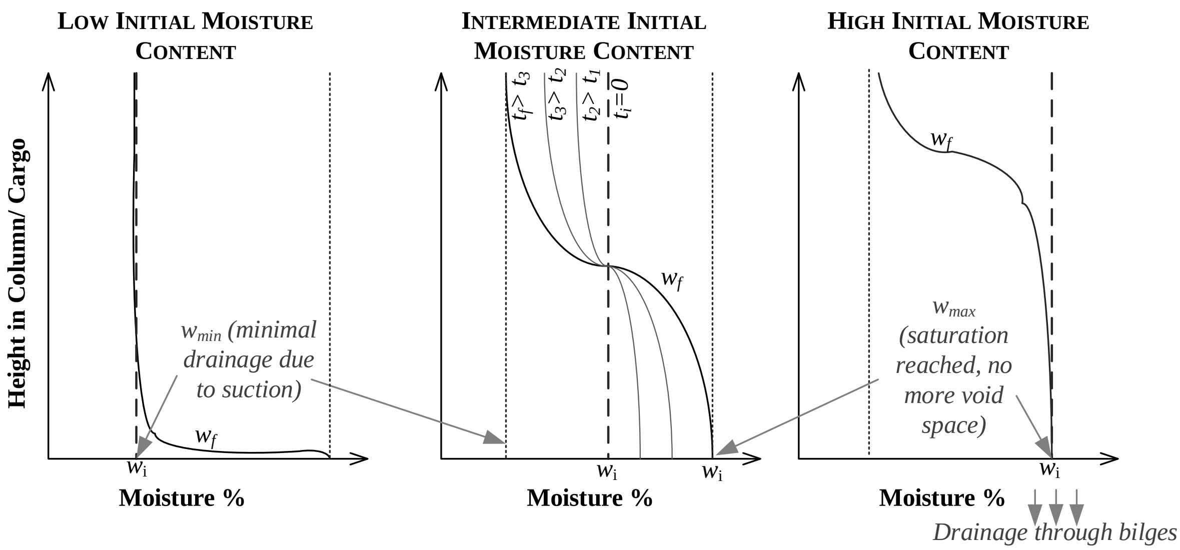


Figure 4.10: Typical water drainage characteristics that could be expected to occur through a cargo at different initial moisture contents (under part drainage through the bilges). Most solid bulk cargoes are loaded within the intermediate range (*i.e.* w_{min}<w_i<w_{max}) and therefore the formation of a saturated base is likely. Note that this only shows two-dimensional flow and is therefore significantly simplified (three-dimensional flow can be numerically modelled)

4.4.2.4 Overall Changes in Volume over a Voyage

During a voyage, the cargo's **final volume** $V_f\left[m^3\right]$ can be expected to decrease due to cargo compaction and this can be expressed by:

$$V_f = aV_i; \tag{4.7}$$

Where a is less than one and represents the compaction that occurred through the journey (this will vary depending on the cargo type, the initial properties from above, and the applied energy—reported compaction is typically 2-10%).

4.4.2.5 Overall Changes in Bulk Density over a Voyage

Assuming mass balance of dry cargo through the voyage ($m_{f,\,dry} = m_{i,\,dry}$), then overall dry density ($\rho_{f,dry}$) increases as a function of the change in volume (a), whereby:

$$\rho_{f,dry} = \frac{m_{f,dry}}{V_f} = \frac{m_{f,dry}}{aV_i} = \frac{m_i}{(aV_i)(1+\ w_i)};\ \text{ where } a<1 \tag{4.8}$$

4.4.3 Assessing the Cargo's Physical Changes through a Voyage

4.4.3.1 Changes in Volume:

In order to assess the effects of moisture content on the compaction characteristics of a granular material under constant cyclic load, Redhill 110 sand was prepared to a range of moisture contents (11-26%), filled into a 1 meter Perspex tube and then subject to a constant cyclic vertical load by repeated knocks of the flow table (one drop per second)[i]. The results from this assessment are shown in Figure 4.11.

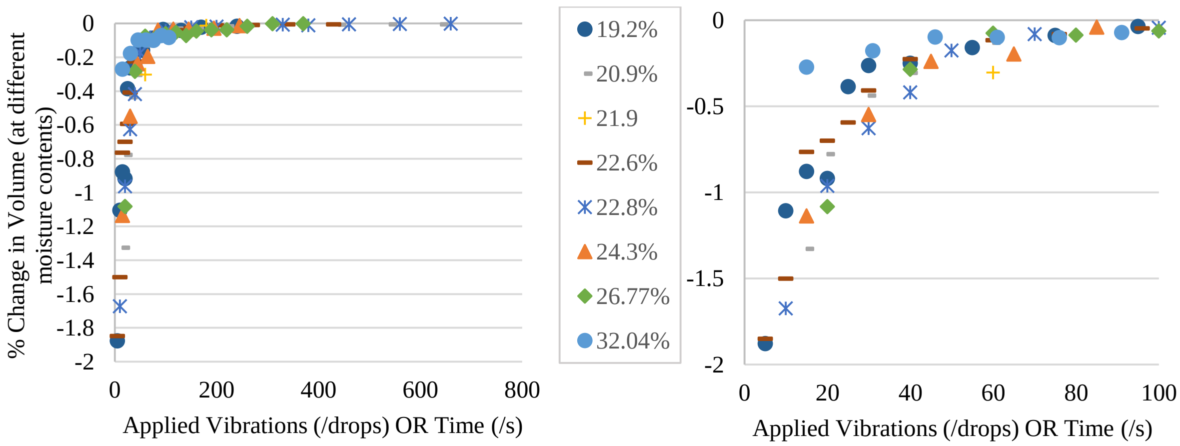


Figure 4.11: Percent change in volume of the dry mass of Redhill 110 at various w_i above and below saturation (applying 1 Hz cyclic forces by dropping the flow table).

[i]Note that the magnitude of the cyclic force is unlikely to accurately represent that of a cargo—however these tests were performed to provide insight into the cyclic motion-volume relationship at different moisture contents.

This indicated that if sufficient moisture migration can occur within a sample of material subject to cyclic vibration, then compaction of the granular portion of material with respect to time occurs approximately exponentially and almost independently of the initial moisture content or degree of saturation. At high moisture, after a certain number of knocks, a layer of free surface-water would develop above the granular material and negligible gross volume change would occur.

It was found that for a given cargo the shape of this curve depends on the compaction energy and also on the initial state, *i.e.* 'looseness', of the cargo. Figure 4.12 presents a qualitative assessment of these effects.

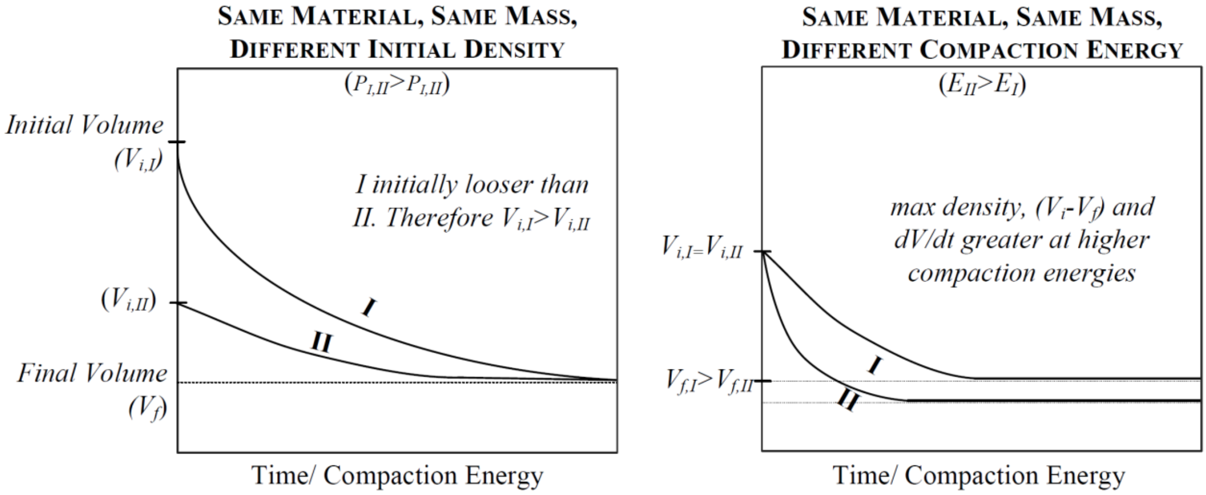


Figure 4.12: Schematic illustration of typical compaction curves obtained when a constant energy is applied to a sample (through vibrations), with respect to time.

Therefore, for a known initial volume and (V_i) and final volume (V_f), the compaction of Redhill 110 over the duration of a voyage can be approximated by:

$$V(n) = (V_i - V_f) \times E(n)^n + V_f \text{; where } 0 \leq E(n) \leq 1 \text{ and } n = No.\ of\ cycles \quad (4.9)$$

Where the variable $E(n)$, which ultimately affects the rate of compaction, will be unique for a given material type and applied compaction energy (and therefore ship's motions).

In the case where compaction energy is constant with respect to time, $E(n)$ can be approximated by a constant (say, E), where the rate of change of $V(n)$ during compaction is given by:

$$\frac{dV}{dn} = (V_i - V_f) \times E^n \ln E \quad (4.10)$$

For Redhill 110 material, E was determined to be 0.96—the measured results for Redhill 110 sand in comparison to the calculated results (*i.e.* with V_i and V_f and E=0.96) is shown in Figure 4.13. This comparison indicates that Equation 4.9 can provide a reasonable indication of changes in volume during a voyage (although it overestimated the measured volume at lower degrees of compaction and underestimated the volume change at higher degrees of compaction, likely due to the effects of a rise in pore-water pressure that may occur). It also highlighted that where drainage can occur (and a free surface can develop) there was no significant dependency on moisture content in respect of shift.

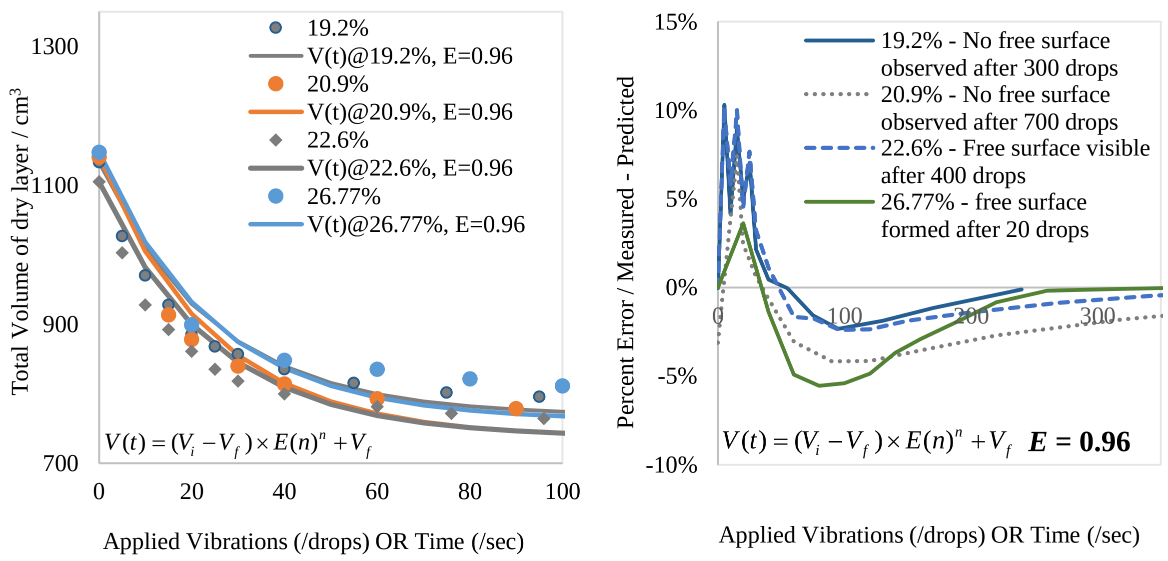


Figure 4.13: *(a)* A plot which shows the compaction characteristics of Redhill 110 with time (at an applied compaction energy of one flow table drop per second) in comparison to the curve predicted from Equation 3.9, with the variable E optimised to 0.96 *(left)*; and *(b)* the percentage error from the fit, for the different moisture contents at applied vibrations *(right)*.

