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Variation of the geotechnical properties of Iron Ore Fines under cyclic loading

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ABSTRACT

Liquefaction, which can result in a vessel capsizing, is one of many hazards involved when transporting bulk cargoes. The objective of this study is to determine the variability of the geotechnical properties of Iron Ore Fines (IOF) under cyclic loading at different moisture contents to determine the liquefaction potential. The geotechnical properties include the void ratio, dry density, degree of saturation and angle of repose. Previous studies have proven that in a partially saturated material, under cyclic loading, these properties directly effect the shear strength and may cause a material to liquefy. Also, by measuring the penetration of a free floating IOF Plunger (IOFP), developed during this study, the loss of shear strength was monitored. The results from this study show that significant variations occur in the geotechnical properties of IOF under cyclic loading at the varying moisture contents tested. Penetration from the IOFP was also observed, which indicated a reduction of effective stress and therefore shear strength within the samples IOF. The samples tested showed signs of liquefaction between the Proctor/Fagerberg and Modified Proctor/Fagerberg transportable moisture limits. It was concluded that the liquefaction potential of IOF is a function of the time of cyclic loading and initial moisture content.

1. Introduction

1.1. General

Iron Ore Fines (IOF) is a product produced from refining iron ore and commonly has a maximum particle size of 6.3 mm and a natural iron content of approximately 40–60%. Producing pig iron, which is used to make steel, from iron ore has been around since the Iron Age. Over the previous century improvements in the smelting process, used to create pig iron, has allowed companies to process ores with higher impurities, including IOF. Due to the improved processing abilities and therefore value of IOF, transporting this material around the world using bulk carriers has also increased. There are many hazards involved in the transportation of bulk granular mineral cargoes, one of which is liquefaction. Although not well understood at the time, liquefaction of bulk cargoes has been known to occur since 1910 with the loss of the Bengal (Sandvik and Rein, 1992). When a cargo such as IOF shifts in the hold of a bulk carrier, it is possible the weight of the unconstrained cargo can't be corrected with the available ballast. This, or a rapid change in the centre of gravity, can result in the transport vessel listing or even capsizing. Over the past eight years, liquefaction of IOF has been suspected of being the cause of at least ten cargo shifts, eight of which have resulted in the total loss of the vessel, as seen in Table 1 (Munro and Mohajerani, 2016) (Figs. 1 and 2).

The International Maritime Solid Bulk Cargoes Code (IMSBC Code) has procedures to be followed when transporting solid bulk cargoes, which are considered to be potentially liquefiable (International Maritime Organization, 2013b). According to the IMSBC Code, these potentially liquefiable solid bulk cargoes, or 'Group A' cargoes, are to undergo Transportable Moisture Limit (TML) testing. The IMSBC Code infers the TML is the maximum Gross water content (GWC) that a cargo may contain without being at risk of liquefying. The GWC of a material is not as commonly used in geotechnical engineering as the Net Water Content (NWC). The GWC is calculated as a percentage using the moisture divided by the wet mass instead of the moisture divided by the dry mass.

1.2. Transportable moisture limit test methods

Currently, in the 2013 IMSBC Code, there are three test methods

AbbreviationsFMPFlow Moisture PointFTTFlow Table TestGWCGross water content by weightIMSBC CodeInternational Maritime Solid Bulk Cargoes CodeIMOInternational Maritime OrganizationIOFIron Ore FinesIOFPIron Ore Fines PlungerNWCNet Water Content by WeightOMCOptimum Moisture ContentPFTStandard proctor/Fagerberg testPTPenetration TestSdegree of saturationTMLTransportable Moisture LimitTWGIron Ore Technical Working Group

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Table 1
Recent incidents involving bulk carriers transporting IOF (Munro and Mohajerani, 2016; TML Testing Wiki – Incidents, 2015).

