

# Liquefaction of Sand and Olive Pomace Cargo and Its Effect on the Stability of a Bulk-Carrier



I. A. Koromila, C. C. Spandonidis, and K. J. Spyrou

**Abstract** Liquefaction of granular materials in a rectangular container has been experimentally investigated using NTUA's School of Naval Architecture and Marine Engineering "shaking table" facility. Two different materials (sand and olive pomace) in several moisture content scenarios were tested. Harmonic forcing in a range of frequencies and amplitudes has been applied. The intention was to develop some qualitative understanding on how liquefaction comes about for materials of different properties; and also how the phenomenon relates with the duration and intensity of the excitation. The two materials presented substantially different behaviour, interpreted to be due to differences in moisture's diffusion in material's body and in their specific gravity. In a parallel study, was investigated the impact of liquefaction to a bulk carrier's stability by using commercial design software. Different cases of cargo stowage and distribution in the holds were examined. This study confirms that homogeneous cargo loading can lead to substantial loss of stability after cargo liquefaction and that alternating or suitable inhomogeneous loading is often preferable. The current paper is an updated and improved version of a paper presented in the International Ship Stability Workshop, held in Brest in 2013 [16].

**Keywords** Ship · Stability · Liquefaction · Experiments

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# 1 Introduction

Cargo liquefaction is dangerous as it turns a dry cargo into an easily movable one, thus bearing a detrimental effect on the intact stability characteristics of the ship carrying it. Casualty data referring to bulk carriers, collected by the International Association of Dry Cargo Shipowners (INTERCARGO), indicate that cargo-related reasons stand as the dominant factor behind total loss accidents for this category of ships. Notwithstanding the significant decrease of the number of ship casualties due to cargo liquefaction in the last decade, as shown in Table 1 the human lives lost per accident were substantially increased [7, 8]. Actually, the number of lives lost in the last decade due to liquefaction were almost 50% more than those lost in the preceding decade.

Cargoes that are at risk of liquefaction are those constituted of fine particles and containing moisture [4]. Such cargoes, at the time of loading are typically in granular state and look like damp sand. In this state, the shear strength of the cargo is provided by the direct contact between the cargo particles. Nevertheless, sufficient interstitial spaces exist to accommodate the moisture of the transported particles and the interstitial air [1]. The oscillatory movement of the tank leads to resettling of the particles and compaction of the intra-particle spaces. This compaction raises the water pressure, forcing the particles apart, potentially leading to them losing direct contact with each other. The cargo loses shear strength and thus conditions are created for the cargo to behave like a liquid [10].

Recent casualties mostly involved unprocessed or minimally processed ore cargoes; such as nickel ore, iron ore fines, iron sand, and bauxite. According to The Swedish Club [23], the major problem is due to the storage place in the countries of origin. Unprocessed or minimally processed ore cargoes are often stored in open-air stockpiles, even next to the sea, meaning that they are subject to all weather conditions. Any wet weather will therefore cause the moisture content (MC) of the fines to increase, especially during the monsoon season. Furthermore, when it comes to Mediterranean countries, one of the most common material causing liquefaction-based accidents is olive pomace.

An early description and analysis of the problem from a soil mechanics perspective is found in Terzaghi and Peck [22]. Despite the great importance of liquefaction for ship safety, a coherent, science-based, framework for the transportation of wet bulk cargoes has not been fully set up yet. The industry is regulated of course by several national and international codes. As soon as 2008, the International Maritime Organisation (IMO) issued, by resolution MSC.268(85), the International Maritime Solid Bulk Cargoes (IMSBC) Code whereby incorporates provisions aimed at ensuring that

**Table 1** Bulk carrier casualties due to cargo liquefaction

Year	Lost vessels	Lost lives
2010–2019	8	106
2002–2009	48	158

only cargoes with sufficiently low inherent moisture content (based on measurement of Flow Moisture Point-FMP and Transportable Moisture Limit-TML) are loaded [10]. The code contains instructions for the safe handling (loading and unloading) and stowage of bulk cargoes which however are largely empirical. Yet, complexities can arise due to the coupled ship cargo responses to random environmental excitations, the variety of transported materials substantially differing in properties and sizes, the presence of humidity etc. With the experience gained over the years, further cargoes were recognized as prone to liquefaction and incorporated into the code, as well as further requirements were amended [12]. Besides, provisions are encompassed for specially constructed vessels hindering cargo shift and hence allowing the carriage of high-moisture cargoes. For these vessels, it is required to meet the IMO Grain code and Intact Stability code criteria [9, 11].