Although practical limitations prevent the measurement of real-time compaction behaviour through a voyage, Equation 4.9 could be applied to an actual cargo to approximate volume change/compaction—where E may be obtained through measurements during a voyage, or from laboratory tests, on an element of the cargo material at a given moisture content in consideration of the known change in volume. However, for this to provide a reasonable approximation, the following must be assumed during an actual voyage: (*i*) reasonably *constant compaction energy* is applied (*i.e.* compaction is not the result of 'one-off' cyclic anomalies); and (*ii*) compaction occurs at a sufficiently low rate to enable *sufficient drainage* through the cargo during the voyage. Although the former is difficult to ascertain, the latter, based on real-life observations of the formation of free surface, is likely to occur.

With knowledge of a cargo's relative densities and V_i and V_f, it may be possible to then use laboratory tests to back-calculate the compaction energy generated by the ship's motions.

4.4.3.2 Changes in Degree of Saturation

Once both *V*(*t*) and *w*(*t*) have been approximated for a cargo (where *w*(*t*) is also a function of location (x_j, y_j, z_j) within the cargo), it is then possible to assess the changes in S that occur at different elements within the cargo.

Presented here is a simple one-dimensional analysis where **each element will reduce in volume through the voyage, whilst assuming conservation of dry mass** (which appears a reasonable approximation given findings from Redhill 110 and from bulk density measurements taken through actual cargoes, which have indicated that density change is negligible through a cargo pile of material). More specifically, a cargo of depth *h* may therefore be divided into *x* horizontal slices through the cargo (see Figure 4.14), where each slice represents the n^{th} horizontal portion of the cargo extending from depth $h(n-1)/x[\mathrm{m}]$ to $h(\mathrm{n})/x[\mathrm{m}]$ (Figure 4.14). *Initially (at t=0), each slice of volume V_i/x is initially homogenous but after the voyage commences (t>0), each slice will decrease in volume* as a function of *V*(*t*) (Equation 3.9) *due to cargo compaction and meanwhile each slice will obtain its own unique material properties due to moisture migration.*

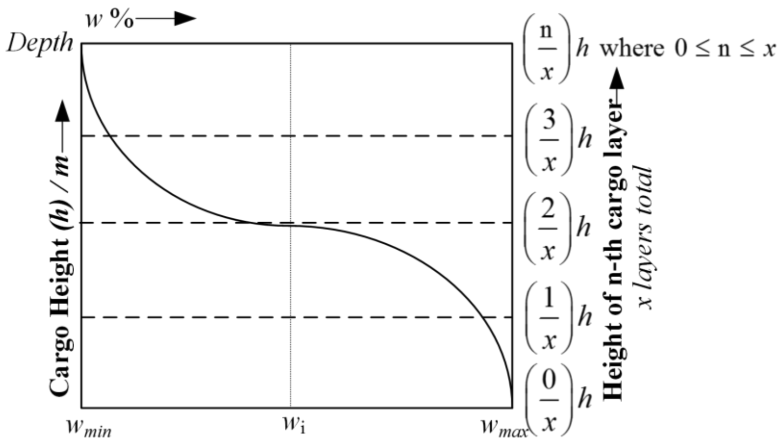


Figure 4.14: Taking slices of one-dimensional flow in a cargo.

Given these changes that occur through a cargo, the degree of saturation can therefore be determined as a function of time and height (*h*):

$$S(t,x) = \frac{w(t,x)G_s}{e(t,x)} = \frac{w(t,x)G_s\rho_{dry}}{G_s - \rho_{dry}} = \frac{w(t,x)G_s \, {}^{m_{dry}}\!/_{V(t)}}{G_s - {}^{m_{dry}}\!/_{V(t)}} \qquad 4.11$$

Where *w*(t,*x*) represents the water content as a function of depth.

The results from this analysis are shown in Figure 4.15 and Figure 4.16, where *w(t,x)* for Redhill

110 sand was approximated using drainage results for iron ore concentrate by Kruszewski (1988, 1992). These show the relationship for the changes in saturation and dry density that occur during a voyage, which may then be incorporated into element testing on cargo strength. Note that for application to an actual cargo, $w(t, x)$ would have to be measured or estimated.

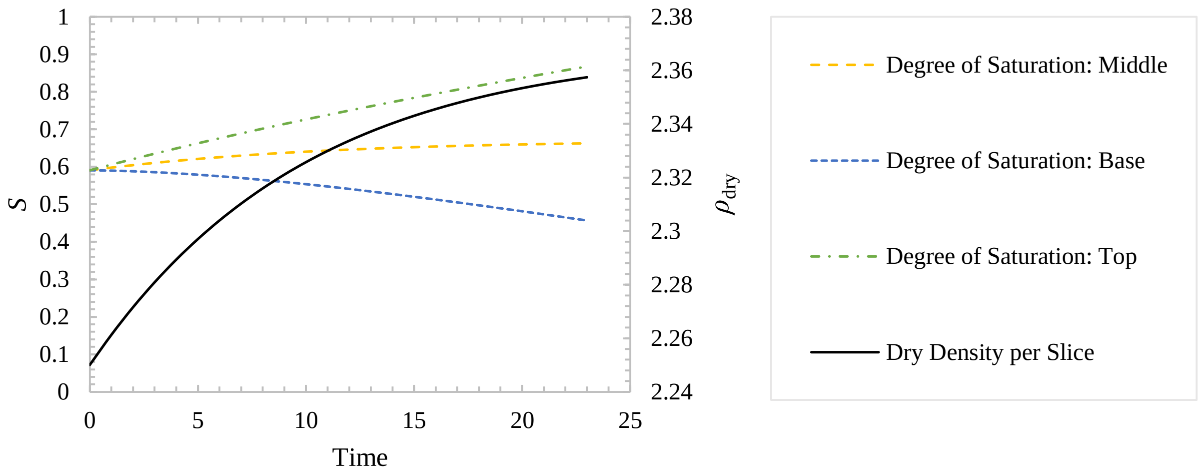


Figure 4.15: Change in dry density and degree of saturation through the cargo, with respect to time, based on an analysis of the macro-behaviour using equations presented through this section. These calculated material properties can then be used as the basis for elemental testing over the entire cargo, through a voyage.

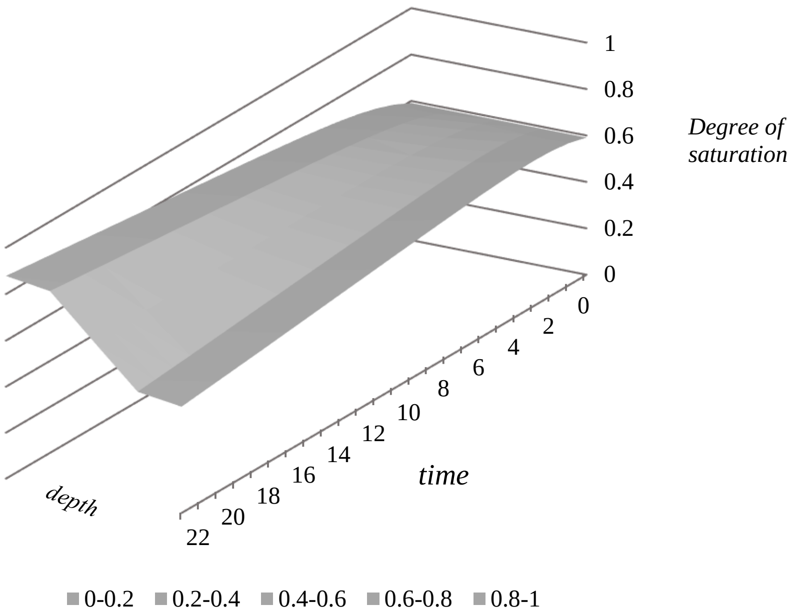


Figure 4.16: A three dimensional representation of the change in saturation through the cargo, with respect to time and depth. This was calculated using the equations presented within this section.

4.4.3.3 Strength Analysis

Utilising the material properties obtained from an analysis such as that above (in Figure 4.15 and Figure 4.16), soil mechanics testing can then performed to determine the likely strength characteristics at different locations and times within the cargo. Static variables such as the friction angle and apparent cohesion can then be obtained, in addition to making assumptions around possible pore pressures and loss of effective stress (which will decrease strength). From this, the likelihood for global displacement to occur from the ship's motions from roll (or otherwise) can then be considered with regard to the cargo geometry.

4.4.4 Remarks/ Limitations

The method described here is an obvious simplification of the complex behaviour within a vessel. A more accurate, higher resolution model could be obtained by: (*i*) increasing the number of slices through the cargo, *i.e.* increasing x; (*ii*) using real drainage, volume change and compaction data; (*iii*) using more accurate and complex cargo geometries (that reflect actual dimensions); (*iv*) increasing the dimensions (for example, three dimensional drainage analysis); and (*v*) incorporating the effect of bilges (the simple one-dimensional model of drainage presented here is unlikely to be very accurate). FEM analysis may improve resolution of data and allow both the micro behaviour of an element to be explored along with the cargo's macro behaviour (*i.e.* through interactions between these different elements of material).

Although this may give a reasonable approximation of changes that occur through a cargo, it does fully account for the secondary effects of pore-water pressures, which influence compaction. More specifically, changes in void ratio and dry bulk density that occur through the depth of the cargo are not completely accounted for, as the void ratio and dry density are calculated as a function the volume and dry mass for each slice (both which have been assumed fixed with depth, at a given time). In reality the dry mass of the material is unlikely to be constant through each layer, due to the relationship between dry bulk density ρ_{dry} with moisture content, at a given compaction energy—as demonstrated in the Proctor test. Moisture migration may result in some parts of the cargo packing more densely as it becomes wetter (*i.e.* ρ_{dry} increases), whilst wetter portions of the cargo (approaching saturation) may experience increase in pore-water pressures that prevent significant increases in density without consolidation (ρ_{dry} cannot increase). If $E(t)$ is assumed as fairly constant through a voyage (*i.e.* $E(t) \approx E$), then it may be possible to use Proctor compaction results to obtain a realistic relationship between dry density, void ratio and moisture content, *i.e.* $\rho_{dry}(w(h,t)) = \rho_{dry}(h,t)$. From this cargo dry density and thus void ratio could be considered as a function of both time and *depth.*

5. CONCLUSIONS

If some solid bulk cargoes such as concentrates, unprocessed nickel ores and iron ore fines contain sufficient moisture, then cargo compaction and moisture migration during a voyage may result in the development of pore-water pressures and liquefaction. This has been known to result in cargo shift and vessel capsize, causing a number of fatalities over the years.

The IMSBC Code serves as the principal regulatory tool for preventing cargo shift and cargo liquefaction. The IMSBC Code requires that cargoes with potential to liquefy during seaborne transportation, or Group A cargoes, be shipped at a moisture content below the TML. The TML is determined by laboratory based testing, as per the methodologies specified within the IMSBC Code.