Vessel name	Subclass	Total loss	Lives lost	Date	Origin	Destination
Alexandros T	Capesize	Yes	26	03/05/2006	Brazil	China
Chang Le Men	Handysize	No (listed)	0	07/09/2007	India	China
Mezzanine	Handysize	Yes	26	27/11/2007	Indonesia	China
Asian Forest (Fig. 1)	Handysize	Yes	0	17/07/2009	India	China
Hodasco 15	General Bulker	Yes	0	30/08/2009	India	China
Black Rose (Fig. 2)	Handymax	Yes	1	09/09/2009	India	China
Bright Ruby	Handymax	Yes	7	21/11/2011	Malaysia	China
Sun Spirits	Handysize	Yes	0	22/01/2012	Philippines	China
Bingo	General Bulker	Yes	0	12/08/2013	India	China
Anna Bo	Handymax	No (listed)	0	04/12/2013	Indonesia	China

Fig. 1. Asian Forest (Cargo ship off Mangalore, India, 2009).

Fig. 2. Black Rose (Searching for Missing Crew – Black Rose, 2009).

used to determine the TML of 'Group A' cargoes, which are those that are potentially liquefiable, including IOF (International Maritime Organization, 2013b). The three test methods are the Proctor/Fagerberg (PFT), Flow Table (FTT) and Penetration (PT) test methods and are discussed in Sections 1.2.1–1.2.3. Typical results produced when testing IOF can be found in a related publication (Munro and Mohajerani, 2015).

Also discussed in Section 1.2.4. is the new Modified Proctor/Fagerberg Test (MPFT). After the temporary reclassification of IOF, in 2011, as a potentially liquefiable material (International Maritime Organization, 2011), industry and research institutions began comprehensive research in order to understand the causes of liquefaction of IOF while being transported. The early implementation of this research was introduced, in 2013, by the IMO in the circular DSC.1/Circ.71 (International Maritime Organization, 2013a). Included in this circular is a draft schedule for iron ore, a draft schedule for IOF and a draft for a new test method for determining the TML of IOF, the MPFT. The circular states that although more research is required, the draft schedules and test method will be included in amendment 03–15 of the IMSBC Code in 2015 and entered into force on January 1, 2017 (International Maritime Organization, 2013a). Some flag administrations, including Brazil, Australia and the Marshall Islands, have voluntarily adopted the aforementioned schedules and test method as recommended by the IMO (International Maritime Organization, 2013a; UK P&I Club, 2014). Further information on the recent developments of TML testing of IOF can be found in a related publication (Munro and Mohajerani, 2016).

1.2.1. Proctor/Fagerberg test (PFT)

The PFT was first published in Stockholm in 1962 by Bengt Fagerberg and Kjell Eriksson as part of a committee established by the Swedish Mining Association and several Scandinavian mining companies. The committee was given the task to develop a simple method for determining the TML of ore concentrates (Fagerberg and Stavang, 1971). The test method is based upon the use of the Proctor apparatus (ASTM Standard D-698 (American Society for Testing and Materials, 2012)), which was developed by Ralph Proctor for use in soil mechanics (Proctor, 1933), and was adopted by the IMO, for use in the IMSBC Code, between 1991 and 1998.

The procedure involves compaction of a material, into a standard litre compaction mould, at varying moisture contents, to produce a compaction curve with a minimum of five data points. The compaction is executed in five layers by dropping a 350 g hammer, 25 times, through a guided pipe from a height of 200 mm. For each point the GWC and void ratio is calculated then plotted on a graph along with the corresponding degree of saturation (S). The resulting GWC is then interpreted, from the graph, where S equals 70%. This value is referred to as the TML (International Maritime Organization, 2013b). The PFT uses approximately 14% of the standard proctor compaction energy (e.g. AS1289 5.1.1 (Standards Australia, 2003a)) and requires the particle density (e.g. AS1289 3.5.1 (Standards Australia, 2006)) to produce the corresponding S. A typical compaction curve of IOF, produced during this study, can be seen in Fig. 3 and the PFT apparatus can be seen in Fig. 4.

1.2.2. Flow Table Test (FTT)

The FTT has been widely used in the cement industry to test hydraulic cement (American Society for Testing and Materials, 2008). The early IMSBC Code included a modified procedure, created by the Department of Mines and Technical Surveys in Canada that can be used to determine the TML of ore concentrates and coal (Fagerberg and Stavang, 1971). In 2000, this method branched out into an ISO (International Organization for Standardization) guide (International Standards Organization, 2007).

The FTT is performed by compacting a sample, in three layers, into a conical shaped mould in the centre of the Flow Table. Compaction is