The primary research in the field of granular materials liquefaction was related to a few prominent problems, mostly of soil mechanics nature. Bjerrum et al. [2], Lee and Fitton [17], and Castro [3] were among the pioneers who paved the way for the development of methods for determining the possible liquefaction of a granular material. Typically, sand samples (both clear and mixed with fines or silts) were used for experimental investigation to determine shear strengths and deformations that cause excessive pore water pressure and lead to liquefaction [5, 24]. Research on the liquefaction phenomenon in marine cargoes is still at the stage of infancy [13, 14, 19]. Modelling approaches based on discrete particles behaviour have appeared, yet these mostly address the behaviour of particles with humidity on their surface, rather than the full liquefaction condition [20, 21]. A few efforts to address, via modeling, phenomena such as sloshing due to the movement of slurry cargoes in ship holds have also appeared [15, 25–27].

The initial version of the current paper presented during the 2013 International Ship Stability Workshop was perhaps the first documented experimental effort in the maritime field addressing the liquefaction process [16]. It referred specifically to sand and olive pomace cargoes. The current paper is an update of this work. Liquefaction of a medium weight material (sand) and a light one (olive pomace) have been investigated experimentally using the shaking table equipment installed at the School of Naval Architecture and Marine Engineering of the National Technical University of Athens. The interest was on identifying essential qualitative differences in the two materials' behaviour. Results were evaluated in the light of the requirements of the IMSBC code. Appropriate ways of cargo's distribution for avoiding capsizing in case of liquefaction, were also considered.

## 2 Investigation Through Experiments

### 2.1 Facility

The experimental facility is presented in Fig. 1. It is consisted of a 6-DOF table that is driven to move as desirable, at a low to medium range of frequencies. The motion of the table can reach up to  $\pm 30^\circ$  in rotation, and  $\pm 0.5$  m in translation.

For the current experiments, a rectangular tank was used and placed on the top of the shaking table. The tank is made from non-coloured Perspex of 20 mm thickness to permit direct observation. Its size was 0.23 m—0.31 m—0.15 m (width—length—height). The dimensions of the tank correspond to a Panamax bulk carrier with a beam of 32.2 m. It is considered that the ship (full scale) is excited in roll and sway with maximum frequency 0.29 Hz. The amplitude for sway ranges between 0.26 m and 17.7 m and for roll it ranges between 0 and  $30^\circ$ . By applying the dimensionless frequency, which is principally defined as  $\omega\sqrt{l/g}$  ( $\omega$  denotes the wave absolute frequency,  $l$  denotes the tank width, and  $g$  denotes the gravity acceleration), the model scale frequency for roll is 3.0 Hz. In addition, the amplitude for sway ranges between 0.25 cm and 17 cm (the relation  $a/l$  is applied;  $a$  denotes the excitation amplitude), while the roll angle remains the same as that of the full scale.



**Fig. 1** The shaking table equipment of NTUA's School of Naval Architecture and Marine Engineering



**Fig. 2** Visualisation of the samples of sand (left) and olive pomace (right) through optical microscope

## ***2.2 Used Materials and Procedure of Investigation***

Two materials of different composition, particle size and behaviour were selected, namely sand and olive pomace. Sand constitutes a large conglomeration of granules that are consisted at least of O, Si, Fe, Al, K, Mg, Ca and Na. However, the specific chemical composition of individual particles can be quite different (amount of Ti, S and C can be found in different granules). The specific gravity of the tested sample was  $1.386 \text{ t/m}^3$  and the average diameter, as found from analysis with an optical microscope, was 0.5 mm (Fig. 2). Olive pomace, on the other hand, is a by-product of olive processing. The specific gravity was  $0.52 \text{ t/m}^3$  and the average diameter of particles 4.5 mm.

