EXIGÊNCIAS DE LIMITE DE UMIDADE TRANSPORTÁVEL (TML) PARA TRANSPORTE MARÍTIMO DE MINÉRIO DE FERRO*

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Resumo

Cargas a granel, incluindo finos de minério de ferro, devem ser embarcadas de acordo com as diretrizes acordadas entre os membros da Organização Marítima Internacional (IMO). Uma medida de segurança crítica é o Limite de Umidade Transportável (TML), exigido para cargas do Grupo A (cargas que têm tendência à liquefação). Diversos acidentes com navios envolvendo finos de minério de ferro da India, cuja causa suspeita-se ser a liquefação da carga, trouxeram à atenção o tema do TML de finos de minério de ferro. Um trabalho extenso de pesquisa foi desenvolvido pelos principais produtores de minério de ferro da Austrália e do Brasil para dar suporte à IMO no desenvolvimento de normas para o embarque desse tipo de material. Com essa finalidade, mineradoras patrocinaram o projeto AMIRA P1097, que foi conduzido pela TUNRA Bulk Solids (TBS) e o Centre for Bulk Solids and Particulate Technology (CBSPT), CSIRO e a Universidade de Auckland, com a gestão do projeto sendo feita pela Creative Process Innovation, a fim de estabelecer uma abordagem modificada de testes de TML específica para finos de minério de ferro. Esse estudo deu suporte aos resultados dos testes e conclusões do Technical Working Group do IMO, que publicou suas conclusões e descobertas em Setembro de 2013.

Palavras-chave: Limite de umidade transportável; Embarque de minério; Manuseio de granéis sólidos; Cargas a granel.

MARITIME BULK CARGO TRANSPORTABLE MOISTURE LIMIT REQUIREMENTS FOR IRON ORE SHIPMENTS

Abstract

Bulk cargoes, including iron ore fines, must be shipped according to the rules agreed by the member states of the International Maritime Organisation (IMO). One critical safety measure is the transportable moisture limit (TML), required for Group A cargoes (cargoes that may liquefy). A number of shipping incidents involving iron ore fines from India, where liquefaction of the cargo was suspected to be the cause, have brought the issue of iron ore fines TML into the spotlight. Extensive research work has therefore been undertaken by the major iron ore producers from Australia and Brazil to support the IMO in developing regulations for the shipment of iron ore fines. To this end, iron ore companies sponsored the AMIRA P1097 project, which was undertaken by TUNRA Bulk Solids (TBS) and the Centre for Bulk Solids and Particulate Technology (CBSPT), CSIRO and the University of Auckland with project leadership provided by Creative Process Innovation, to establish a modified TML test approach specific to iron ore fines. This program of work supported test work findings from the IMO Technical working group that reported its findings in Sept 2013.

Keywords: Transportable moisture limit; Ore shipment; Bulk solids handling; Bulk cargoes.

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1 INTRODUCTION

This paper was originally published by AusIMM in the Iron Ore 2015 conference proceedings. The replication of the paper for the ABM conference and proceedings in Brazil is made as the research and outcomes presented within this paper will benefit the industry with regards to increasing the knowledge of the development and current requirements for iron ore transportable moisture limit determination.

Mineral ores and concentrates have been shipped by sea in bulk for over 100 years. Iron ore is commonly shipped as either a lump or a fines product. Lump ore is typically coarser than 6mm (nominal) and have typical nominal top sizes of 31.5mm or 40mm. Fines are typically -6.3mm (nominal) or up to -12mm (nominal) in some cases. It is the world's most common solid bulk cargo at a yearly shipping mass of over 1 billion tonnes.

In 1937, sea borne trade of all mineral ores only amounted to 25 million tonnes and this could be carried in conventional freight vessels. By the 1950s, however, movement of bulk cargoes increased as the world economy ramped up. Very often ores and other commodities were sourced far away from where they were required and the most convenient and cheapest way of shifting them was by sea. As demand increased and shipbuilding technology advanced, the ships built tended to become bigger in size and carrying capacity. By the 1970s, bulk carriers of more than 200,000 dead weight tonnes (DWT) were operating. Commonly, iron ore is shipped in ‘Capesize’ bulk carriers of ~200,000 DWT and nine separate holds. Recently, ships of 400,000 DWT have been designed for transporting iron ore lump and fines.

The International Maritime Organization (IMO), known as the Inter-Governmental Maritime Consultative Organization (IMCO) until 1982, was formed in 1959 and one of its first tasks was to consider new measures for improving the safety of bulk carriers. The IMO developed the International Maritime Solid Bulk Cargoes Code (IMSBC), which was adopted in 1965. The IMSBC Code has been updated at regular intervals since then and is kept under continuous review by the Sub-Committee on Dangerous Goods, Solid Cargoes and Containers (DSC) (now known as the IMO Subcommittee on Carriage of Cargoes and Containers (CCC)). The practices contained in the IMSBC Code are intended as recommendations to Governments, ship operators and shipmasters. Its aim is to bring to the attention of those concerned an internationally-accepted method of dealing with the hazards to safety which may be encountered when carrying cargo in bulk and is the most relevant code to the safety of iron ore bulk carriers. The IMSBC Code highlights the risks associated with the shipment of certain types of bulk cargoes, gives guidance on various procedures which should be adopted, lists typical products which are shipped in bulk, gives advice on their properties and how they should be handled and describes various test procedures which should be employed to determine the characteristic cargo properties.

The IMSBC code was again updated in 2009 (then known as the BC code). However, ships continued to sink carrying mineral cargoes which were said to have liquefied. In 2009, four bulk cargo incidents occurred with ships carrying iron ore which capsized or developed permanent lists which were potentially attributable to bulk cargo shift either due to liquefaction and/or sliding failure however detailed investigation reports of the incidents and all the possible factors are not available (see Table 1). It is important to note that in all these incidents the port of loading originated from India with the vessel en-route to China. It is also important to note that the vessel size was less than 40,000 DWT.

Table 1. List of bulk carrier accidents carrying iron ore in 2009.

Date of Accident	Vessel Name	Voyage Details	Vessel size(t)/type	References
17/07/2009	Asian Forest	From New Mangalore to China. Sank in the Arabian Sea 8 miles southwest Of Mangalore, India	14,434 t General Cargo Ship	Marine Buzz, 2009; Maritime Accident Casebook, 2009
08/2009	Hodasco 15	From Calcutta to China. Capsized and sank off Malaysia.	6,519 t General Cargo Ship	Steel Guru, 2009
09/09/2009	Black Rose	From India to China. Sank off Paradip port, India	37,657 t Bulk Carrier	Bulk Carrier Guide, 2010
09/2009	Vinalines Mighty	From Paradip India to China. Developed a list.	22,625 t Bulk Carrier	Intercargo, 2010; Jonas 2010

The IMSBC code deals with three basic types of bulk cargo:

- Group A- those materials which may liquefy;
- Group B- materials which may possess chemical hazards; and
- Group C- materials which fall into neither of these categories.

