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# Bulk cargo liquefaction incidents during marine transportation and possible causes

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A B S T R A C T

During marine transportation, a combination of cyclic loading, fine particles and moisture within a bulk cargo can result in liquefaction causing the bulk carrier to list or capsize. The objective of this study is to investigate incidents where bulk cargoes liquefied during transportation and what resulted from these incidents, including the loss of human life and industry assets. In addition, the effectiveness of determining the Transportable Moisture Limit (TML) using the Modified Proctor/Fagerberg Test (MPFT) for Iron Ore Fines (IOF) is questioned by developing an apparatus used to observe the apparent shear strength of a sample of IOF. Between 1988 and 2016, 23 incidents were reported where liquefaction of a bulk cargo was suspected. These incidents resulted in 138 casualties and the loss of 17 vessels. It was found that incidents are continuing to occur even after the implementation of mandatory testing. Using an apparatus developed for this study, samples of IOF showed a sudden loss of shear strength at moisture contents lower than the TML with indications liquefaction had occurred. Although further testing is required to confirm some assumptions made, the study concluded that the IOF tested was assumed to be liquefiable at the TML determined using the MPFT.

## 1. Introduction

Liquefaction of solid bulk cargoes on board bulk carriers is a frequent problem whereby a combination of fine particles, moisture and changing pore pressures within a cargo result in the mass acting like a liquid. Liquefaction of a solid bulk cargo on board a bulk carrier can cause the vessel to list and possibly capsize resulting in the loss of human life and industry assets. Sladen et al., and the National Research Council Committee (1985) provide a more definite description of liquefaction: *“Liquefaction is a phenomenon wherein a mass of soil loses a large percentage of its shear resistance, when subjected to transient or periodic loading, and flows in a manner resembling a liquid”* (National Research Council Committee (NCR), 1985; Sladen et al. (1985)).

For a bulk carrier to list, the vessels overturning moment, $M_O$, must exceed the vessels restoring moment, $M_R$. This unstable condition is depicted in Fig. 1 (right) where it is shown that the centre of buoyancy of the hull, B, stays inwards of the centre of gravity of the vessel, G. The resulting metacentre, M, under these conditions is below the centre of gravity, and causes the overturning moment, $M_O$, which exceeds the restoring moment, $M_R$. This causes the vessel to develop a permanent list and may possibly capsize if measures are not taken to right the vessel, which is commonly achieved using water as ballast.

There are two occurrences resulting from the liquefaction of cargo that can cause a bulk carrier to list. As being examined herein, if the cargo mass as whole begins to behave as a liquid the resulting free surface effect will reduce the metacentric height, distance from G to M. The other occurrence is if partial liquefaction takes place at a point within the cargo mass resulting in the cargo shifting to one side. In that case the centre of gravity will move and the vessel will have a permanent heel angle.

To minimise the risk of liquefaction, the International Maritime Organization (IMO) outlines test methods that are used to determine the Transportable Moisture Limit (TML) of liquefiable cargoes. The TML is the maximum Gross Water Content (GWC) that a liquefiable cargo may contain without being at risk of liquefying (International Maritime Organization, 2016). Currently, four methods are used to determine the TML of ‘Group A’ or liquefiable solid bulk cargoes: i. Flow Table Test, ii. Penetration Test, iii. Proctor/Fagerberg Test, and iv. Modified Proctor/Fagerberg Test for Iron Ore Fines.