For the many stakeholders involved in the carriage of Group A cargoes[i], the TML results given by these test methods, and their subsequent utilization within the Shipper's Declaration, are one of the most important components of the IMSBC Code. Firstly, this is because they intend to prevent liquefaction and therefore loss of life, ship and cargo. Secondly, they also introduce an upper moisture limit at which cargoes can be transported. An erroneous TML result that is too high may introduce a safety risk, whilst a TML result that is too low may erroneously restrict the ability to transport that cargo. Both the problem of liquefaction and its regulation have significant safety and commercial implications.

The key concerns raised from previous test method assessments regarding the effectiveness of these methods (as outlined in Chapter 3) are that:

(a) a given TML Test Method gives highly variable results when performing multiple tests on the same sample of material, particularly amongst different laboratories;
(b) the different methods give different TML results when testing the same cargo sample;
(c) there is no indication of what is a 'correct' TML result (*i.e.* there is no knowledge of how accurately the TML represents the moisture at which liquefaction may occur during a voyage).

[i]Stakeholders include the Shipper (for example, the commodity producer), the Master and Ship's Crew, the Ship Owner and insurers.

This thesis is aimed at addressing these concerns and deficiencies by contributing to an improved understanding of the two most common and, arguably, most important TML tests in the IMSBC Code; the FTT and PFT.

5.1 Findings on FTT and PFT Variability

In order to identify the reasons for low repeatability and reproducibility of FTT and PFT methodologies, a number of tests were performed on Redhill 110 sand and iron ore fines material. An in-depth, stepwise variability assessment of these methodologies, in addition to observation of TML testing at five different laboratories, and a review of the literature, revealed a number of inherent issues with these methods. More specifically, this work identified the following concerns with the TML Test Methods:

- There are sources of random errors arising from the **poor prescription of good laboratory techniques** within the IMSBC Code that leads to *low repeatability of TML results* (for example, cone expansion measurement errors for the FTT);
- There are sources of systematic errors arising from **ambiguities within the IMSBC Code methodology** that lead to variations in how the method is performed and these cause *TML bias between laboratories* (for example, determining mc from moisture added or dried)
- **Issues inherent within the test methods** also cause *TML bias between laboratories* (for example. the visual interpretation of flow and the IMSBC Code intersection method of determining flow for the FTT, and the consideration of the specific gravity and 70% intersection condition for the PFT);
- A number of requirements and/or ambiguities in the IMSBC Code result in the **TML test sample being unrepresentative of the cargo** (for example, sample rescreening or drying pre-test); and
- There are issues applying some of the **provisions in the IMSBC Code to shipping practice** (for example, with regards to sampling and reporting requirements) that result in an *unrepresentative TML being reported* in the Shipper's Declaration.

The research presented here contributes to an improved understanding of how each of the different stages of FTT and PFT methodologies influence the TML result, and their effect on method variability. It has also revealed a number of issues within the IMSBC Code in respect of its requirements for sampling, reporting and handling during precipitation, when applied within actual shipping practice. If these recommendations were incorporated into the IMSBC Code in the form of a non-ambiguous, robust methodology then it will ensure that more reliable TML results can be obtained (and declared within the Shipper's Declaration), regardless of the laboratory selected to test a sample.

Unlike other similar studies, the findings presented here are intended to be applicable generally to all cargoes and the recommendations are independent of commercial incentives. Furthermore, this assessment has addressed the issues of previous studies by incorporating information from a broad range of sources, including different laboratories, operators and literature. Importantly, the recommendations presented here are practically applicable and relevant to industry.

5.1.1 Recommendations for the FTT

For the FTT, significant recommendations (for implementation within the IMSBC Code) included:

- To reduce subjectivity associated with flow determination, visual examples of flow should be included for a range of materials (perhaps in the cargo Schedule) (Section 3.5.1).
- Observation should always be complemented by use of cone expansion measurements, and therefore a method for determining flow by measurements should be incorporated within the 'primary FMP test' methodology (Section 3.5.1).
- Instead of the IMSBC Code measurement methodology that considers the intersection, the turning point of w against Δd should instead be taken as the FMP. This is independent of number of drops and cone expansion rate, and more directly reflects the strength characteristics of the material (Section 3.5.1 and Section 3.5.4).
- There should be a requirement for the Shipper to provide the TML testing laboratory with the correct calculation inputs for tamping (Section 3.5.2).
- Commentary should be included in the methodology that highlights the importance of correct tamping procedures and its impact on the TML result (Section 3.5.2).
- In-text details of the ASTM standard setup for the apparatus should be included in the IMSBC Code. Simply referring to these standards is not sufficient. More specifically, it should specify that a rigid base be used (*i.e.* cement block) (Section 3.5.5).

5.1.2 Recommendations for the PFT

For the PFT, recommendations included:

- The TML should be derived directly from the OMC, instead of 70% saturation (a 10% factor of safety was suggested) (Section 3.6.1).

- An unrepresentative compaction energy is applied in the PFT, resulting in an underestimation of the TML. Therefore compaction energy should be 'calibrated' on a per-cargo basis so that density conditions within the mould represent those prevailing in an actual hold (Section 3.6.2).
- Further to the recommendation above, the PFT compaction hammer should be modified so that compaction energies can be adjusted (for example, by changing drop height) (Section 3.6.2).
- Contrary to the requirements of the IMSBC Code, a sample should not be oven dried prior to PFT testing (Section 3.6.3).
- To ensure homogeneity within the Proctor mould, a sample must be compacted to the top of the proctor mould extension piece (Section 3.6.4)

5.1.3 Recommendations for All TML Testing

General recommendations applicable to all methods included:

- Moisture addition increments should be smaller, within 0.2% by mass, to improve precision (Section 3.7.1)
- Further to above, there is a need to develop a simple, quick test that can accommodate liquefiable cargoes with a large particle top-size.
- Moisture loss must be understood and controlled (Section 3.7.2).
- Moisture determination should be performed by drying, to internationally recognised standards, the entire portion of sample that underwent testing on the flow table. It should not be performed on only a portion of this sample, or by considering only the moisture added to the test sample (Section 3.7.2).
- TML testing must be performed on a PSD representative of the cargo and a sample should not be screened (Section 3.7.4).
- The TML test sample should not be re-used for further TML testing (Section 3.7.3).
- To avoid particle degradation, mixing should be performed by hand. The act of compaction must be checked to ensure no degradation has occurred. Repeated PSD tests (*i.e.* sieving) will confirm this (Section 3.7.4).

5.1.4 Recommendations Regarding Reporting and Sampling

The moisture and TML samples tested, and results declared to the Master must be comparable and representative of the cargo. Therefore, the IMSBC Code must:

- incorporate improved prescription of what constitutes a "representative" sample or "significant change" in the shipped material (see Section 3.8.1 for suggested approach)'
- require the Shipper to report the sampling and testing regime from which a declared TML result is derived (Section 3.8.1);
- improve prescription of moisture reporting requirements, to ensure that for cargoes that exhibit high moisture variability amongst holds, cargo moisture is reported on a per-hold basis (see Section 3.8.2 for suggested approach).
- give consideration to the fact that that TML analysis and moisture analysis are carried out in different laboratories, and include provisions that prevent moisture analysis techniques varying amongst laboratories (Section 3.8.3);
- give consideration to sampling errors, perhaps by adjusting of safety factor (Section 3.8.4); and
- consider the extent and impact of a precipitation event on the moisture content of a cargo. If overall impact is negligible, then cargo handling restrictions should not apply (Section 3.8.5).

5.1.5 Possible Limitations of this Assessment and Future Work

Although the variability assessment has contributed to a greater understanding of the TML Test Methods, the Author acknowledges the limitations of this assessment, which may need to be addressed by further work. These include:

(a) It was not possible to assess the improvements that the recommendations made to overall variability, as *(i)* the ambiguities within the IMSBC Code mean that no 'base-line' variability' can be reasonably established (this would be dependent on the initial interpretation of this methodology); and *(ii)* an inter-laboratory trial would be required to assess reproducibility and this was not possible within the scope of the present study.

(b) The 'best-practice methodology' presented does not constitute a reduction of ambiguity of the methods—this can only be achieved through drafting of a full, robust methodology that incorporates the findings presented.

(c) The present study has presented a number of significant amendments to the test methodologies (for example, for the PFT considering the OMC instead of 70% saturation and for the FTT taking the turning point as the FMP). These offer improvements to the existing methods, but must be further assessed and subsequently developed into a robust methodology (by testing a wide range of cargoes and laboratories).

(d) TML test work has been limited to two material types (although this Author has observed and had experience testing on other cargoes). Whilst this Author believes that all variability related recommendations are generally applicable to all cargoes, this can only be confirmed once an improved methodology has been established and a wide range of materials are then tested.

Ultimately, the findings and proposals from the present study must be incorporated within shipping regulation to effectively improve TML reproducibility amongst laboratories testing cargoes internationally. This will involve the complete drafting of a significantly more robust, less ambiguous methodology than that currently in Appendix 2 of the IMSBC Code. Without this, laboratories will continue to perform their TML tests differently and therefore variability in results will continue. To validate this new methodology, and any incorporated recommendations, an inter-laboratory trial would need to be established.

5.2 Accounting for the Different TML Results Obtained from the Tests

Other investigations have shown that the TML Test Methods may each give different TML results when testing the same material. The present study found that FTT gave a lower result than the PFT, which was consistent with findings by other researchers. This not only raises questions as to the suitability of these methods, but also presents challenges for the Shipper who must decide which method to use.

In order to assess this issue, the measured PFT and FTT behaviour was therefore compared for both iron ore fines and Redhill 110, so that any differences could be established (Section 3.10). The ultimate aim of this work was to account for the bias between methods, and ascertain whether any ‘calibration’ between the two test methods was possible (*i.e.* to achieve alignment of TML results).

The research conclusively shows that the results from the TML Test Methods cannot align in their current form. The primary test parameters, such as sample density and the cyclic energy applied through the flow table (*i.e.* which influence material strength and therefore measured behaviour), could not be reasonably adjusted to account for the bias. Therefore, no calibration of the TML was possible using primary test parameters. Secondary approaches (*i.e.* flow interpretation, for a given set of measurements) are also unsatisfactory, as they do not directly reflect the strength behaviour of the tested material in their current form in the IMSBC Code (except indirectly via observation of deformation). Any adjustments on this basis are essentially arbitrary and unlikely to be generally applicable to all cargoes (*i.e.* the TML obtained from both methods is based on a different arbitrary assumption of when flow occurs).

However, by assessing a sample's measured behaviour from the different tests, comparisons can be made in terms of the strength properties. It is on this basis that any TML must be derived if the methods are to be comparable; although this would require a significant departure from the current state of the methods in the IMSBC Code. For example, for Redhill 110 sand there was a relationship between the measured properties from both tests, whereby: (*i*) just after the OMC in the PFT, the FTT ceases crumbling and begins to obtain strength; and (*ii*) as saturation is reached in the PFT, the FTT cone began to rapidly lose strength and cone expansion began to increase linearly. If the TML from both tests is to be comparable, it must be derived from these types of relationships.

5.3 Accuracy of the TML Test Methods

Although the findings presented on variability of the TML test methods (Section 4.1) will contribute to an improved understanding and more reliable TML results, there is little evidence available to indicate how well they actually represent the likelihood of a cargo to liquefy—and therefore which method gives a more 'correct' TML result (Section 4.2).