In October 2010, the DSC released a circular (IMO, 2010) which stated that “iron ore fines may liquefy and should be treated as such”, effectively classifying all iron ore fines as a Group A cargo. At this time, the IMSBC Code details three alternative laboratory transportable moisture limit test procedures for materials which may liquefy:

a. The Flow Table Test
b. The Proctor/Fagerberg Test
c. The Penetration Test

None of these test procedures were specifically designed for iron ore fines cargoes, and no specific Schedule for iron ore fines existed at this time in the IMSBC Code. The historic basis of these tests is reported in the P1097 Literature review [9], and the results of these tests and their sensitivity to a range of variables are summarised in this report. The DSC subsequently formed a Correspondence Group in 2011 to consider the issue of iron ore fines and to establish a schedule for iron ore fines. Subsequently, three major iron ore companies were asked to form a Technical Working Group (TWG), to report directly to the DSC Correspondence Group on the issue of iron ore fines by September 2013.

In parallel with the TWG work, the AMIRA P1097 project was established in April 2012 to develop fundamental understandings of the potential for iron ore fines to liquefy and use this knowledge to recommend how best to assess the liquefaction potential of an iron ore fines bulk cargo. This project was executed by three highly credible research organisations, the CSIRO Minerals Down Under Flagship (now the Mineral Resources Flagship), TUNRA Bulk Solids Handling (TBS), and the University of Auckland with project leadership provided by Creative Process Innovation.

This paper summarises the AMIRA P1097 work with its contents containing summaries and extracts from the P1097 Final Public report [10]. The key deliverables from the project were:

1. A quantitative understanding of the potential for iron ore fines liquefaction and cargo behaviour under cargo-transport related conditions, including a literature review; and
2. A recommendation for how the liquefaction potential of iron ore fines should best be measured in a practical way for cargo loading, along with a draft Standard Operating Procedure for that test.

The P1097 sponsors were five iron ore producers from Australia and one from Brazil, the Minerals Council of Australia, and the Western Australian Chamber of Minerals and Energy. Eleven [11] samples of iron ore fines from Australia and Brazil and one iron ore concentrate sample were supplied by Sponsor companies, with the main properties summarised in Table 2.

Table 2. Overview of ores studied. Goethite % measured by quantitative x-ray diffraction(QXRD).

Ore ID	Description	% Goethite (QXRD)
A	Hematite (martite) – goethite ore	42
B	Martite – goethite ore	23
C	Hematite ore	18
D	Iron ore concentrate	0 (Reference material)
E	Goethitic channel iron deposit ore	82
F	Hematite ore	9
G	Martite – goethite ore	75
H	Goethitic channel iron deposit ore	82
I	Goethitic channel iron deposit ore	84
J	Martite – goethite ore	61
K	Martite – goethite ore	72
L	Martite – goethite ore	56

The majority of the AMIRA P1097 investigative work was carried out on 5 priority ore samples (ores A to E), covering a wide range of iron ore properties. Further work was carried out on an additional 7 iron ore fines samples to expand the range of iron ores tested with the aim of confirming the results observed for the priority ores. These samples were comprehensively characterised and subjected to the three standard TML tests from the IMSBC code. The potential for cargo failure during ocean transport of iron ore fines was then evaluated from two perspectives; geotechnical earthquake engineering and bulk materials handling.

In evaluating the potential for cargo failure cases, it was important to incorporate realistic estimates of vessel motion into the analysis, and this was done through input from the Australian Maritime College and the TWG. This knowledge, combined with observations of Sponsor companies on the state of the cargo during shipments of iron ore fines, led to the co-development with the TWG of an alternative TML test based on the existing Proctor/Fagerberg test. The modified Proctor/Fagerberg test, or PFT D80 test, has been calibrated to the properties of iron ore fines.

Extensive characterisation of all of the iron ore fines samples was also carried out as part of the AMIRA P1097 project, including particle size distribution, chemical assay, mineralogy determined by quantitative X-ray diffraction and by optical point counting, thermogravimetry, particle density, porosity, and scanning electron microscopy. Some correlation between the resistance to liquefaction and the ore characteristics has been found.

2 SUMMARY OF THE EVALUATION OF THE THREE IMSBC PRESCRIBED TML TEST METHODS

TML testing was carried out on four different iron ore fines samples (A, B, C and E) using the three methodologies listed in the IMSBC Code, with the results compared in Figure 1. The absolute TML value (moisture content on a wet basis) has been masked by subtracting a different value (X) for each iron ore sample to comply with international anti-trust requirements. Tests were performed in duplicate and the averages of the individual test results are shown.

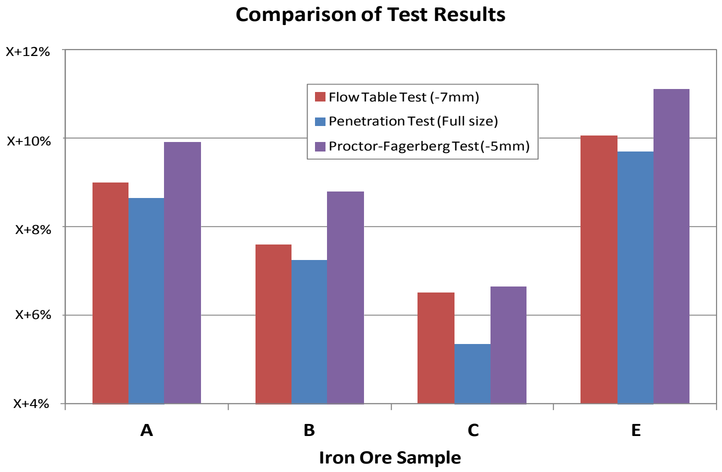


Figure 1. TML test result comparison

Using the standard methodology presented in the IMSBC Code, it was found that there is a considerable discrepancy between results obtained using the Flow Table, Penetration and Proctor/Fagerberg methods. Depending on which iron ore fines sample was chosen, the overall difference between the test procedure yielding the lowest transportable moisture limit and the one yielding the highest value can be as much as 1.5% in absolute terms.