## ***2.3 Results for Sand***

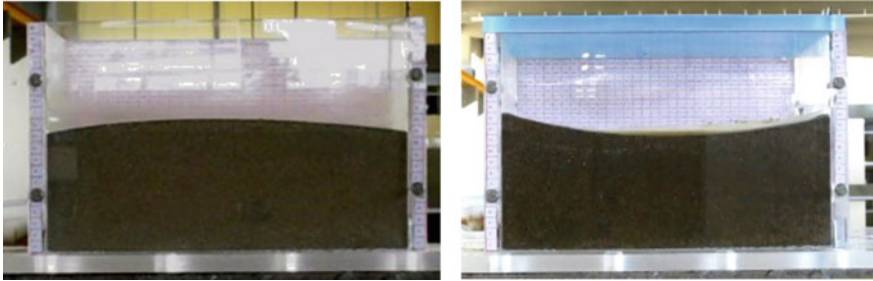
The initial moisture content of the sand was 0% and it was achieved by heating it in a furnace. The moisture level was later increased in steps, up to 40% of the total weight of the material. A wide range of excitation frequencies and amplitudes were applied to the model scale tank. Specifically, for roll: 0.1—3.0 Hz/2.09—22.2° (in full scale these correspond to 0.0098—0.29 Hz/2.09—22.2°), and for sway: 0.6—3.0 Hz/0.25—17 cm (in full scale these correspond to 0.058—0.29 Hz/0.26—17.7 m).

As it turned out, there is a critical moisture level (at about 27%) below which the material behaves almost like a solid; in the sense that it follows container's motion without flowing, no matter what the external frequency and or amplitude value is. Right after the critical moisture content is reached however, two phenomena emerge. For frequencies between 0.1 and 0.2 Hz (in roll as well as in sway) the material forms a small heap with its peak appearing at the centre of the free surface, while a

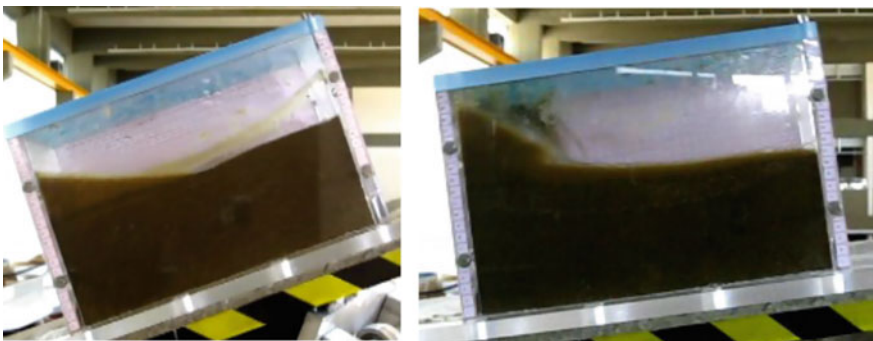
small amount of water appears at each side of the tank (Fig. 3, left). For frequencies between 0.4 and 0.8 Hz for roll and above 1.2 Hz for sway oscillations a shift of sand to the sides of the container is formed while water appears in a thin layer at the top of the free surface (Fig. 3, right). It is noted that these findings are in good agreement with simulation results presented by Ahmed [1].

Moreover, further increase of moisture means that the amount of water on the top increases too and, for low external frequency, it moves separately from the lower, solid like, material (Fig. 4, left). The frequency range in which shifting of the sand underneath the water occurs, appears now at relatively lower values (e.g. 0.7 Hz instead of 0.8 Hz for the roll motion, see Fig. 4, right). For higher excitation frequency the water layer enters a resonance area and moves following the corresponding natural mode (Fig. 5). At the same time, the material underneath the water layer rearranges itself.

Last but not least, the time duration of the experiment seems to be directly related to the appearance of liquefaction. Increase of the duration leads to lowering of the

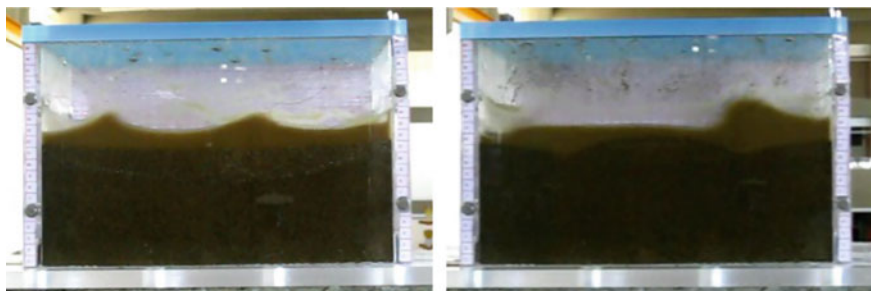


**Fig. 3** Sand with MC 27.5% after being excited in roll. Left:  $f = 0.15$  Hz,  $\varphi_{\max} = 4.2^\circ$ ; Right:  $f = 0.5$  Hz,  $\varphi_{\max} = 13.2^\circ$