The International Maritime Solid Bulk Cargoes Code (IMSBC Code), which came into force on a mandatory basis on 1 January

*Abbreviations:* CFC, Critical Failure Curve; DWT, Dead Weight Tonnage; FT, Failure Threshold; GWC, Gross Water Content; IMO, International Maritime Organization; IMSBC Code, International Maritime Solid Bulk Cargoes Code; IOF, Iron Ore Fines; IOFP, Iron Ore Fines Plunger; MDD, Maximum Dry Density; MPFT, Modified Proctor/Fagerberg Test for IOF; NWC, Net Water Content; OMC, Optimum Moisture Content; TML, Transportable Moisture Limit

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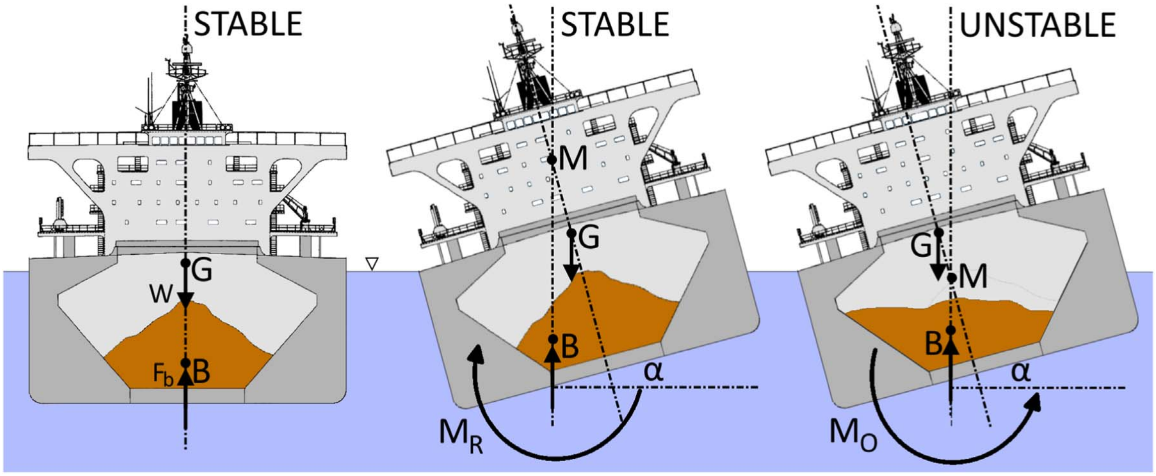


**Fig. 1.** Illustrations depicting stable vessels (left and middle) and an unstable vessel (right). Where: B = Centre of buoyancy of hull; $F_b$ = Buoyancy force; G = Centre of gravity of vessel; M = Metacentre; $M_O$ = Overturning moment; $M_R$ = Restoring moment; W = Vessel weight; α = Angle of heel.

**Fig. 2.** Three strainer plates blocked by the crew of the Canadian Leader ex Feux Follets using cardboard, plastic sheeting, and duct tape to prevent entry of the cargo of iron ore pellets into the bilge pipes and pumps (Transportation Safety Board of Canada, 2005).

**Fig. 3.** Bulk Carrier 'Chang Le Men' after suspected liquefaction incident off Mangalore India (2007) (Mangalorean, 2007) – see Appendix A.

2011 (International Maritime Organization, 2008) and is published by the IMO, is an internationally recognized code of safe practice to be followed when transporting hazardous solid bulk cargoes. Appendix 2 of the 2013 IMSBC Code outlines three of the four test methods: Flow Table, Penetration and Proctor/Fagerberg. These three test methods are currently used to determine the TML of solid bulk cargoes listed as 'Group A' or liquefiable in Appendix 4 of the IMSBC Code (International Maritime Organization, 2013b). These tests are described in detail in a related publication (Munro and Mohajerani, 2015).

Industry and research associations have recently introduced the fourth test method specifically designed for determining the TML of Iron Ore Fines (IOF) (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e). The Modified Proctor/Fagerberg Test for IOF (MPFT) was first introduced in November 2013 in the circular DSC.1-Circ.71 for implementation on a voluntary basis (International Maritime Organization, 2013a). The use of this test became mandatory on 1 January 2017 (International Maritime Organization, 2013a, 2015a) and is now included in Appendix 2 of the 2016 IMSBC Code (International Maritime Organization, 2016).

The MPFT procedure involves compaction of the 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 150 g hammer 25 times through a guided pipe from a height of 150 mm. For each point the GWC and void ratio is calculated and plotted on a graph along with