Despite a number of studies aimed at assessing cargo behaviour at sea, there have been few (if any) holistic accounts of the liquefaction problem by previous researchers—with many disparate work efforts resulting in inconclusive findings. Whilst many researchers have presented geotechnical analysis of cargo shift (including research on a specific test method or type of ore), this has typically had little impact within the context of IMO. This is because many of its delegates, usually from the maritime industry, are unlikely to possess expertise in this subject area.

The present research addressed this need for clarity by:

- Breaking down the complex variables and the relationship between them that cause shift, whilst, in addition, providing a brief account of previous work on the different areas of the problem (Section 4.1). This representation of the problem is the first concise holistic representation of its type to date, and it aims to establish a framework to guide future investigators working on the topic. Furthermore, it provides a useful reference to previous work that has been performed on the subject.
- In consideration of these variables, the present work explained that material behaviour under the elemental testing conditions of the PFT and FTT, is unlikely to be representative of that in a cargo. These tests do not take into account moisture migration and are unlikely to represent density and confinement conditions within a cargo. In addition, the cyclic vibrations applied in the FTT are very different to those experienced by a cargo at sea (Section 4.2).
- After considering the deficiencies in previous approaches (Section 4.3), a possible approach for determining the dynamic changes through a voyage has been proposed. This lays the foundations for a possible method that aims to simplify the problem by consideration of the global changes in material properties through a voyage, based in part on testing of Redhill 110 (Section 4.4). This could then be used as the basis for determining strength over a cargo. Although the assessment of material properties significantly simplifies the problem, an improved representation may be obtained by further test-work or more complex numerical assessment of compaction and drainage.

5.4 Other Contributions

Unfortunately, through detailed assessment of the IMSBC Code and of the literature that facilitated its development, it appears *that the issues within this regulation are not limited to problems with the TML Test Methods,* and the IMSBC Code remains, in parts, ambiguous and disjointed. The IMSBC Code and predecessors have been developed from IMO's collection of disparate, discrete and often unrelated research efforts by various member countries and organisations. This research has typically focused only on a narrow area or a single aspect or the problem (for example, on the strength of a particular type of shipped ore), and/or been conducted in response to a specific event (such as a maritime accident or suggested regulatory reform). Furthermore, lack of accessibility to these studies has resulted in repeat research efforts in some aspects of the problem, whilst leaving some areas relatively unexplored.

In consideration of these deficiencies with previous research, it is hoped that the contribution of this thesis is not limited to the findings regarding the TML Test Methods. It is envisaged that the broad range of consolidated information and references presented (for example, through the timelines) will also *contribute to an improved understanding of the full range of historical studies that have been performed on cargo shift*.

This document represents a significant advancement in the transparency of available information, presenting information obtained from: (*i*) generally inaccessible literature such as those submitted to the IMO pre-1998 through he BC/DSC Sub-Committees (references to these documents have been intentionally included throughout this document to help steer future researchers), (*ii*) from laboratory visits; and (*iii*) in-person interviews with researchers that have performed some of the most comprehensive and influential research on the topic (through the 1980—1990's). *Future work can and should utilise the findings of historic work and there is potential for further consolidation of these existing materials* (which for IMO date back to the 1950s).

Ultimately, by shedding light on the wealth of available information, this thesis will hopefully provide a useful reference document for future researchers, ensuring they are suitably aware of past efforts—helping them to target research on key and unknown issues. In addition, many of the references presented provide insight into the derivation of many of the current provisions/requirements within the IMSBC Code. Knowledge of how the different requirements of the IMSBC Code were derived can form the *basis for influencing change to these provisions*.

5.5 Final Remarks

There is still significant work required to ascertain whether the TML Test Methods accurately capture the at-risk cargoes, whilst not giving excessively conservative results at the expense of the Shipper. It is likely that the accuracy may never be determined with any great certainty given: (*i*) the limitations associated with assessment of real cargo behaviour; and (*ii*) the many assumptions that would be required within any numerical assessment of the problem. It follows, that *it is likely that any analysis of a cargo shift criteria will at best, only ever give an approximation of the problem* (requiring a significant factor of safety). Furthermore, given that worst-case assumptions would probably be required, any analysis will probably be particularly conservative.

Given that only an approximation of vessel and cargo behaviour may be achieved, perhaps the current test methods are suitable (although not perfect) for the purpose of detecting a cargo's liquefaction potential. In this case, the best possible outcome would be to ensure that the IMSBC Code test methods obtain high precision, reliable and comparable results, which are representative of the cargo. On this count, the research described here makes an important contribution, and if its findings are implemented within international shipping practice (say, in the form of a robust methodology), more reliable results will be obtained. This will provide all parties with confidence in the results presented and contribute to safer shipping practice.

To reduce the incidence of maritime casualties and develop effective regulation in this area, interdisciplinary investigations of the issue are required. These should not only draw from geotechnical and maritime technical disciplines, but for successful implementation within shipping practice, also requires an in-depth knowledge of maritime and commodity shipping practice as well as input from appropriate policy and legal advisors.

Considering these *specific yet essential requirements to approach the science*, as well as the complexities and the challenges of *effectively communicating the science to the regulators*, it is unlikely that there will be any significant advancements in the handling of cargo shift within the IMSBC Code in the foreseeable future.

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Appendix 1: Cargo Liquefaction Fatalities (1988 to Present)

Table 5.1: Recent fatalities that have been widely attributed to liquefaction (note: in most cases due there can be no certainty as to the cause of shift).

DATE	VESSEL NAME	DEATHS	VESSEL SIZE (TONNES) / TYPE	VOYAGE DETAILS	CARGO TYPE	REFERENCES
Jan 1987	*Testarosa*	30	Cargo - Bulk Carrier (ship weight 66903 d.w.t.)	The cargo ship foundered in the Atlantic Ocean off the coast of Portugal - Strait of Gibraltar to Arquipélago da Madeira.	*Iron Ore*	
Dec 1988	*Mega Taurus*	20	-	From Philippines to Japan. Capsized while en route	*Nickel Ore*	(Grant, 2008' Roberts, 2012)
Jun 1990	*Finn-Baltic*	7	Pusher (Finn) and Barge (Baltic)	From Raahe to Koverhar (Finland), Capsized outside Hanko (Finland)	*Iron Ore Conc.*	(BC32/INF.12 1992)
Sep 1991	*Melete*	25	Bulk Carrier	From Dampier to Wales. Foundered in South Indian Ocean	*Iron Ore Fines*	(ATSB, 1991)
Sep 1998	*Sea Prospect*	10	-	From Indonesia to Japan. Capsized while en route	*Nickel Ore*	(Grant, 2010)
Aug 07	*Wen Qiao*	1	4500 t/ Bulk Carrier	From India to Tianjin, China. Capsized off the Wonsan anchorage, North Korea	*Iron Ore Fines*	(China P&I, 2010)
Sep 2007	*Heng Tai*	2	16120 t/ General Cargo Ship	From India to Bangladesh. Capsized and sank in Andaman Sea - west of Bangkok	*Iron Ore*	(China P&I, 2010)
Sep 2009	*Black Rose*	1	37657 t/ Bulk Carrier	From India to China. Capsized off Paradip port, India	*Iron Ore*	(Bulk Carrier Guide, 2010)
Oct 2010	*Jian Fu Star*	13	45108 t/ Bulk Carrier	From Indonesia to China. Sank in the South China Sea 90 miles southwest of Cape Eluanbi, Taiwan.	*Nickel Ore*	(Lloyd's List, 2010)
Nov 2010	*Nasco Diamond*	21	56893 t/ Bulk Carrier	From Indonesia to China. Developed a list to port, capsized in the south of Iromote Island, Pacific Ocean	*Nickel Ore*	(Lloyd's List, 2010)
Dec 2010	*Hong Wei*	10	50149 d.w.t Bulk Carrier, (40,000 t cargo)	From Indonesia to China. Capsized in the South China Sea.	*Nickel Ore*	(Maritime Accident Casebook, 2010)
Nov 2011	*Vinalines Queen*	22	56040 t/ Bulk Carrier	From Indonesia to China. Developed a 18° list and eventually capsized in the Philippine Sea	*Nickel Ore*	(London P&I Club, 2012)
Feb 2013	*Harita Bauxite*	15	47450t t/ Bulk Carrier	From Indonesia to China. Developed a list from heavy rolling and engine failure and capsized	*Nickel Ore*	(The Economist, 2013; Vittone, 2013)

NOTE: In most of these cases there is no certainty as to the cause of shift and the cause of capsize is therefore speculative. Further details regarding maritime accidents can be found in maritime accident reports, maritime insurers such as Lloyds Marine, or documents submitted to IMO.

Appendix 2: Details of the Regulation

A. Overview of Regulatory Structure

The *International Maritime Organization* (IMO)[i], a maritime focussed agency of the United Nations, oversees global maritime regulation.[ii] The *Maritime Safety Committee* (MSC), one of IMO's four technical committee, overseas safety related maritime issues. The MSC is guided by nine Sub-Committees. Matters related to the carriage of solid-bulk cargoes (and therefore cargo shift) fall within the responsibilities of the *Sub-Committee for Carriage of Cargoes and Containers (CCC)* [iii]. Any amendments or additions proposed by the CCC must pass through the MSC for approval/adoption.

One of the main responsibilities of the CCC Sub-Committee is to maintain the *International Maritime Solid Bulk Cargoes* (IMSBC) Code. The IMSBC Code incorporates both recommended and mandatory practices related to solid bulk shipping, aimed primarily at Governments, ship operators, Shipmasters and Shippers. Its intention is present an internationally accepted method of dealing with hazards to safety; and more specifically to present: (*i*) the dangers associated with the shipment of a number of bulk cargoes; (*ii*) guidance on various procedures and methodologies; (*iii*) the typical products which are shipped in bulk, (*iv*) advice on their properties and how they should be handled; and (*v*) various test procedures which should be employed to determine characteristic cargo properties. Because the IMSBC Code regulates the safe transport of solid bulk commodities, the IMSBC Code has evolved as one of the most important IMO instruments.[iv]

Any documents relating to cargo shift, including any research, proposals, suggested amendments or information ('INF') documents are submitted to the CCC Sub-Committee for consideration by Member States (or its Editorial & Technical (E&T) Group.

It is of note that enforcement of the IMSBC Code occurs *domestically*; and is the responsibility of the "*Competent Authority*" of the jurisdiction in question. For example, the Competent

[i]Known as the Inter-Governmental Maritime Consultative Organization (IMCO) until 1982.

[ii]Strictly speaking, it overseas the regulation of its 170 Member States (*i.e.* countries) and 3 Associate Members, but this comprises of nearly all major shipping nations.

[iii]In 2014, the CCC replaced the Sub-Committee for Dangerous Goods, Solid Cargoes and Containers (DSC). In 1995, the DSC replaced the Sub-Committee for Bulk Cargoes (BC). Relevant submissions regarding cargo shift prior to 2013 are found within IMO's BC (BC 1-34 [1965-1995]) and DSC (DSC 1-19 [1995-2014]) meeting documentation. At the time of writing, any documentation submitted prior to DSC4 (1998) can be accessed only in hardcopy through the IMO Knowledge Centre, in the IMO headquarters London.

[iv]International Maritime Organization (IMO) DSC6/15 (2002). Report to the MSC by the the Assistant Secretary General. International Maritime Organization.

Authority in the United Kingdom is the Maritime and Coastguard Agency (MCA), or in Australia it is the Australian Maritime Safety Authority (AMSA). For SOLAS member states, requirements of the Competent Authority typically align with the IMSBC Code—although domestic variations of how the IMSBC Code provisions are permitted. To avoid any potential conflict of interest, IMO recently adopted resolution which includes the requirement for the Competent Authority to operate independently of the shipper[i].