**Fig. 4** Sand with MC 40% excited in roll: Left:  $f = 0.1$  Hz,  $\varphi_{\max} = 22.2^\circ$ . The upper water layer is the only part that moves; Right:  $f = 0.8$  Hz,  $\varphi_{\max} = 9.05^\circ$ . At the higher frequency, the material below water moves too, albeit sluggishly





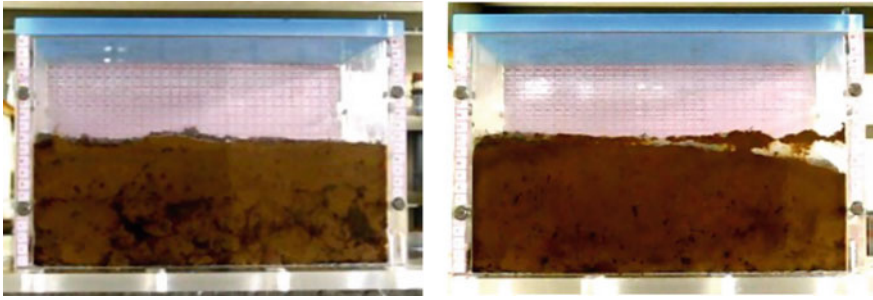
**Fig. 5** Sand with MC 40% excited in high frequency—small amplitude sway. Left:  $f = 2.5$  Hz,  $a = 2.37$  cm; Right:  $f = 1.4$  Hz,  $a = 4.3$  cm

frequencies where liquefaction first appears. The key findings are basically similar irrespectively of the direction of excitation (roll or sway).

## 2.4 Results for Olive Pomace

The olive pomace used for the experiments was supplied from two different olive mills in Greece (one in Corfu and one in Kalamata). Samples of “dry” and “wet” olive pomace, having moisture content that is commonly found when such a material is transported by sea, were examined. The focus of this work now turned from the identification of the critical moisture level, to the differences of material’s behaviour in realistic moisture scenarios for this material’s transportation. Similarly, to the dry sand, dry pomace behaves like a solid too, basically following container’s motion. Yet, for the wet olive pomace, two phenomena should be noted: (a) Moisture diffusion from specific areas of moisture concentration (black areas inside the material appearing in Fig. 6) towards the entire material body through the formation of moisture layers, leading to a jelly like motion of the material. This result is in good agreement with the findings of Jian-Ping [13] for a heavier material (wet nickel ore), and (b) Excitation at frequencies above 1.0 Hz leads to noticeable shift of a portion of material to the sides of the container.

For examining the change in the semi-static behaviour of the olive pomace before and after liquefaction occurrence, further comparative tilting tests were conducted. In accordance with the tilting box test method prescribed in IMSBC code [10], the tank was tilted with rate  $0.3^\circ/\text{s}$ . Due to physical limits (container’s height) the tilting stopped when  $30^\circ$  was reached. In the second test where the material had already been shaken and liquefaction had been established, the material started to move earlier (by about  $10^\circ$ ). However, due to the moisture (almost 60%), the angle observed is not the typical angle of repose. Here, the entire body of material has tended to move and not only some portion of it near to the free surface.



**Fig. 6** Wet olive pomace before (left) and after (right) the application of sway excitation ( $f = 2.2$  Hz,  $A = 4.3$  cm). Moisture's diffusion is apparent (the black spots in the first picture have become moisture layers in the second). Also, there is some shift of material after liquefaction occurred

### 3 Stability Analysis

The computer code “AVEVA Marine” was used to investigate how cargo liquefaction can affect the static stability of a bulk carrier. The bulk carrier used, was designed by the first author as part of the requirements of diploma course of NTUA's School of Naval Architecture and Marine Engineering. The main dimensions of the ship are presented in Table 2. Different cases of cargo's specific gravity, namely heavy and light cargoes, and cargo's distribution were examined.