Based on the AMIRA P1097 investigation as well as extensive prior experience testing iron ore fines at the independent TUNRA Bulk Solids testing laboratories at the University of Newcastle, the following conclusions are made:

1. A number of issues have been identified with the Flow Table Test. These are the limitation on particle size distribution, too small a sample mass and a result that is dependent on operator judgment. In addition, a single energy input is given to the samples during testing, which may or may not represent the appropriate energy input for shipment of iron ore fines.
2. The Penetration test overcomes some of the limitations of the Flow Table Test; however, a single energy input is still given to the samples during testing, which may or may not represent the appropriate energy input for shipment of iron ore fines. Furthermore, the results are considerably different to those measured using the Flow Table and Proctor/Fagerberg test when applied to iron ore fines, and it is not clear that the results represent conditions experienced in actual shipments of iron ore fines.
3. The Proctor/Fagerberg test is based on soil mechanics principles and has been calibrated in the past to shipments of iron ore concentrates. A number of issues have been identified with the application of the Proctor/Fagerberg Test to iron ore fines. These are the apparent limitation on particle size distribution, uncertainty around the correct particle density to utilize for porous solids, the specification of complete drying of the samples prior to testing, moisture equilibration time, and the applicability of the compaction energy to real values measured in shipments of iron ore fines. These issues are addressed in the following section.

2.1 Modifications to the Proctor/Fagerberg Test for Application to Iron Ore Fines

Out of the three current TML methods available for use, the TWG assessed that the Proctor/Fagerberg test method was the most applicable test to investigate with respect to iron ore fines TML. Subsequently, the AMIRA P1097 project also conducted an assessment on this method in parallel with the TWG work.

In order to investigate the impact of the limitations of the Proctor/Fagerberg test on the TML value, at a saturation ratio (Sr) of 70%, the Proctor/Fagerberg test was carried out under a range of different conditions. Based on the recommendation from the TWG research, the TML was also calculated at Sr = 80% for comparison. The range of test variations conducted is listed below:

- IMO Proctor/Fagerberg test procedure (25 drops of a 350 g hammer from 20 cm onto 5 layers), using the -5 mm size fraction, no moisture equilibration
- IMO Proctor/Fagerberg test procedure (25 drops of a 350 g hammer from 20 cm onto 5 layers), using the full size distribution of the iron ore fines, no moisture equilibration
- IMO Proctor/Fagerberg test procedure (25 drops of a 350 g hammer from 20cm onto 5 layers), using the full size distribution of the iron ore fines, 24hours allowed for moisture equilibration prior to testing
- Modified Proctor/Fagerberg test procedure (25 drops of a 150 g hammer from 15 cm onto 5 layers), using the full size distribution of the iron ore fines, 24 hours allowed for moisture equilibration prior to testing
- Modified Proctor/Fagerberg test procedure (25 drops of a 150 g hammer from 15 cm onto 5 layers), using the full size distribution of the iron ore fines, 24hours allowed for moisture equilibration prior to testing, and Sr = 80%

The results of the Proctor/Fagerberg style tests described above are shown in Figure 2The absolute TML value (moisture content on a wet basis) has been masked by subtracting a different value (X) for each iron ore sample to comply with international anti-trust requirements. Tests were performed in duplicate and the averages of the individual test results are shown.

An example P-F compaction curve is shown in Figure 3 for ore B. This shows the comparison between the void ratio and moisture content when compacted using the IMO procedure with the 350 g hammer, and the modified P-F test with the 150 g hammer, as well as the void ratio for ore B on loading, measured in the vessel hold by the sponsor company. There are three important observations from the Proctor/Fagerberg curve analysis, namely:

- Sponsors’ in-situ void ratio data indicate that lower levels of impact style compaction/consolidation occur during ship loading in comparison to all the 350 g impact hammer tests.
- The levels of compaction are near or less than the 150 g Proctor/Fagerberg test work, suggesting that this is a more appropriate level of compaction for TML testing of iron ore fines cargoes
- The maximum compaction state, which appears as a minimum in the Proctor/Fagerberg compaction curve (known as the Optimal Moisture Content or OMC) occurs at the degree of saturation (Sr) greater than 90% for all of the ores.

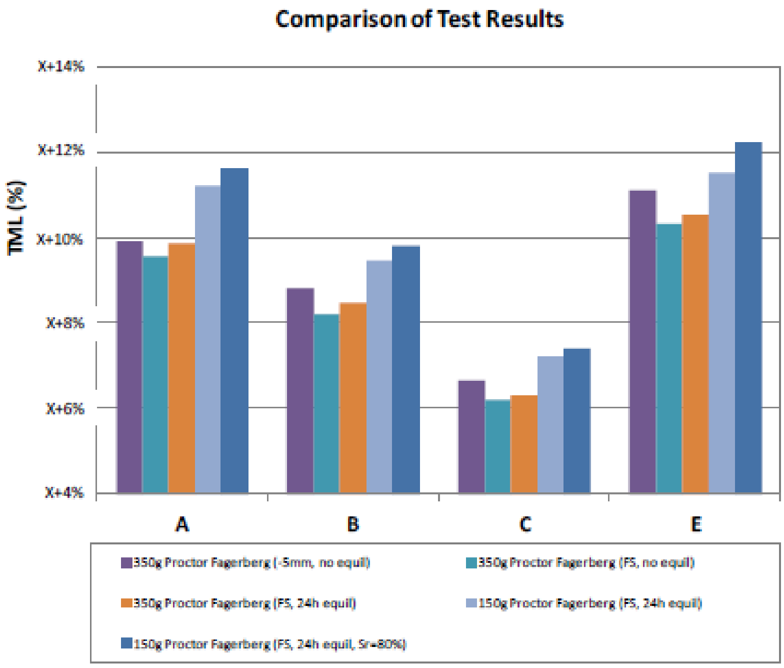


Figure 2. Comparison of TML testing methods for 4 different iron ore fines samples evaluated

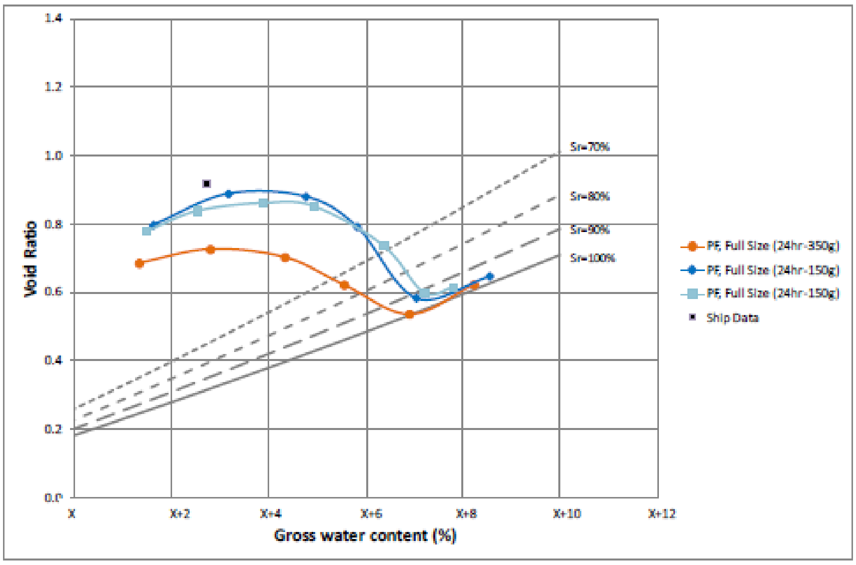


Figure 3. Ore B Proctor/Fagerberg compaction curve comparison

Based on these results and the TWG research, a modified Proctor/Fagerberg test (PFT D80) was proposed with the following key differences:

- Use of the full size distribution of the iron ore fines.
- No full drying of samples prior to testing.
- Moisture equilibration, because it has a significant impact on the measured TML for porous ores. Ores should be tested to determine whether this is significant and, if so, these ores should be left for 24 hours or overnight to allow moisture equilibration prior to testing.
- Modification of the compaction to 25 drops of a 150 g hammer from 15 cm for each of the 5 layers, to match compaction conditions measured in shipments of iron ore fines.
- Use of an Sr value of 80% to calculate the TML value. This better reflects the optimum moisture content of iron ore fines with a safety factor.

- Particle density is a significant parameter in the Proctor/Fagerberg type TML analysis. A water based pycnometry method should be used to determine the density of the solid material in accordance with a recognised standard, e.g. AS 1289.3.5.1, NZS 4402.2.7.2. If a water pycnometer is not available, gas pycnometry can be used in accordance with a recognised standard, e.g. ASTM D5550.

2.2 Iron Ore Fines Bulk Strength

TUNRA Bulk Solids apply well known techniques for bin, hopper, stockpile, feeder, transfer and conveyor design, utilising laboratory tests aimed at duplicating field conditions and providing the designer with such parameters as:

- Yield loci and flow functions (FF) for instantaneous and time storage conditions for the range of moisture contents and, as relevant, temperatures occurring in practice. The flow functions represent the variation of unconfined yield strength σc with major consolidation stress σ1 as occurs during storage and flow.
- Effective angle of internal friction δ as a function of major consolidation stress.
- Static angle of internal friction φt as a function of major consolidation stress and time consolidation.
- Wall friction angles φ as a function of normal stress for different storage vessel and transfer wall materials and finishes.
- Bulk density ρ as a function of major consolidation stress.

The foregoing tests are based on the original work of Jenike [18] and have been subsequently documented by others such as Roberts [19]. These same techniques can be applied to analysis of the state of iron ore fines bulk cargoes in a ship’s hold.

Changes in moisture content can significantly influence the strength of bulk solids. Experience has shown that at low consolidation, the peak bulk strength of virtually all bulk solids, including iron ore, may occur at a moisture content somewhere between 60% and 90% of the free drained saturation limit (FDS). By way of illustration, the unconfined yield strength of the four different iron ore fines is shown in Figure 4**Figure 4**. The highest strength of Ore B is clearly evident at 70% of FDS. This behaviour is also clearly evident for ores A, B and E. Ore C shows a maximum yield stress between 40-60% of FDS, however, its absolute strength at 80% FDS is still relatively strong in comparison to ores A, B and E at much lower FDS values (30-40%).

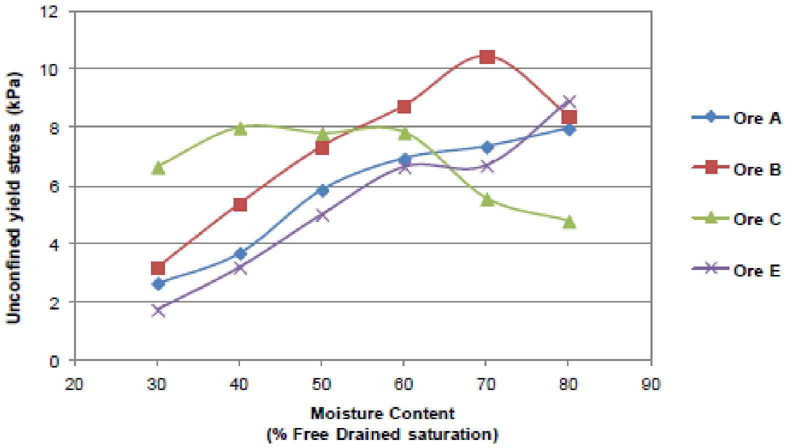


Figure 4. Unconfined cohesive yield strength of 4 iron ore fines samples evaluated as a function of free drained moisture content for low consolidation conditions.

From a bulk materials handling perspective, the iron ore fines samples still retain significant bulk strength at the PFT D80 TML values measured, as these TML values are contained within the 70-90% range of the free drained saturated moisture content. The consequence of this bulk strength and the slip resistance of the ore due to ship motion roll is the focus of work presented below.

2.3 Laboratory Cyclic Triaxial Tests (CTT)

The laboratory CTT has been used extensively in geotechnical earthquake practice to evaluate the liquefaction potential of a material. CTT is generally conducted under a fully saturated, undrained and stress-controlled environment to identify the conditions that will lead to liquefaction, i.e. in terms of material properties (e.g. relative density, degree of saturation, etc.) and system variables (conditions to which the material is subjected, e.g. cyclic shear stress amplitude, number of cycles of shearing, effective confining pressure, drainage condition, etc.). However, CTT is a very complicated test and it requires specialised laboratory equipment and expert knowledge to interpret results. Because of the inherent difference in material properties and system variables associated with soil subjected to earthquake loading vis-à-vis iron ore fines subjected to vessel motion, CTT has not typically been used for iron ore fines. Nevertheless, CTT results can provide indications of the susceptibility of iron ore fines to liquefaction under certain laboratory conditions, which then can be extrapolated to the more general shipping conditions.

A series of cyclic undrained triaxial tests were conducted on iron ore fines to determine their liquefaction resistance. Isotropically consolidated tests were conducted on fully saturated specimens and partially saturated specimens (Sr=80%) at an effective confining pressure of 250 kPa. Isotropically consolidated tests are commonly used to represent level-ground sites where no initial shear stresses exist on horizontal planes. Liquefaction resistance curves were then plotted to represent the relationship between the applied cyclic shear stress ratio (CSR) and the number of cycles required to produce either a 95% excess pore water pressure ratio or a 5% double amplitude axial strain.