B. Development of the Regulation

The International Maritime Consultative Organization (IMCO, now IMO) was established through a Geneva Convention in 1948, entering into force in 1958, with the purpose to: *"to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade"* and *"to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships."*[ii] IMO was also given administrative and legal powers to deal with these.[iii]

IMO's first task was to adopt the International Convention for the Safety of Life at Sea (SOLAS), which dealt with maritime safety (1960). At this meeting, delegates recognised the dangers associated with shipping bulk solids, recommending that an internationally acceptable code of safe practice for the shipment of bulk cargoes be drafted under the sponsorship of the IMO.

The first session of the Working Group (WG) on Bulk Cargoes (BC) was held in 1960, which aimed to establish ways to facilitate the safe shipment of bulk cargoes. There was general recognition that concentrate cargoes could act like a slurry, and thus were dangerous, if loaded excessively moist. Member states therefore submitted information on domestic practices used to determine if a concentrate is safe for carriage.[iv] Many member countries reported setting a fixed maximum moisture limit for concentrate cargoes (for example, Norwegian regulations restricted the shipment of cargoes exceeding 9% moisture). Other countries used laboratory

[i]International Maritime Organization (IMO) MSC 92/26/Add.1 (2013). Resolution MSC.354(92) Amendments to the IMSBC Code, The International Maritime Organization

[ii]International Maritime Organization (IMO) MSC 85/26/Add .2 (2008). Adoption of the IMSBC Code, Resolution MSC.268(85), The International Maritime Organization (adopted on 4 December 2008)

[iii]International Maritime Organization (IMO) (2014). Brief History of IMO. International Maritime Organization, Retrieved online from: <www.imo.org>

[iv]International Maritime Organization (IMO) BCI/Conc (1964)

based test-methods to determine a safe maximum moisture content for shipment. Six different methods were presented, including Canada's flow table test, the UK's 'Vibration Viscometer' and Norway's Vibration (Glass Rod) tests (an overview of these methods have been provided in Chapter 3 of thesis of this thesis, including references to original BC Code documents. That year, delegates from Canada, the UK and the USA participated in an inter-laboratory trial to trial these different methods, with the aim of deciding on a single test to recommend to the BC Working Group.[i]

The Code of Safe Practice for Bulk Cargoes (BC Code) 1st Edition (1965) was published in 1965[ii], which included recommendations to Governments, Ship Operators and Shipmasters. The FTT methodology, adapted from the Canadian Concentrates Code, was the test method chosen for inclusion within the BC Code (within Section 9). The concept of the TML and FMP was also introduced. Most member states considered the FTT the simplest, most robust methodology for determining the safe shipped moisture content (TML) of a concentrate.[iii]

In the early years of the BC Code, some governments expressed practical difficulties obtaining TML results from the FTT. At their request, Canada added additional explanatory notes to the method in the BC Code (made available by the Canadian delegation).[iv] Germany reported a lack of awareness of the Code, particularly amongst Shippers, resulting in disputes in contracts requiring moisture analysis, etc. They highlighted the need to contact mines and Shippers regarding the new Code in order to urge them to apply its principles of moisture test procedures and certification.[v]

There have been a number of other amendments to the wording, content and structure of the BC Code over the years. Minor amendments include the inclusion new sampling practices[vi], handling requirements during precipitation[vii], ship loading practices and rewording of methodologies to improve clarity and/or precision. Major amendments, in relation to cargo

[i]More details of this discussion can be found in IMO's Sub-Committee for Bulk Cargoes (BC) 1964-1965 meeting documents BCI/2, BCI, BCI/ 5, BCI/ 7, and BCI/Conc.

[ii]Later renamed the Code of Safe Practice for 'Solid' Bulk Cargoes and later still to the International Maritime Solid Bulk Cargoes (IMSBC) Code.

[iii]International Maritime Organization (IMO) BC/Conc./7 (1994)

[iv]International Maritime Organization (IMO) BCV/ 5 (1967)

[v]International Maritime Organization (IMO) BCIX/12 (1967)

[vi]See IMO BC Sub-Committee documents BCVIII/WP.5; BCXV/4(a)/1/Add. 1, BCXVIII/WP.1 /Add.1, BC23/WP.11, BC24/ WP.4; ,BC30/5/10; BC32/INF.6

[vii] See BC Sub-Committee documents BCI, DSC18

shift, include:

(a) Standardising the tamper pressure in the Flow Table Test (*i.e.* to improve precision). [i]

(b) Inclusion of a recommended method for determining the angle of repose for non-cohesive cargoes, namely the tilt box test. [ii]

(c) Adoption of two new test methodologies for determining the TML into the Code, namely the PTT and the PFT[iii]; and more recently

(d) Adoption of a new test for testing iron ore fines material (based on the PFT). [iv].

Statistics compiled by Lloyds Register of Shipping from the decade 1954-1964 showed that out of 149 foundering ships in the first decade, 69 were ore carrying ships. From 1964 to 1974, of a total of 205 foundering ships, 61 ore ships were lost. This reduction may largely be attributed to the positive impact of moisture control regulations and/or awareness of the dangers—although there was a significant increase in the ship carriage capacity and average parcel-size during this period which may skew these statistics. Nevertheless, most consider the regulation to have been successful in reducing the risks of cargo liquefaction: "…*one is unable to discover an incident where a ship was lost or endangered as a result of concentrate cargoes shifting where the actual moisture was within the TML. Although the current IMCO Code does satisfy the essential requirements for safe shipping, it is a test that does not contribute towards an improved understanding of the problem of concentrate stability in vessels."* [v].

Since 1 January 2011, the Code (now the IMSBC Code) has become mandatory under the provision of the SOLAS Convention. However, in respect to the cargo shift issue, the latest Editions of the Code remains very similar to the form of the 1965 BC Code. Indeed, the 1992 introduction of the PFT and FTT has improved the ability to test some liquefiable materials, that were not suitable for testing with the FTT (for example coals with a large topsize). However, some of these new methods, such as the PTT, have been calibrated to TML results obtained by the FTT (for example the Penetration Test). And the accuracy of this method is unknown.

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[i] See IMO BC Sub-Committee documents BCXVII/WP.6, BCXVIII/6/1, BCVII/3(b), BC32/INF.5

[ii] See IMO BC Sub-Committee documents BCXII/7/1; BCXIV/4/1; BCXV/(b); BCXVII/3(d); BCXVIII/6; BCXVIII/6/2; BCXVIII/WP.1 /Add.3; BCXX/5/3; BCXXII/5/6; BCXXII/5/7; BCXXII/5/11; BC26/WP.9

[iii] See IMO BC Sub-Committee documents BC32/WP.2 and BC32/3/17 for original adoptions of Penetration Test and Proctor/ Fagerberg Test by the Sub-Committee, respectively.

[iv] See IMO BC Sub-Committee documents DSC.1/Circ.63; DSC.1/Circ.66/ Rev.1; DSC.1/Circ.71.

[v] International Maritime Organization (IMO) BC23/INF.3

Appendix 3: Sources of Information

Table: Sources of knowledge that have informed this thesis (excludes literature review/ test work) and the knowledge area that these contributed to..

SOURCE	SUMMARY	*Soil Mechanics*	*Shipping Practice*	*Maritime Regulation*	*Maritime Engineering*
The IMO Knowledge Centre, London (i.e. the BC/ DSC Sub-Committee Archives 1965-present)	Performed a unique, complete assessment of all archive material presented to IMO on cargo shift, from 1965 to the time of writing (only available in hardcopy). Until now, most of this research has remained un-reviewed since original submission. This revealed how the IMSBC Code was formed.				
Attendance as an observer at IMO's CCC1 (Carriage of Containers and Cargoes) meeting (London, U.K)	Observed the UN forum where regulatory decisions relating to cargo shift are made. This helped develop an understanding of the regulatory constraints. Discussions with delegates on the topic also helped develop regulatory understanding.				
In-depth assessment of commercial literature	Assessing member circulars, insurance assessments, etc, to understand the different maritime issues encountered globally.				
In-person interview/ discussion with Dr Andrew Kruszewski who performed work in Warren Springs Laboratory (United Kingdom,, 1985-1995)	Met with the lead researcher of one of the most comprehensive assessments of cargo shift that has been undertaken to date (conducted in conjunction with City University). Some of this work was been adopted by IMO. In addition, Dr Kruszewski has acted as expert witnesses in some high profile insurance cases related to possible liquefaction (e.g. MV Derbyshire)..				
In-person interviews/ discussion with Professors John Atkinson and Neil Taylor (City University, London)	Met with leading geotechnical professors who performed soil mechanics assessment of cargo shift (1986-1998) within City University, some of which has been presented to IMO. In addition, This provided an opportunity to gain insight into some of the soil mechanics aspects, and previous approaches.				
Meetings/ discussions with commercial based researchers	Numerous meetings with personnel from the Technical Working Group (TWG) for iron ore fines, who have been performing a scientific assessment of cargo shift since 2011.				
Meetings/ discussions with subject-matter experts in the maritime field	Discussions with 'experts' that work for P&I clubs and assess claims related to liquefaction. This helped to identify the gap between where regulation meets practice.				
Site visits to TML testing laboratories and geotechnical testing facilities (five in total)	Visited experienced and influential laboratories, including Alfred H. Knight laboratory and Fugro (U.K., 2013-2014) to discuss and observe TML test methods and cyclic triaxial work.				
Site-experience within bulk commodity Shipping operations	Experience in a number of iron ore port operations, where TML testing and moisture assessment was required. Provided a background to the practical limitations of the regulation.				
Boarding a number of solid bulk carrier's	Gave perspective and context on the scale of the problem. This helped ensure recommendations can be practically implemented.				

Appendix 4: Detailed Breakdown of IMSBC Code Methodology

For the FTT, the tables below present the *required* methodologies, and the *suggested* methodologies within the IMSBC Code. This was developed at the preliminary stages of the present study, from the in-depth assessment of the methodology wording (*i.e.* by considering words such as “should” or “must”). It thus helped guide the test-work.

Apparatus

VARIABLE	STANDARD IN IMSBC CODE	PREFERRED/ SUGGESTED IN IMSBC CODE
Standard flow table and frame	ASTM Designation (C239-68) See 3	
Flow table mounting	ASTM Designation (C239-68) See 3	
Flow table flat and level?	Should be level!	
Mould	ASTM Designation (C239-68) See 3	
Tamper	Controlled pressure applied via a 30mm diameter tamper head	“*May”* be achieved using calibrated, spring loaded tampers.
Scales and Weights ((ASTM Designation (C109-73) See 3)	ASTM Designation (C109-73) See 3	*“Suitable”* containers
Glass graduated measuring cylinder	100-200 mL capacity	
Glass graduated burette	10 mL capacity	
Mixing apparatus	Mechanical mixer must not reduce particle size or consistency of material.	Hemispherical mixing bowl~30 cm in diameter; rubber gloves and drying dishes or pans OR Automatic mixer of similar capacity
Drying oven	Controlled temp *up to* 110°C	*Should* be without air circulation…

Environmental Factors

VARIABLE	DESCRIPTION	STANDARD	PREFERRED/ SUGGESTED
Accomplished in reasonable space of time?	Moisture loss to the environment can cause loss of accuracy/ precision.		Minimise time that sample is left open to the external environment to control moisture loss.
Protected from excessive temps, air currents and humidity variations?	Moisture loss to the environment can cause loss of accuracy/ precision.		Take note of environmental conditions; should encourage minimal evaporation.
Sample containers covers?	Moisture loss to the environment can cause loss of accuracy/ precision.		Sample containers *should* be covered.