As heavy cargoes were selected nickel ore ( $1.7\text{--}3.0$  t/m<sup>3</sup>), iron ore ( $1.2\text{--}3.5$  t/m<sup>3</sup>), sand ( $1.0\text{--}2.0$  t/m<sup>3</sup>) and bauxite ( $1.2\text{--}1.4$  t/m<sup>3</sup>). In the light cargo category ( $<1.0$  t/m<sup>3</sup>) were considered olive pomace and coal. It is common for large bulk carriers to stow high density cargo in odd numbered holds, with the remaining holds kept empty [6]. Nevertheless, heavy cargoes, such as iron ore, are sometimes loaded homogeneously. Hence, alternate and homogeneous loadings were considered.

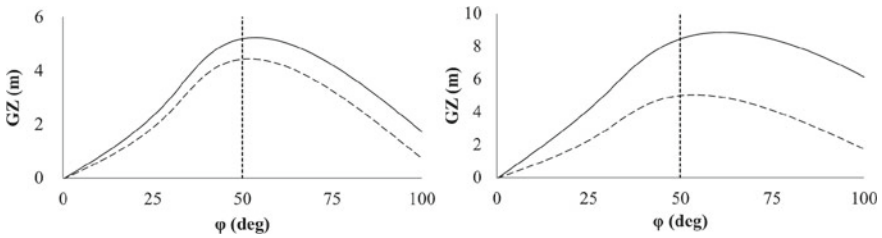
#### 3.1 Heavy Cargoes

In case of alternate loading of heavy cargoes, with specific gravity 1.6 and 3.6 t/m<sup>3</sup>, as the cargo becomes heavier the loss of stability after liquefaction becomes greater,

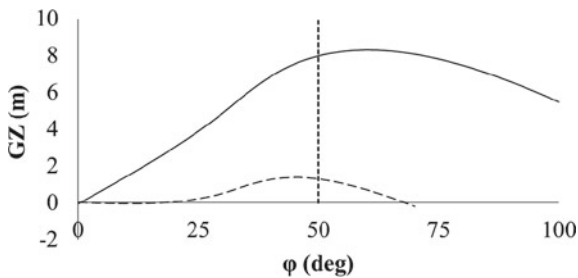
**Table 2** Ship's main dimensions

Length Overall ( $L_{OA}$ )	290.049 m
Breadth Mld (B)	44.600 m
Depth Mld (D)	25.700 m
Design Draft (T)	18.000 m
Deadweight (DWT)	172,000 t





**Fig. 7** Effect on GZ of liquefaction for alternate loading of cargo having specific gravity  $1.6 \text{ t/m}^3$  (left) and  $3.6 \text{ t/m}^3$  (right). Solid line indicates the situation before liquefaction while dashed line indicates the situation after liquefaction



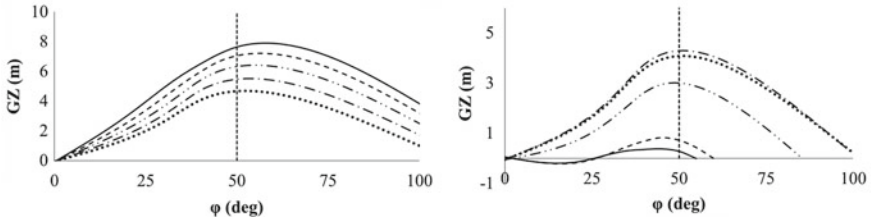
**Fig. 8** GZ curves for homogeneously loaded cargo of specific gravity  $1.6 \text{ t/m}^3$  before (solid) and after (dashed) liquefaction

as shown in Fig. 7. In the case of homogeneous cargo loading (all holds are filled to 50%) with specific gravity  $1.6 \text{ t/m}^3$ , it was found that, after liquefaction there can be a serious loss of stability (Fig. 8), despite the fact that the stability was initially better than that of alternate loading.