To compare the liquefaction resistance of the different ores, the CSR corresponding to N=500 cycles (considered as the representative number of significant cycles an iron ore cargo is subjected to), is read from the liquefaction resistance curve for each ore; this is taken as the liquefaction resistance (or cyclic resistance ratio, CRR) of the ore. A comparison of the CRR for all ores at an effective confining pressure of

250kPa under both fully saturated and partially saturated (80% saturation) conditions was conducted, as shown in Figure 5.

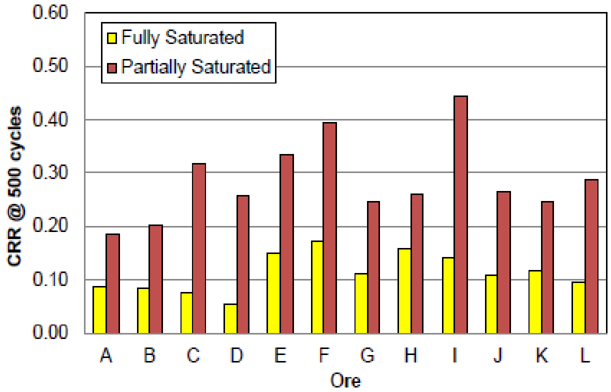


Figure 5. Comparison of liquefaction resistance of the iron ore fines samples evaluated at N=500 cycles

Based on the results of the CTT, some of the key findings are as follows:

- The liquefaction resistance of ores from isotropic undrained CTT tests increases as the degree of saturation decreases.
- There is a strong correlation between the goethite content and particle size distribution of the ore and its liquefaction resistance.
- In half of the isotropic tests involving fully saturated ores, liquefaction was characterised by the development of both large axial strain and high excess pore water pressure. On the other hand, when liquefaction was observed in isotropic tests on partially saturated ores, in most cases it involved the development of large strain with the pore water pressure not reaching 95% of the initial confining pressure. The low degree of saturation at the start prevented the development of high excess pore water pressure during cyclic loading.
- The liquefaction resistance is also affected by the confining pressure, with the liquefaction resistance decreasing with increasing initial effective confining pressure.

It is important to note that the iron ore fines investigated herein were subjected to undrained CTT testing under fully saturated and isotopically consolidated conditions such that liquefaction eventually occurred when the ore was subjected to high enough cyclic shear stresses over a long period of time. In order to determine if liquefaction of fully saturated ore can occur within the ship hold, the results of these CTT tests need to be compared with the possible range of stresses (and number of significant cycles) that the ores may be subjected to during actual ship motion. For this purpose, numerical modelling of the response of an iron ore cargo during ship motion was carried out.

2.4 Ore Characterisation Summary

The iron ore fines samples were characterised to allow investigation of the factors that affected the potential for liquefaction. Characterisation techniques applied to the iron ores included wet and dry sizing, chemical assay by x-ray fluorescence (XRF), mineral composition by quantitative x-ray diffraction (QXRD), mineral composition by optical microscopy, thermogravimetric analysis, and determination of particle specific gravity, specific surface area and porosity.

The potential for liquefaction was characterised by the cyclic resistance ratio (CRR) at 500 cycles under fully saturated conditions as described above. CRR was shown to correlate well with the iron ore fines goethite content, as shown in Figure 6, with higher goethite content iron ores having a greater resistance to liquefaction. Liquefaction resistance was also shown to correlate well with median particle size (D50) as shown in Figure 7.

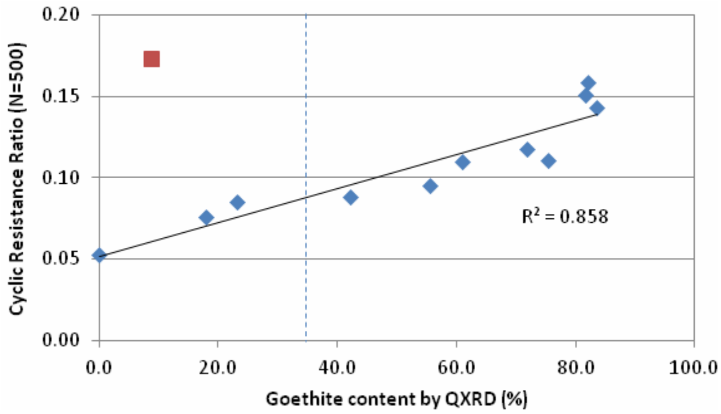


Figure 6. Comparison between the Cyclic Resistance Ratio and the goethite content as determined by QXRD for the iron ore fines samples evaluated. (NB: Ore F is indicated by the red square and is not included in the linear fit analysis).

Ore F is a coarse free draining hematite ore, which is the product of wet mineral processing operations that greatly altered its particle size distribution in comparison to the other iron ore fines samples. This ore sample has the highest median particle size of the ores tested, and also the highest liquefaction resistance under fully saturated conditions.

Considering these trends, it was concluded that although the liquefaction resistance generally increases with increasing goethite content, the mineralogy may be a proxy for other physical properties of the iron ore fines such as size distribution, specific gravity and porosity. At a degree of saturation of Sr = 80%, as specified in the PFT D80 test, a porous iron ore sample will have much less “free water” (total water subtracting water contained in pores) available on the surface of particles to influence bulk strength or participate in liquefaction. This is shown schematically in Figure 8, where the ratio of free water to air is much lower for porous ores. Taking the measured TML from the PFT D80 test at Sr = 80%, and assuming that all internal porosity in the iron ore fines is filled with water, a “effective saturation” can be defined as the volume of free water in cm3 / (1000 cm3 – volume of solids in cm3). It can be seen from Figure 9 that this effective saturation is much lower than 80% for the highly porous, high goethite iron ore fines samples. This, coupled with the particle size distribution, is thought to control the liquefaction resistance of the samples tested.

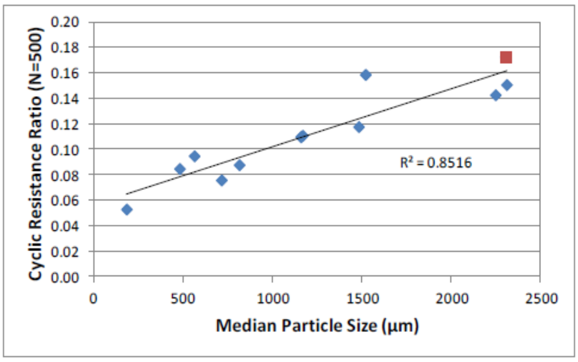


Figure 7. Comparison between the Cyclic Resistance Ratio and the median particle size for the iron ore fines samples evaluated. (NB: Ore F is indicated by the red square and is included in the linear fit analysis).