General Conditions

VARIABLE	DESCRIPTION	PREFERRED/ SUGGESTED
Direction of water addition	FMP can be reached by either *increasing* or *decreasing* moisture towards FMP	*Increasing* the moisture up to the FMP is more accurate.
Performing Preliminary FMP Test	Indicates the condition of test sample; *i.e.* quantity/rate of water to be added and whether it should be air-dried first to reduce its moisture content before commencing main flow moisture test	Recommended, in accordance with the procedure
Weighing of sample after each stage	If some mass is lost from sticking to the bowl, etc, then it's important to re-weigh and then dry the sample for moisture determination...	The whole moulded sample *“should”* be placed in a container, weighed immediately and retained for moisture determination if required.

START: Bulk Sample

VARIABLE	DESCRIPTION	STANDARD
Quantity of material	Should be enough to produce 3 representative sub-samples; varies according to specific gravity.	2kg for coal to 3kg for mineral concentrates;

Sample Mixing/ Splitting

PROCEDURE	DESCRIPTION	PREFERRED/ SUGGESTED
A 'representative' sample is thoroughly mixed. 3 sub-samples (A) (B) and (C) removed from mixing bowl.	Three samples, each ~1/5 of the gross weight are created; sample (A) is to determine actual sample moisture; (B) is for preliminary FMP test; (C) is for main FMP test.	Each (A), (B) and (C) ~ 1/5 of gross weight.
Sample (A) immediately weighed and placed into drying oven to determine moisture content of the sample "as received"	(B) sample is for preliminary FMP test. (C) sample is for the main FMP determination	
Starting moisture		(C) Sample adjusted to within 1-2% of FML calculated in preliminary test

Placing the Mould/ Filling the Mould/ Removing the Mould

PROCEDURE	DESCRIPTION	STANDARD	PREFERRED/ SUGGESTED
Mould placed in centre of Flow Table?	"Should" be placed in centre to ensure equal force is applied through the sample when dropped		
Filled in three separate 'charges' (stages)?	The quantity of sample required to achieve this will vary from one material to another, but can be readily be established after some experience has been gained of material being tested		~1/3 of its depth filled with each charge; ~equal for each charge; filled to top of mould following 3 charges
Tamping Pressure?	Aim is to attain a degree of compaction similar to that prevailing at the bottom of a shipboard cargo of the material being tested…	According to the Equation *or* Table 1.1.4.1 in IMSBC Code	
Number of Tamping Actions?	Even, consistent tampering important to ensure integrity of test.	*Should* be *about* 35 for bottom layer, 25 for middle and 20 for top layer	Correct, steady pressure applied each time
Tamping Area?	Even tampering important to ensure integrity of test	Uniformly flat surface for each layer (Tamping successively over the area completely to edges)	
Tapping method?	Even tampering important to ensure integrity of test	Tapped *on its side* until it becomes loose; sample left in shape of a truncated cone on the table.	

Activating ('Dropping') the Table

PROCEDURE	DESCRIPTION	STANDARD	PREFERRED/ SUGGESTED
Time between removing mould and starting test		Should occur immediately after removing mould	
Number of drops	Until crumbling occurs; if crumbling doesn't occur then continue to 50 drops. If no bulging occurs after 50 drops then FML not reached…	*Up to* 50 times	
Drop height		12.5mm	
Drop frequency		25 times/minute	

Identification of Flow State

PROCEDURE	DESCRIPTION	STANDARD	PREFERRED/ SUGGESTED
Plastic deformation occurrence…	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…	Moulded sides *deform*—not just the diameter… *convex or concave profile...*	
Template indicator?			Potential indicator; increase in diameter >3mm could indicate FMP been reached
Measurement of diameter of cone (half height; bottom)			May be "useful".
Moisture sticking to mould	Could indicate above FMP—however absence of tracks is not necessarily an indication of being below FMP		Potential indicator that >FMP
Cone sticking to mould?	Could indicate above FMP		Potential indicator that >FMP
FMP Calculated from diagram?	Draw line of best fit in order to interpolate back once FMP exceeded	For preliminary FMP test	

Remixing of Material/ Water addition

VARIABLE	DESCRIPTION	STANDARD	PREFERRED/ SUGGESTED
Amount of water added	If FML not reached, then water added and the mould is again filled (as per above) and dropped. This is repeated until FML reached.	MAIN: No more than 0.5% mass	PRELIMINARY: ~5-10mL
Recording of water addition			Is the amount of water added recorded properly?
Accuracy of water addition equipment			Added by Burette (as per equipment above)

Process Results

VARIABLE	DESCRIPTION	STANDARD	PREFERRED/ SUGGESTED
Determination of moisture content		When flow state has been reached, moisture content *should be* determined on 2 samples; one with moisture content just above FMP and the other with moisture content just below FMP. The FMP is the mean of these 2 values.	
Tolerance of results			The difference between the two values *should* be 0.5% or less

Appendix 5: Summary of Issues, Impact and Recommendations for the FTT and PFT

Table 1: FTT Findings, Impacts and Recommendations

FINDINGS	IMPACT	RECOMMENDATION
Assessing flow by observation is subjective.	Reproducibility: Random errors associated with determining the FMP amongst operators.	IMSBC Code should include visual examples of flow for a range of materials (perhaps in the cargo Schedule). Observation should always be complemented by use of cone expansion measurements
The IMSBC method for determining the FMP by measurements (i.e. intersection method) is subject to biases.	*Reproducibility:* Leads to a lower TML result. Bias increases for lower gradient of $\frac{\Delta \text{expansion}}{\Delta \text{mc}}$ and lower number of drops.	Turning point of the *w Vs d* should be considered as this is independent of number of drops and cone expansion rate. IMSBC Code method must reduce ambiguity associated with measurement method.
Calculation of the tamper energy is often estimated, leading to variations in tamper pressure.	*Reproducibility:* Leads to variability amongst operators/ laboratories. Has an unpredictable impact on TML, therefore introducing random errors.	Shipper must provide TML testing laboratory with correct inputs into calculation and these must be input correctly for all laboratories testing that cargo.
Tamper pressure calculations may be incorrectly applied for apparatus.		IMSBC Code must include a description of correct scaling procedure.
Tampering may be susceptible to kneading effects.		IMSBC Code must highlight importance of correct tamping procedures and its impact on the TML result
There are biases associated with tamping (i.e. over/ under exertion).		
The moisture determination method can vary amongst laboratories.	Moisture determination from water added leads to bias and a systematic overestimation of the TML, whilst moisture loss also leads to random error. This effects reproducibility amongst laboratories.	Moisture determination must be performed on the entire portion of sample that underwent testing on the flow table.
Cone expansion measurements are subject to error (for example, from unsymmetrical expansion, suction to mould, measurement error).	Introduces small random errors in the determination of cone expansion which can lead to loss of reproducibility.	Taking multiple measurements at different heights of the cone increases accuracy/ precision but may not be practical in a commercial laboratory.
Number of drops impacts ability to determine flow.	Cone expansion increases with number of drops of the flow table (this was almost linear for 100 drops just beyond the FMP).	50 drops currently required in the IMSBC Code appears reasonable to determine flow.
Variations in apparatus setup can lead to variation in TML results.	*Reproducibility:* A flow table mounted on a surface which can absorb energy may result in systemic overestimation of TML.	FTT should always be mounted on cement base.

Table 2: FTT Findings, Impacts and Recommendations

FINDINGS	IMPACT	RECOMMENDATION
The 70% saturation condition on which the TML is based is essentially arbitrary and does not hold true to all cargoes.	Some materials may possess a minimum void ratio significantly higher than S=70%, resulting in an underestimation of the TML, and vice versa.	The OMC/ minimum void ratio should be taken as the condition for carriage instead of 70% saturation.
TML results are highly sensitivity to specific gravity (G_s) determination.	Overestimating the G_s typically overestimates the TML, and vice versa. The magnitude of this effect is typically greater for 'flat' compaction curves. This leads to biases based on *reduced reproducibility* for different G_s determination methods.	The OMC/ minimum void ratio should be taken as the condition for carriage instead of 70% saturation.
An unrepresentative compaction energy is applied through the PFT.	Overestimation of the compaction energy results in an underestimation of the TML.	Method should be 'calibrated' so that density conditions within the mould represent those prevailing within the cargo.
Drying a sample prior to moisture addition may prevent preventing the 'as-shipped' state moisture state from being attained.	Removal of inherent moisture may lead to a systematic underestimation of the TML	Contrary to the IMSBC Code, a sample should not be oven dried prior to PFT testing.
The IMSBC does not specify the maximum height to which the sample should be compressed within the extension piece, which can result in variable compaction conditions at the top of the levelled mould.	For fast draining materials, moisture loss and/or underestimations of the dry bulk density will result in random errors of TML results; leading to low reproducibility amongst laboratories.	The IMSBC Code must specify the height to which the material should be filled within the removable extension piece on the Proctor mould.

In addition, several sources of general variability that were identified which apply to both the TML test methods. Recommendations with regards to these include:

- Following a test, sample re-use and further addition of moisture during testing may result in the random underestimation of TML results. *Testing should only ever be carried out on a sample that has not undergone testing*.
- Drying of the sample prior to testing can affect the chemistry and/or remove interstitial moisture within the granular pores, which cannot be replaced by subsequent moisture additions—resulting in an underestimation of the TML. A *sample should never be dried prior to TML testing.*
- Screening of a sample prior to testing may result in a sample which has different strength properties from that of the unscreened sample, whereby the removal of large particles often increases the TML. Therefore, *TML testing should be performed on the PSD representative of the cargo*.
- Degradation of particles can change the PSD and influence the TML results, effecting reproducibility. *Mixing should be performed by hand and the act of compacting must not result in particle degradation*.
- Moisture loss before, during or after the test will impact the TML result and lead to random errors that particularly impact method reproducibility. Moisture loss must be *understood and controlled*.
- Moisture determination techniques can vary amongst laboratories (for example, drying temperature) and these can impact TML results and reproducibility. *Drying should be performed by internationally recognised standards*.

Appendix 6: Previous Soil Mechanics Studies

The Table below is a non-exhaustive summary of the geotechnical focused research submitted to IMO. This has aimed to assess cargo shift by assessing a cargo's strength properties.