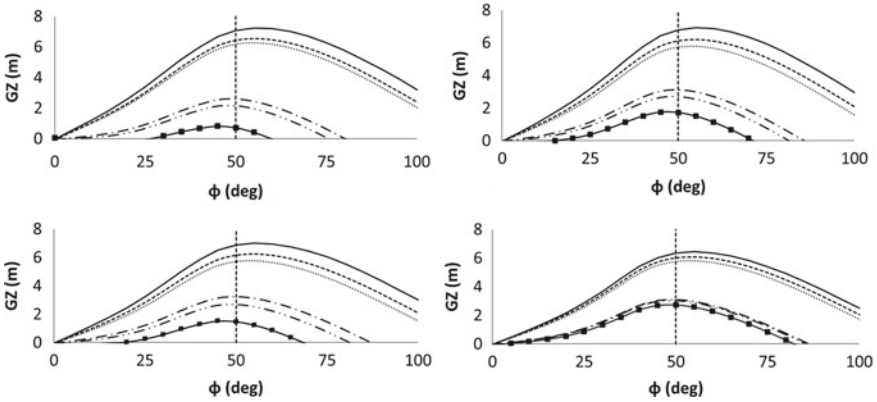
### 3.2 Light Cargoes

For light cargoes ( $0.77 \text{ t/m}^3$ ) homogeneously loaded, and after considering a range of filling ratios, it was found that, while prior to liquefaction the stability of the vessel improves as this ratio is raised (Fig. 9, left), after liquefaction stability significantly drops (Fig. 9, right). Greatest reduction occurs for 60–70% filling of the holds, producing a lolling phenomenon.

Several other cases of cargo quantity and distribution were investigated whose results are summarized in Fig. 10. Alternate loading cases corresponded to partial filling of the odd-numbered-holds with complete filling of all remaining holds. Inhomogeneous loading cases related to partial filling of the holds No. 4, 5, and 6 and complete filling of all others. When liquefaction occurred under inhomogeneous loading as described above, there was little reduction of stability. For the cases of



**Fig. 9** GZ curves for examined light cargoes before (left) and after (right) liquefaction. Five different holds filling are shown corresponding to homogeneous loading; Solid line: 60% filled holds. Dashed: 70% filled holds. Double dot - long dashed: 80% filled holds. Dot - dashed: 90% filled holds. Dotted: 100% filled holds



**Fig. 10** GZ curves for the examined light cargoes before and after liquefaction. Four different cargo distributions (for homogeneous, alternate and inhomogeneous loading) are shown, corresponding to 70% (up-left); 73% (down-left); 74% (up-right); and 80% (down-right) filled holds (in total). Curves are distinguished as follows; Solid line: Before liquefaction, for homogeneous loading. Solid - square: After liquefaction, for homogeneous loading. e Dashed: Before liquefaction, for inhomogeneous loading. Double dot - long dashed: After liquefaction, for inhomogeneous loading. Dotted: Before liquefaction, for alternate loading. Dot - dashed: After liquefaction, for alternate loading

homogeneous loading, there is a critical filling ratio (73% of hold volume) below which, whilst the vessel satisfied the intact stability criterion before liquefaction, after liquefaction substantial loss of stability occurred.

### 4 Concluding Remarks

A first step towards a systematic investigation of the liquefaction phenomenon, based on experimental procedures, was presented. Roll and sway oscillations were applied

on a scaled container containing two commonly transported materials (sand and olive pomace). Results indicated that, although the same liquefaction mechanism appears in both materials (oscillation of short duration under critical frequency led to a water layer formation at the top of the material) the difference in their size, shape and specific gravity give rise to qualitatively different behavior. The olive pomace seems to be more dangerous as the whole volume of material tends, after liquefaction, to behave like a fluid.

Stability calculations indicate that homogeneous loading of heavy cargoes can lead to a significant reduction in stability in case that liquefaction occurs. On the other hand, alternate loading produces a smaller reduction of stability. Similar behavior has noted for light cargoes: alternate and inhomogeneous loadings lead to less loss of stability. When cargo is converted to a liquid-like behaving mass due to liquefaction, having fewer free surfaces would definitely enhance the safety against capsizing.

The presented work was expanded recently to the experimental examination of heavier materials (nickel and iron ore) (see the NTUA diploma thesis of Pittara [18]). A step forward would be the computational investigation of liquefied-cargo shift based on Discrete Element Methods and comparison with the experimental results.

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