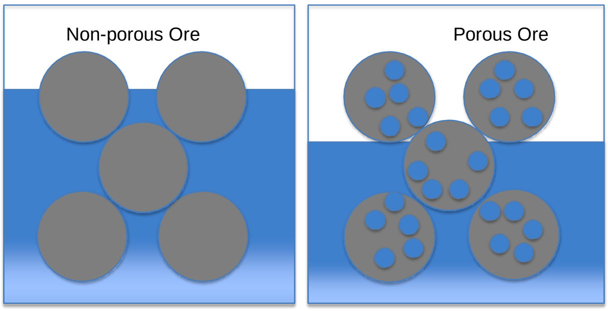


Figure 8. Schematic diagram of the distribution of water for two different iron ore samples at Sr = 80% in the PFT D80 test (iron ore is grey, water is blue and air is white).

During characterisation of the iron ore samples a range of goethite measurement techniques were investigated, including quantitative x-ray diffraction, optical mineralogy, thermogravimetric analysis and loss on ignition measurements. QXRD was considered to be the most suitable reference method provided it is carried out by expert operators at a reputable laboratory. Comparison of the results of the various goethite measurement techniques suggests that measurement of weight loss at 425°C appears to be a practical approach for the ores encountered in this study, provided the ores have been fully characterised so that a correction can be applied for any weight loss not associated with goethite (Figure 9).

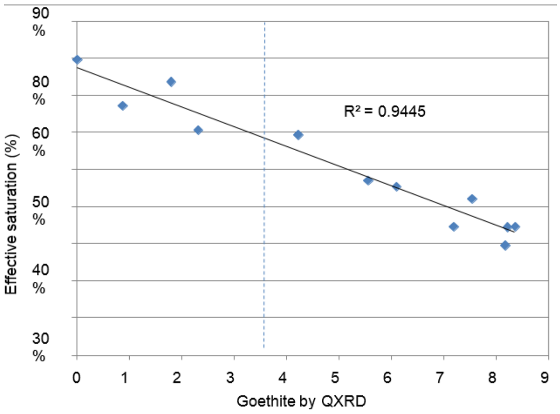


Figure 1. Comparison between "effective saturation" and the goethite content as determined by QXRD for the iron ore fines samples evaluated.

2.5 Numerical Modelling

Laboratory scale tests give valuable information about the behaviour of small elements of iron ore when subjected to uniform changes in stress conditions. To extend this analysis for considering the behaviour of iron ore fines as bulk cargo subjected to vessel motion, the following numerical modelling approaches have been used in the AMIRA P1097 project from the “wet” geotechnical approach to the “dry” bulk materials handling approach:

- Sub-surface failure modelling
- Liquefaction modelling

Both analyses predict that even if a wet base forms in an iron ore fines bulk cargo, the overburden still has sufficient strength to prevent failure.

2.6 Vessel Motion

Understanding the behaviour of iron ore fines cargoes during ocean transportation requires a knowledge of the actual forces to which the vessel is subjected during a voyage and the consequent behaviour of the vessel. Measurements of these forces are not readily available or well documented. An in-depth study of vessel motion as defined in Figure 10 was made available to the AMIRA P1097 project by the Technical Working Group. This study, entitled the Marine Report (TWG 2013b), aimed to identify and quantify the forces experienced by different sized vessels by both calculating and measuring vessel motions and vibrations in a range of sea states.

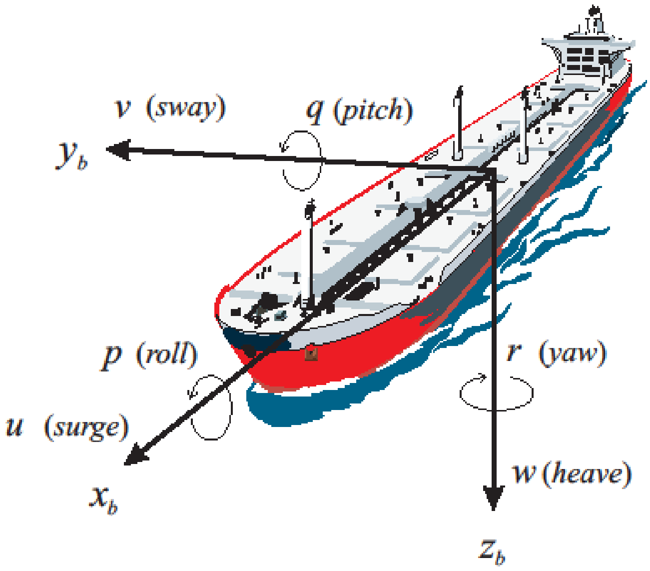


Figure 2. Body reference frame and co-ordinate system used in ship motion description.

The conclusions of the TWG Marine Report (TWG 2013b) on vessel motions and forces were:

- The contribution from vibrations associated with engines is negligible.
- In respect of rigid body motions, based on vessel motions captured and calculated, only the vertical and the transverse motions are significant compared to longitudinal motion.

- For vertical and transverse motions, accelerations in Handysize vessels are up to twice those of Capesize vessels.
- Capesize vessels have a natural roll period of 10 seconds or 0.1 Hz based on various RAOs (Response Amplitude Operators) and response spectra.
- Hold 1 (forward hold) experiences the largest accelerations.
- Real-world accelerations measured during voyages are typically lower than those predicted by voyage calculations.
- The observed vessel accelerations are less than 1 G, typically 0.1 G.
- Weather routing as an outcome of good seamanship reduces the maximum accelerations experienced.

The conclusions of the TWG Marine Report [21] with respect to cargo observations were:

- Laser scans show quantitatively that the iron ore fines cargo mass did not move significantly within a hold during the voyages undertaken.
- Cargo volume compaction varies from 0-10%, but is typically around 1-2%.
- Laser scanning/survey allows for precise determination (+/-0.5% volumetric) of cargo bulk density.
- Volumes of pumped bilge water indicate up to 1% moisture reduction (absolute percent change) during a voyage for Brazilian cargoes. The moisture reduction for Australian iron ores is at least an order of magnitude less.
- Bilge pumping data as well as discharge inspections and observations show Australian iron ore fines have no appearance of free water at discharge. Some Brazilian ores do show the appearance of free water during the voyage, but can be managed by the pumping of bilges.
- Limiting trimming to the natural angle of repose impedes the surface impacts of free water.

2.6.1 Sub-surface failure modelling

Sub-surface failure of the iron ore cargo within the ship hold has the potential to occur in the region adjacent to the floor of the cargo hold, and involve a large portion of the material within the hold. The material may also fail at a shallower roll angle if a sufficiently large portion of the cargo is saturated at the base of the hold. In considering the failure mechanism, the side walls of the hold have a limited influence on the slipped material with the insipient failure plane dominated by internal shear. As such, the slipping planes may be considered as ether a circular curve or a compound curve depending on whether the curve intersects the saturated layer or the floor of the cargo hold. Such a failure mode will lead to a greater cargo centre of gravity shift than surface slip failure, and thus poses a greater concern to vessel stability.