TEST MATERIAL	TEST TYPE	TEST DESCRIPTION	INPUTS: ACCELERATION/ AMPLITUDE; FREQUENCY; TEST CONDITIONS	DIMENSIONS OF TEST APPARATUS	FINDINGS	REFERENCE
Malgberget A Fines (MAF) Iron Ore Concentrate	Shear box (300x300mm) and triaxial test	Shear-box and triaxial tests were performed, aiming to determine *(i)* the friction coefficient between a steel plate and MAF iron ore concentrate; and *(ii)* the friction angle and cohesion internally within the MAF concentrate. Tests were performed at different bulk densities (*i.e.* 3 t/m^3 and 3.5 t/m^3) and at two different moistures (2.5% and saturated [around 10% moisture]).	• Horizontal acceleration was approx. one third of vertical acceleration (case 1a and 1b) and 18/25 times (case 1c)		•Friction angle decreased slightly at higher moistures (around 2 degrees); •Friction angle and cohesion coefficient between steel plate and MAF was lower than for MAF-MAF (i.e. 0.524-0.608kPa/ 28-31 degrees between MAF and steel plate compared to 40-43 degrees – cohesion 1.1 kPa compared to about 3-6 kPa). They concluded that cargo shift is more probable along the deck surface than inside the cargo itself. The residual shear strength is similar for both loose and dense MAF. •The triaxial test did not produce reliable results about the post peak behaviour of strength of MAF iron ore. The shear box apparatus (in a reasonably large box of 300x300mm) gave better results.	[BC32/INF.11, 1992] [BC32/INF.12, 1992]
Malgberget A Fines (MAF) Iron Ore Concentrate	Scale Model: "Cylinder Tests" and "Trough Tests"	"Cylinder Tests" and "Trough Tests" were performed to determine whether pore pressures may develop in MAF iron ore from cyclic loading; and if this will affect the stability behaviour of saturated iron ore. For the Cylinder Tests, a cylinder was filled with loose saturated iron ore. Cyclic loading was applied and settlement and pore pressure were recorded For the Trough Test: a trough was filled with pile of MAF, at slope height of 400 mm and at varying slope angles (31 to 40 degrees). A wet base layer, of varying depths, was then created (50 to 100 mm). Tests were made at a frequency and amplitude range corresponding to the vertical accelerations that the M/S Finn-Baltic is assumed to have experienced before it capsized. Pore pressure and settlement were then measured	• The simulated roll angle (amplitudes) was varied between 5 to 12 degrees. • Cycle periods varied from 1 - 2.4 seconds (frequency 0.42-1Hz.	Trough test: 1:5 model of MS Finn-Baltic	•Upon applying the accelerations, the density of all samples (and therefore the degree of saturation) increased significantly (from 2.77-2.83gcm-3 initially up to 3.2-3.26 gcm-3). •When the saturated layer was high, the material could lose strength and collapse. They found that abrupt movements, for example a rapid inclination or roll of a ship, caused an immediate increase in pore pressure level, which in turn decreases significantly the shear strength of the iron ore and caused collapse even after one or two cycles.	(BC32/INF.12, 1992) (Hathmayer and Laaksonen, 1992)
Canadian Carol Lake Concentrate	Shear box; triaxial; scale models; centrifuge.	Aimed to determine a new or better criteria for determining cargo shift. Focus was given to assessing drainage. This was assessed in vertical cylinders, under applied vibration, and by numerical modelling (Kruszewski, 1985, 1988, 1991, 1992). Atkinson and Taylor (1998, 1992) performed test work in the City University centrifuge to validate the numerical work. Further, a scale model was fitted to the centrifuge to assess modes of failure, and a limit equilibrium analysis was presented.	Varied significantly. See references.	Varied significantly. See references.	•In this analysis, the researchers concluded that Carol Lake Iron Ore Concentrate could readily drain to form a saturated base. •No conclusive relationship could be found between PSD and the cargoes potential to liquefy. •The friction coefficient between the steel hold/cargo interface is lower than that internally within the cargo.	(Atkinson. and Taylor, 1988, 1992); Kruszewski,1985, 1988, 1990, 1992, 1993)
N/ A (Numerical analysis)	Numerical	Aimed to determine a criterion of non-shifting cargoes in bulk based on a theoretical study and observation of vessels Used formula K=R/F (where R = sum of cargo forces resisting shear and F = sum of forces attempting to cause the shear (shift) of the cargo). Provided that K is greater than 1 the cargo is deemed fit for shipment. The R factor, in brief, is derived from the Coulomb equation and is primarily dependent on the angle of internal friction which increases as the degree of compaction of the cargo increases. The F factor is the measure of the forces provided by the ship rolling in a seaway. The basic principle of this new criterion is that "A cargo is suitable for shipment without the need to resort to complete trimming or the fitting of shifting boards, provided its shearing resisting properties within the hold (R) are greater than the shearing forces that might develop at sea).	Max. roll 36; max pitch 10 degrees; vertical vibration up to 1.5 mm, frequency 2-6c.p.c			Submissions by the U.S.S.R. to IMO [BCXII/7/2, 1971; BCXIII/4/1, 1972 BCXIV/4/1, 1972; BCXV/4(b), 1974]
Australian Talcum (6.1%>30mm; 13.3%>20mm; 34.6%>2.5mm; 82.3%more than 1.25mm)	Triaxial, scale test-work and numerical assessment of non-shifting criterion	Aimed to: *(i)* determine *the* effect of changing bulk density on the angle of friction and cohesion; *(ii)* determine the impact of cohesion; *(iii)* investigate a non-shifting criterion for bulk cargoes. In addition to triaxial test work, they performed tests on a 'tilting platform' using a rear-dump truck as a tilting platform, where the tilt angle was visually recorded while the platform was slowly tilting. From this, they obtained the angle of shifting. They then used these results for computer-assisted calculations of a non-shift criterion λ1 in the ranges of φ and C determined by laboratory tests especially for this cargo.	Performed scale-work on back of dump-truck, varying angles of tilt between 12-35 degrees. The stress state on a slipping surface of the under-surface area was determined by normal stress figures normal stress (σ_n) of 10-30 kPa. Then, in triaxial test-work, they performed tests under normal pressure of 0.5-1.5 kgf/m3 or 50-150 kPa and horizontal confining (lateral) pressure σ3 of 20-40kPa.		•Varying the density increment from 1.5 to 1.7 t/m3 led to an internal friction angle increase of Δφ = 5 degrees. Thus, the initial stowage density of the cargo in the under surface area substantially effects the non-shifting criterion in this area. •When estimating the strength in the under surface area, they found the cohesion value of the bulk cargo never exceeded 10-20 kPa. They showed that there is cohesion in the under-surface area, though it is less than in the bedding of a pile.	Submission by the U.S.S.R. to IMO: ([BC23/5/16, 1982])
Barite Concentrates (True SG = 4.36; Min/ Max void ratio = 0.56/ 1.24; Coefficient of curvature = 1.66; Uniformity coefficient = 2.87)	Cyclic Triaxial, Scale Model feeding into numerical assessment	Firstly, cyclic triaxial test-work was undertaken. The liquefaction criteria was axial strain, where liquefaction was assumed to occur if axial strain, in terms of double amplitude, becomes 10% (*i.e.* a pore-water pressure criteria was not used). Then, they undertook scale modelling, containing 6 kg of barite concentrate levelled flat in a box shape hold (based on the M/V B-Maru). Moisture content, roll angle and period and GM were varied. Application of the Law of Similitude was neglected. The periodic heeling moment was produced by swinging an on-board dead weight and corresponding angles of roll were measured. Results from cyclic triaxial tests and scale model (in a box shaped hold) fed into numerical test work in which they assessed the region of concentrate that liquefied. This was performed based on the characteristics of liquefaction from the scale model testing, namely: *(i)* through varying rolling period, *(ii)* rolling amplitude, *(iii)* moisture content of cargo loaded, *(iv)* its condition of stowage; and *(v)* the critical number of rolling motion. They then assessed stability based on the cargo moving like a viscous fluid.	Cyclic Triaxial: frequency = 0.5 Hz Scale model tests: roll 16.6-28.2 degrees, rolling period 1.26-5.27 degrees. GM was 3.3 cm in all cases but one, where double bottom was removed to increase GM up to 5.8cm Cyclic triaxial: cell pressure = 2.8kgf/cm2; duration of consolidation = 2 hrs	Cyclic Triaxial: Test specimen diameter=7.5 cm; height = 15 cm; Scale model dimensions: LxDxH = 19x16x28c, (Based on B-Maru).	Japan assess stability based on the cargo moving like a viscous fluid – although they state that Newtonian fluid motions in the post liquefaction period are generally on the conservative side as the effects of restoring of shearing strength due to dilatancy and permeation are likely to reduce the effects. Overall, results were inconclusive.	(IMO: BC28/INF.4, 1988) (Ura, 1983a, 1983b, 1983c)

TEST MATERIAL	TEST TYPE	TEST DESCRIPTION	INPUTS: ACCELERATION/ AMPLITUDE; FREQUENCY; TEST CONDITIONS	DIMENSIONS OF TEST APPARATUS	FINDINGS	REFERENCE
Mitui-Miiki Coal (SG = 1.31)		Japan investigate the deformation characteristics of coal; in regards to the liquefaction characteristics.	Frequency 0.2 Hz effective confining pressure, 15-40 kgf/cm2; Effective confining stress set at 0.3 kgf/cm2. Plotted Stress Ratio (SR) [shearing stress/normal stress] - with N_c = 100 (*i.e.* 100 cycles) set as the criterion for liquefaction	25-100 mm specimen diameter; 150-200 mm specimen height	The coal is liable to liquefy by applying a cyclic stress of SR=0.3 at a moisture content ranging from 16-19%. The liquefaction may take place even when the degree of saturation is 50% or below; and also by applying a cyclic stress of SR=0.15 when saturated. Therefore, the degree of saturation is not considered to be a criterion to judge the liquefaction of coals. *But if a coal collapses (say, through the tamping process), then isn't this incorporated in any degree of saturation calculation (*i.e.* reduced volume, same amount of water) - therefore the reasoning that it can liquefy at S=50% seems wrong, when in fact the degree of saturation is increasing due to the application of the shear stress which is causing the reduction in volume (from, say collapse) and therefore an increase in degree of saturation?	IMO: (BC30/5/2, 1990; BC30/5/2 Annex 1, 1990)
Copper concentrate (angle of repose 48 and TML 9.4%) and Ferrosilicon (angle of repose 45 degrees).	Triaxial; Cyclic Triaxial	Norway undertook tests to determine the friction angles on two different types of bulk material; with the aim to establish a better understanding of the effect of forces acting upon bulk cargoes and to develop a simple method of determining the safe transport by sea of certain bulk cargoes. The project was divided into a theoretical and experimental part, whereby the theoretical work aimed at obtaining a calculation method for a safety evaluation for different bulk cargoes in different cargo and ship configurations (the safety factor being calculated in accordance with geotechnical principles). They also investigated the effects of dynamic forces with respect to the sliding stability of the material (to see if the material strength would decrease).	No details were provided of the parameters applied in this study.		For the copper concentrate they found that the friction angle varied between 25 to 35 degrees for different material densities, and that the angle of repose varied with the size of the cargo pile. They showed that the cargo varied at different densities and therefore concluded that it is essential to use full scale values of the material density when performing triaxial test-work.	IMO: (BC25/14, 1983; BC26/5/11 1984)
Copper concentrate (75% passing 0.06 mm) and two types of coal (0-20 mm and 0 – 1 mm)	Shear Testing	The Polish propose to introduce the utilization of shear measurements of granular materials for the determination of changes of the cohesion as a function of the water content of the material. During the shear tests the internal friction (shear stress) is determined, the friction angle and the cohesion are determined. Five measurements were used made in each experiment with the use of different normal stresses.	Normal stresses were applied equal to the corresponding compaction energies frequently used in the Proctor Mould (32.2, 49, 85.8, 294 and 588 kN/m^2). Shearing velocity was 10 mm/min.	Shear-box apparatus, shearing area of 64 cm^2	They compared the results from these tests (from which they obtained a ‘critical moisture content’) to the results obtained from various TML test methods, including the Modified Norwegian FTT method CMC, Norwegian Vibration Method, the PFT (compaction energy 589J/dm^3) the PFT (compaction energy 85.8Jdm^3). They found that these aligned well. They then calculated the ‘safety margin’ between TML and the actual obtained value from the shear test by consideration of the velocity of diminishing cohesion of the material after passing the point of maximum cohesion (*i.e.* instead of just fitting an arbitrary 10%).	IMO: (BC26/INF.2, 1984)
Brazilian (Vale) and Australia (Rio Tinto and BHP Billiton) iron ore fines.	Numerical Modelling (FEM)	The TWG performed FEM analysis on a cargo. Software modelling packages used included Femap, Plaxis, FLAC3D, LIQCA2D and UWLC. Model input parameters included: (*i*) Vessel motions from the numerical modelling and measurements (real-life and worst case). These focused on vertical and transverse motions as these were found to be the most significant contributors to cargo acceleration. (*ii*) Simplified cargo geometry; (*ii*) Soil mechanical properties, obtained from cyclic triaxial and shear-box test work. The maximum CSR's obtained within this model were used to inform cyclic triaxial and cyclic simple shear laboratory test work.	Varied, refer to full report in DSC17/INF.13 (2013)		From numerical modelling of a cargo in a Capesize hold, the TWG concluded that an induced CSR of 0.4 be used as a failure criteria for IOF. Cyclic triaxial test-work on iron ore fines samples showed that the measured cyclic shear resistance exceeded the induced CSR – and therefore that liquefaction was unlikely to occur on a ship.	IMO: (DSC17/INF.11, 2013; DSC17/INF.13, 2013)
Nickel ore, from three mines (Karembe in New Caledonia, Gebe in Indonesia and Hinatuan in the Philippines)	Direct Shear Tests	Japan conducted research aimed at finding a method to determine the upper bound of moisture content of nickel ore, which loses static shear strength due to high moisture content, to minimise the risk of shifting (NOTE: This work was performed prior to nickel ores being classed as Group A, *i.e.* before TML testing was required for this cargo). They perform limit equilibrium analysis to determine a ‘safe slope angle chart,’ in which shear strength for the safe transportation of a material can be evaluated by the trimming condition through consideration of the non-dimensionless cohesion. The shear strength of the nickel sample was measured at different moisture contents by direct shear tests or triaxial compression tests. Through consideration of these results, along with estimates of how dry bulk density changes with moisture content (from the test results) and cargo geometry, the non-dimensional cohesion was calculated. The ‘safe slope angle chart’ could then be constructed, from which the shear strength relating to moisture content was plotted.	Constant vertical load (value not provided); Sample tamped at 30kPa to control void-ratio (samples stuffed by hand into box at higher moisture contents); tangential load obtained by measuring force used to confine the horizontal movement of the upper shearing box. For dry samples, this had a peak value; at other tests where there was no peak, the resisting tangential stress was calculated from the tangential load at horizontal displacement of 8 mm.	60×60 mm box and 30 mm test specimen	Their results showed that nickel ore loses static shear strength due to increase of moisture content. From these results, Japan concluded that the safe upper bound of moisture contents of the samples of nickel ores from Karembe, Gebe and Hinatuan were 29.1, 36.7 and 30.7 percent, respectively (with a safety factor of 1.2). However, from observation of the plots which show void ratio/ bulk density against moisture content, the OMC for these three materials was 27, 35.2 and 28.4 percent, respectively. These values, which could be obtained from a simple proctor test, therefore the approximate safe condition – albeit slightly more conservative.	IMO: (BC33/3/2, 1994; BC33/3/2 Annex 1, 1994)”

