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Laboratory scale reproduction and analysis of the behaviour of iron ore fines under cyclic loading to investigate liquefaction during marine transportation

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ABSTRACT

Specific hazards come with the transportation of solid bulk cargoes on bulk carriers. One unexpected hazard is the liquefaction of the cargo. Liquefaction is a phenomenon whereby cyclic or shock loading causes a commonly loose saturated material to flow like a liquid. Over the past 30 years, there have been 23 incidents in which liquefaction of the solid bulk cargo was the suspected cause of a bulk carrier foundering. The result from performing the Modified Proctor/Fagerberg Test (MPFT) on iron ore fines provides what is referred to as the Transportable Moisture Limit (TML). The TML is a safe moisture content under which a cargo is considered unable to liquefy while undergoing marine transportation. The objective of this study is to design and construct a scale model to test the conditions under which iron ore fines may liquefy, and to monitor the changes that occur within the material that may adversely affect the stability of the cargo during marine transportation. The parameters that are believed to influence the liquefaction potential of iron ore fines, including pore air and water pressures, moisture migration, segregation as well as other changes in physical properties, are monitored and compared to the behaviour at the TML determined from the MPFT. This study concludes that moisture migration, caused by an increase in the pore pressure within the material, also causes segregation of the material to occur. This process creates portions of the sample that are much more likely to liquefy than the sample as a whole. The moisture content where this begins takes place is 1.5% less than the resulting MPFT TML. Overall, it is considered that the TML as a parameter to indicate liquefaction is inadequate, as liquefaction is much more complicated and cannot be simplified in this manner.

1. Introduction

Specific hazards come with the transportation of solid bulk cargoes on bulk carriers. One unexpected hazard is the liquefaction of the cargo. Described in more detail in related publications [25,26] this is a phenomenon whereby cyclic or shock loading causes a commonly loose saturated material, such as sand, to lose all bearing capacity and flow like a liquid [5]. During marine transportation, it is said that shock or cyclic loading can be transferred through the structure of the bulk carrier to the cargo from ocean waves under varying sea states [11].

Over the past 30 years, there have been 23 incidents in which liquefaction of the solid bulk cargo was the suspected cause of foundering of a bulk carrier. Of these 23 incidents, 17 vessels were lost and 138 people perished [20,24]. Although these incidents

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involved a number of different types of cargo, including nickel ore, bauxite and manganese, the cargo focussed on in this study, which was being transported in 30% of the aforementioned incidents, is iron ore fines.

In 2011, a code of safe practice, which is to be followed when transporting hazardous solid bulk cargoes, became mandatory [8]. This code, known as the International Maritime Solid Bulk Cargoes Code (IMSBC Code), is regularly amended by the publisher, the International Maritime Organisation (IMO) [7].

In Appendix 2 of the IMSBC Code, the Modified Proctor/Fagerberg Test (MPFT) procedure is specified. With conditions, this procedure must be performed on a cargo of iron ore fines that is to be shipped via bulk carrier. The MPFT, which is specifically designed for iron ore fines, produces what is referred to as the Transportable Moisture Limit (TML). The TML is inferred by the code as being the maximum moisture content that the cargo may contain at which it is considered unable to liquefy while undergoing marine transportation. More information on the introduction and history of the MPFT, related test methods and IMSBC Code can be seen in related publications [18,19,21,22].

This publication has been created to standalone, but with this said, the preliminary concept, creation and implementation of the scale model presented herein, can also be seen in two related publications [23,25].

The objective of this study was to design and construct a scale model to test the conditions under which iron ore fines may liquefy and to monitor changes that occur within the material that may adversely affect the stability of the cargo during marine transportation. The parameters that are monitored include the pore air and water pressures, moisture migration, and segregation, as well as the changes in physical properties, such as density, degree of saturation and resistivity. All the parameters that are monitored are believed to influence the liquefaction potential of iron ore fines and are compared to the behaviour at the TML produced by the MPFT.

2. Material and method

2.1. Material

The specimen of iron ore fines tested during this study was chosen due to it being representative of typical cargoes of iron ore fines that commonly undergo marine transportation on bulk carriers [19]. The physical properties of iron ore fines can be seen in Table 1.

2.2. Method

2.2.1. Theory

Liquefaction is a phenomenon that frequently occurs during earthquakes of significant magnitude. Seismic activity causes pressure within certain types of soil to increase resulting in a flow like behaviour of the material. This is the same behaviour that may be experienced by a cargo undergoing marine transportation, where the sea states being traversed, rather than seismic activity, are

Table 1
Physical properties of the iron ore fines specimen used during this study.

Property	Standard/Apparatus	Results
Specimen Identification	N/A	MA004
[a,b,c] Modified Proctor/Fagerberg TML	MSC 95/22/Add.2 [6]	10.9% GWC or 12.2% NWC at 80% Saturation (OMC occurring at 96% Saturation)
Maximum Dry Density	AS1289.5.5.1 [32]	2.76 t/m^3 (e = 0.50)
Minimum Dry Density	AS1289.5.5.1 [32]	2.18 t/m^3 (e = 0.90)
Atterberg Limits		
[a] Liquid Limit	AS1289.3.1.2 [35]	17% NWC
[a] Plastic Limit	AS1289.3.2.1 [36]	16% NWC
[a] Plasticity Index	AS1289.3.3.1 [37]	1% NWC
[d] Particle Size Distribution		
Gravel (> 2.36 mm)	AS1289.3.6.1 [38]	51%
Sand (75 µm–2.36 mm)	AS1289.3.6.1 [38]	38%
Clay (< 2 µm)	Mastersizer Aero 3000 [9]	1%
Classification	AS1726 [31]	Poorly graded gravel to silty gravel (GP-GM)
Particle Density, G_s	AS1289.3.5.1 [34]	4.15 t/m^3
Hydraulic Conductivity, K	AS1289.6.7.1 [33]	2.08×10^{-5} m/s
Quantitative X-Ray Diffraction		
Haematite (Fe_2O_3)	X'Pert Pro PW3040	36% Total Weight
[b] Goethite (FeOOH)	X'Pert Pro PW3040	62% Total Weight

[a] The percentage of moisture is reported according to the relevant standard first (i.e. NWC or GWC). In geotechnical engineering and soil mechanics, the Net Water Content (NWC) is commonly used, whereas, in most other cases, including metallurgy and marine transportation, the Gross Water Content (GWC) is favoured. NWC is referred to as the percentage of moisture to dry material, while GWC is the percentage of moisture to wet material; hence, net and gross. Throughout the rest of this publication GWC is used.

[b] According to MSC 95/22/Add.2, if a cargo of iron ore fines has more than 35% goethite total weight, then the schedule for iron ore is to be followed, and, therefore, the cargo does not need to undergo testing using the Modified Proctor/Fagerberg method, as it is considered unable to liquefy [6].

[c] The Modified Proctor/Fagerberg test compaction curve and TML for this specimen of iron ore fines can be seen in Fig. 1.

[d] The particle size distribution for this specimen of iron ore fines can be seen in Fig. 2.