To model sub-surface failure, a 2D slice through the centre of a cargo hold was selected. The occurrence of the sub-surface failure is due to the material gravity torque exceeding the shear resistance torque. As illustrated in Figure 11, a circular failure plane under roll and heave motions at the base of the load profile is assumed. If the failure plane extends to the floor of the hold, then a compound failure plane is assumed where failure occurs at the wall-ore interface, or within bulk ore near and parallel to the wall.

Seven iron ore types (Ores A, B, C, E, F, G and J) with flow properties measured at the PFT D80 moisture value were used in the modelling. Based on the sub-surface model proposed above, the following ship dynamic conditions were used to calculate the critical roll angle at which the sub-surface failure occurs:

- Capesize vessel: 1 m/s^2 rolling and heaving accelerations
- Panamax vessel: 1.5 m/s^2 rolling and heaving accelerations
- Handymax vessel: 2 m/s^2 rolling and heaving accelerations
- Handysize vessel : 2 m/s^2 rolling and heaving accelerations

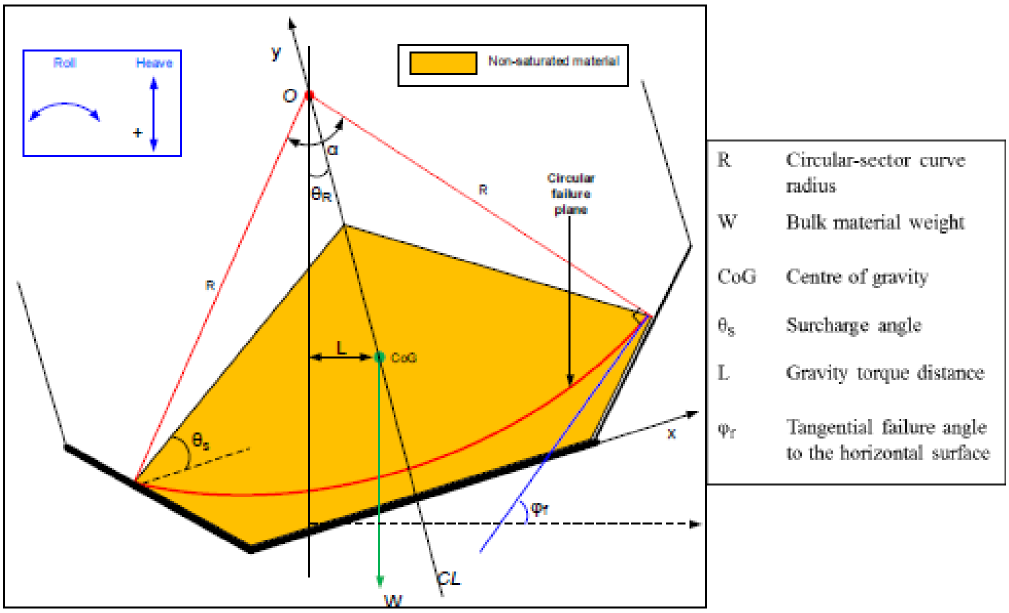


Figure 3. Modelling of the sub-surface failure parameters.

The roll angles required for sub-surface failure are summarised in Table 3.

Table 1. Critical roll angles predicted by sub-surface failure modelling for a range of vessel sizes

Cape size							
Hold	**Critical roll angle – degrees**						
	Ore A	Ore B	Ore C	Ore E	Ore F	Ore G	Ore J
No. 1 cargo hold	46.1	44.6	38.5	45.8	39.1	42.9	46.6
No. 2~7cargo holds	45.9	44.5	38.4	45.6	39.0	42.7	46.4
No. 8 cargo hold	46.2	44.8	38.7	46.0	39.1	43.0	46.7
No. 9 cargo hold	47.1	45.7	39.4	47.2	39.5	43.7	47.5
Panamax size							
Hold	**Critical roll angle - degrees**						
	Ore A	Ore B	Ore C	Ore E	Ore F	Ore G	Ore J
No.1~7cargo holds	45.5	45.3	38.4	45.6	39.2	43.6	47.1
Handymax size							
Hold	**Critical roll angle - degrees**						
	Ore A	Ore B	Ore C	Ore E	Ore F	Ore G	Ore J
No. 1 cargo hold	44.6	44.5	38.3	45.1	38.6	43.1	46.1
No.2~5cargo holds	40.4	38.6	39.3	40.6	38.6	37.9	40.6
Handy size							
Hold	**Critical roll angle - degrees**						
	Ore A	Ore B	Ore C	Ore E	Ore F	Ore G	Ore J
No. 1~3 cargo hold	39.3	37.3	32.3	39.9	31.6	36.5	39.8

The major findings from this sub-surface failure work were:

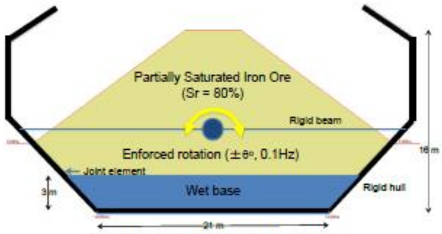
- At the PFT D80 moisture value, all sub-surface failures were predicted to occur at roll angles greater than 30 degrees. This is outside the range of expected vessel motion.
- A circular failure plane occurs for all Capesize and Panamax holds, with Handymax and Handysize holds generally having a compound failure plane.

2.6.2 Liquefaction modelling

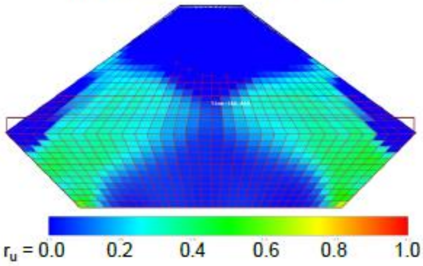
The objective of the numerical modelling was to evaluate how a large volume of ore in the ship hold will respond to ship motion while making use of the element behaviour observed in the laboratory cyclic triaxial tests. The effects of various factors, such as the geometry and density of the cargo hold and the intensity and frequency of ship motion among others, can be evaluated. Finally, the modelling can provide a means of evaluating various initial cargo conditions (in terms of degree of saturation and location of the wet base within the cargo profile) and drainage state (drainage possible or inhibited).