Appendix 7: Results from Cyclic Studies on Iron Ore Fines

Results from a research submission by Australia/Brazil to the Sub-Committee for Dangerous Goods, Cargoes and Containers (Taken from DSC18/INF.13, 2013)

The Figure below presents the findings of cyclic assessment of liquefaction of three Australian iron ore fines cargoes (D1, D2 and D3, from Rio Tinto Group), whereby the cyclic stress ratio (CSR) determined from undrained cyclic triaxial testing (at different degrees of saturation) is compared to the induced CSR predicted from FEM modelling of a cargo during transit. From this work, it was concluded that because the cyclic stress resistance exceeds the modelled induced CSR behaviour for the cargo all degrees of saturation, these iron ore fines cargo are stable at the worst-case range of sea-state combinations predicted for voyages. (IMO DSC18/INF.13, 2013)

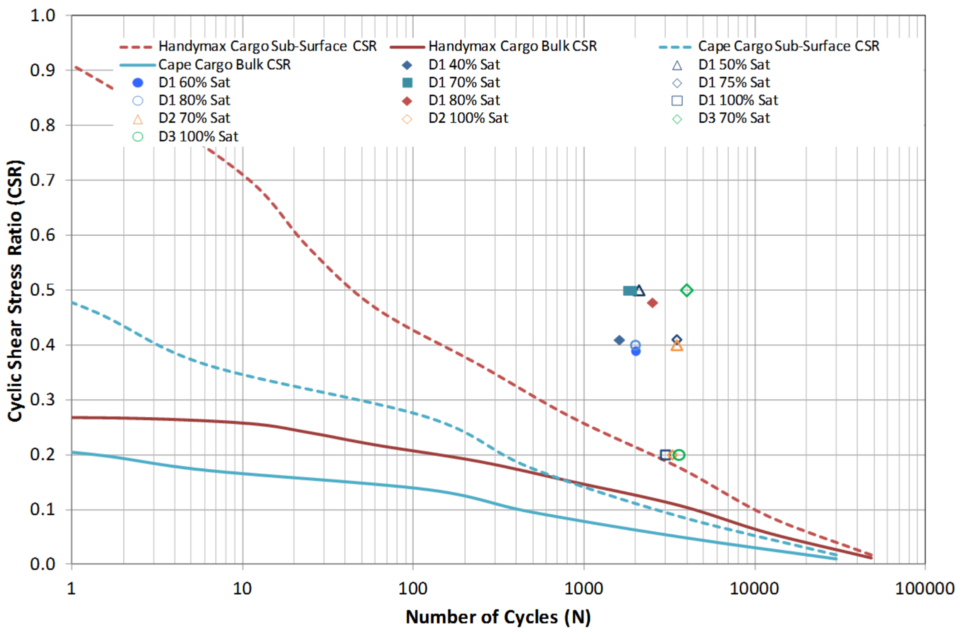


Figure: IOF resistance and vessel induced CSR verses Number of Cycles for Australia – China Voyages, where solid markers represent the results for tests that reached a 5% axial strain failure criteria and the hollow markers indicate those tests that did not met the stop condition criteria (*i.e.* axial strain was less than 5%)—no test met the pore-water pressure criteria. Plot from research submitted to IMO's DSC18 meeting (IMO DSC18/INF.13, 2013)

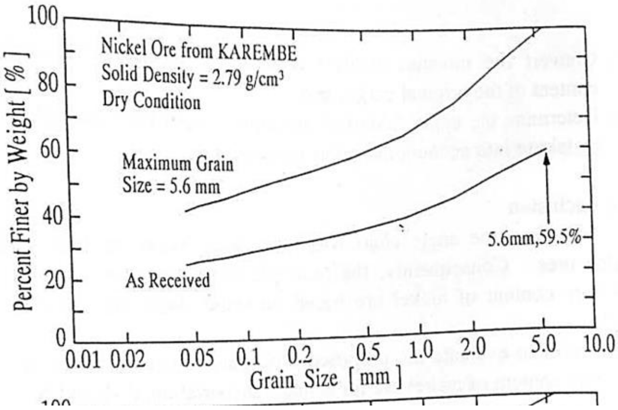
Note that each CTT test was conducted by applying a deviator stress equal to the vessel rigid body motion frequency of 0.1Hz, vertical cargo confining pressures of 400kPa and radial confining pressure of 200kPa (to approximate the pressures at the bottom of the cargo hold). The CTT tests were undertaken under *anisotropic* and *undrained* conditions – because iron ore fines remained unsaturated during voyages. (IMO DSC18/INF.13, 2013)

Appendix 8: Results from Static study on Nickel Ore

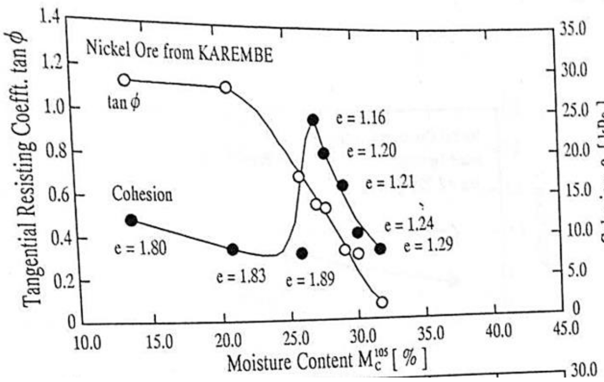
'Determining the Upper Bound Moisture Content of Nickel Ore': *Taken from a research submission by Japan to IMO's Sub-Committee for Solid Bulk Cargoes (BC33/3/2, 1994)*

For each cargo type, the following analyses were performed, aiming to find a 'safe slope angle' that a cargo should be trimmed to prevent its slope failure during passage.

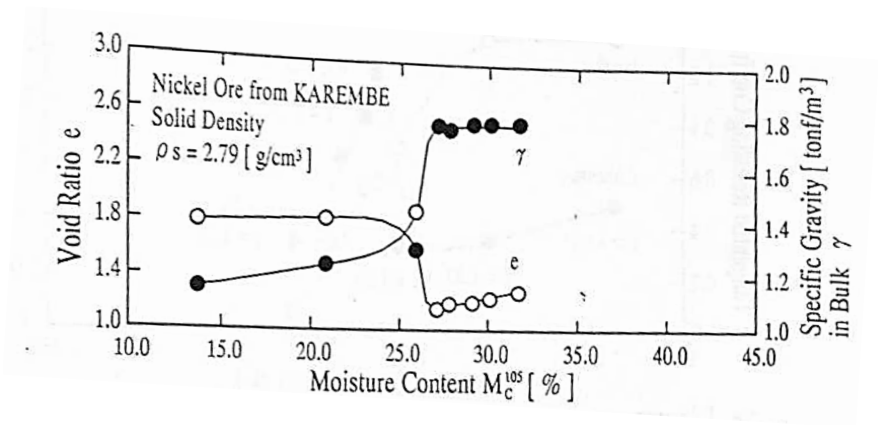
a) Determine material properties:



b) Ascertain relationship between shear strength and moisture:



c) Determine the void ratio and specific gravity in bulk:



d) At the assumed cargo geometry, a 'safe slope chart; was then derived:

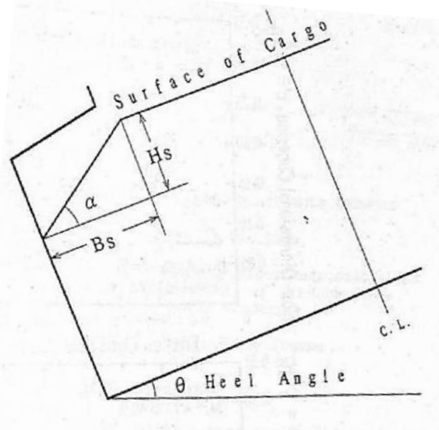


Fig. 4. Shape of Cargo Pile

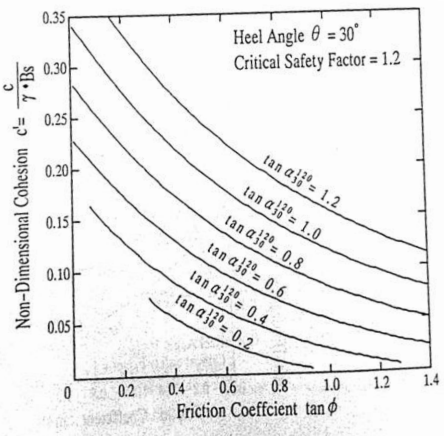


Fig. 5. Safe Slope Angle Chart