For this purpose, the computer program FLIP (Finite Element Analysis of Liquefaction Process) was used. The FLIP program was originally developed in Japan by the Port and Harbour Research Institute, Ministry of Transport (currently Port and Airport Research Institute) [13,14] and advanced through the cooperative efforts with Kyoto University and Coastal Development Institute of Technology. The program, especially formulated for dynamic effective stress analysis of soil-structure systems during earthquakes, including soil liquefaction, has been well-validated using Japanese earthquake case histories and has been applied to design many waterfront structures in Japan (FLIP Consortium 2011) [11]. However, this is the first time that the program was used to analyse iron ore fines cargoes under rolling motion. The advanced version of FLIP program that allows redistribution and dissipation of excess pore water pressures based on the constitutive model called cocktail glass model [12] was employed.

This modelling work attempted to investigate the cyclic response of partially saturated iron ore cargo (Ore B with Sr = 80%), with and without the wet base. A 3 m wet base was assumed based on seepage analysis. Note that this is a very conservative case (i.e. a worst case) as the seepage analysis to define the wet base was performed with a fully saturated initial moisture content. In reality the ore would be loaded below the PFT D80 moisture content and a proportion of this moisture would be contained in internal pores. Two-dimensional analysis with only rolling motion about the centre of gravity of the pile was considered. The models used and the distribution of excess pore water pressure after 10 cycles for gradually increasing roll period are shown in Figure 4.



(a) Iron ore cargo model with wet base



(b) Distribution of excess pore water pressure ratio (r_u) within the ore cargo after N=10 cycles of rotation with gradually increasing roll amplitude. Blue colour represents r_u = 0.0 (no excess pore water pressure) while red colour is for r_u = 1.0 (complete liquefaction). Also, deformed shape of the cargo at the end of the rolling motion shown.

Figure 4. Typical result of FLIP modelling.

The main findings of the numerical modelling are as follows:

- For the realistic ocean going cases of gradually or step-wise increasing roll motion, the development of excess pore water pressure (EPWP) is slow, with almost no EPWP development at the base, indicating no occurrence of liquefaction. Furthermore, the vertical displacement is also very small, showing that the deformation is related to cyclic shearing of the ore due to roll motion and not due to liquefaction. Further work should investigate this important finding further.
- For a gradually increasing or step-wise increasing roll amplitude, both EPWP and settlement showed similar patterns to the applied roll motion. For step-wise changes, the highest increase occurs during the step-wise application of motion and then practically maintaining the same value while the roll amplitude was held constant. For gradually increasing roll amplitude, the rate of increase in pore water pressure and settlement is related to the rate of increase in roll amplitude (i.e., the faster the rate of increase in roll angle, the faster is the development of pore water pressure and settlement).
- For model runs starting stationary and then undergoing an abrupt step change to a constant roll angle, the EPWP and vertical displacement (settlement) are higher when the amplitude of the roll angle is higher. An abrupt step change

from stationary to a constant roll amplitude of 20° predicted that the wet base can liquefy and large crest settlement can occur. However, this theoretical step change in roll amplitude is not considered to be a realistic vessel motion.
- In the latter conservative case where the 3 m wet base liquefied, the crest settlement of the cargo was significant due to consolidation of the cargo. However, the liquefied wet base was confined by the wall of the ship and the significant overburden above the wet base and these prevented the occurrence of liquefaction-induced flow-type failure.

3 SUMMARY AND CURRENT IMO IRON ORE REQUIREMENTS

The research summarised above formed part of the AMIRA P1097 project and was carried out by the CSIRO Minerals Down Under Flagship (now the Mineral Resources Flagship), TUNRA Bulk Solids Handling (TBS), and the University of Auckland with project leadership provided by Creative Process Innovation. Twelve samples of iron ore fines were studied, covering a large proportion of the seaborne iron ores shipped from Australia and Brazil. Major findings from this research were as follows:

- The Proctor/Fagerberg test was chosen as the most appropriate TML test for iron ore fines, and modifications were made to calibrate this test to the specific conditions encountered in shipping of iron ore fines. The resulting test is known at the PFT D80 test. A draft ISO Standard method for the PFT D80 test has been prepared and this was tabled at the ISO Standards meeting in Brazil in April 2014.
- Liquefaction resistance increases with increasing goethite content, particle size and higher porosity.
- Iron ore fines still retain significant bulk strength at the PFT D80 moisture level. While minor surface failures are possible, sub-surface failure modelling predicts that no failure is likely to occur under extreme vessel motions (i.e. worst 1% of possible vessel motion).
- Modelling of the liquefaction potential of iron ore fines at the PFT D80 moisture level subjected to expected vessel motion predicted that build up in excess pore water pressure and cyclic deformation were small and liquefaction did not occur.

In relation to the carriage of iron ore bulk cargo, the current schedule relating to iron ore concentrate (the metal concentrate schedule) still remains current. With respect to iron ore lump and fines products, there are now two schedules that are used for reference as currently defined by IMO Circular DSC.1/Circ.71 , namely:

- Iron Ore Fines schedule (Group A cargo) containing both:
  - 10 per cent or more of fine particles less than 1 mm (D10 ≤ 1 mm); and
  - 50 per cent or more of particles less than 10 mm (D50 ≤ 10 mm); and
- Iron Ore schedule (Group C Cargo) which defines the cargo as:
  - having either:
    - less than 10 per cent of fine particles less than 1 mm (D10 > 1 mm); or
    - less than 50 per cent of particles less than 10 mm (D50 > 10 mm); or
    - both; or
  - iron ore fines where the total goethite content is 35 per cent or more by mass, provided the master receives from the shipper a declaration of

the goethite content of the cargo which has been determined according to internationally or nationally accepted standard procedures.

Subsequently, the TML testing requirements and test method for all iron ore products as per each schedule are as follows:

- Iron Ore Concentrates (as per metal concentrate schedule defined in the IMSBC2013 code):
    - is a group A cargo and requires TML determination with any one of three IMO authorised TML methods as per the IMSBC2013 code:
        - Flow Table Test
        - Proctor/Fagerberg Test
        - Penetration Test
- Iron Ore Fines with less than 35% goethite content (as per the iron ore fines schedule defined in IMO Circular DSC.1/Circ.71)
    - Is a group A cargo and requires TML determination with any one of four IMO authorised TML methods as per:
        - the IMO Circular DSC.1/Circ.71:
            - The modified Proctor/Fagerberg test procedure for Iron Ore Fines if OMC is greater than 90%
            - This method is the preferred method for iron ore fines TML determination, however any one of the other three existing TML methods described in the IMSBC can also be used in preference to the above method.
- Iron Ore Lump or Iron Ore Fines with 35% or greater goethite content (as per the iron ore schedule defined in IMO Circular DSC.1/Circ.71)
    - Is a group C cargo and does not require a TML determination.

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