Experimental investigation of cargo liquefaction and impact on the stability of a bulk - carrier

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ABSTRACT

Liquefaction of granular materials in a rectangular container has been experimentally investigated using our School's "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.

KEYWORDS

Ship stability; liquefaction

INTRODUCTION

Cargo liquefaction is dangerous as it turns what appears to be an apparently safe cargo into an easily movable one that can bear a detrimental effect on a vessel's stability. INTERCARGO's 2011 bulk carrier casualty report noted that 13 bulk vessels and 38 lives were lost in 2011 and that half of the lives lost were on ships that foundered for cargo related reasons (Table 1).

Cargoes that are at risk of liquefaction are those containing at least some fine particles and moisture (Jonas 2012). 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.

Table 1: Balk carrier casualty report

Year	Lost vessels	Lost lives
2011	13	38
2010	7	44
2002-2009	48	158

* INTERCARGO 2011 annual report

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. The cargo loses shear strength and thus conditions are created for the cargo to behave like a liquid (IMO 2012).

Resent casualties mostly involved unprocessed or minimally processed ore cargoes; such as nickel ore, iron ore fines and iron sand. According to The Swedish Club (2012), 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 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 & Peck (1948). 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. The very recent IMSBC Code (IMO 2012) in particular, incorporates provisions intended to ensure that only cargoes with sufficiently low inherent moisture content (based on measurement of Flow Moisture Point-FMP and Transportable Moisture Limit-TML) are loaded. The codes contain instructions for the safe handling (loading, unloading) and stowage of bulk cargos which however are largely empirical. However, 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.

Research up top now has been primarily related to a few prominent problems, mostly of soil mechanics nature (e.g. Castro 1969, Xenaki & Athanasopoulos 2003). In the maritime field only a few research works have appeared, mainly focused on the identification of the acceptable conditions for a shipmaster to accept the loading of nickel ore and on countermeasures to be implemented should, during a voyage, the cargo liquefy (eg. Popek 2010, Jonas 2012).

In the current work, liquefaction was investigated experimentally using the shaking table equipment. A medium weight material (sand) and a light one (olive pomace) have been selected for testing. 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 loading for avoiding capsize, in case of liquefaction, were also considered. For this, a bulk carrier was used, designed by the first author as part of the requirements of our diploma course.

INVESTIGATION THROUGH EXPERIMENTS

Facility

The experimental facility is shown in Figure 1. It consists of a 6-DOF table that is driven to move as desirable, at a low to medium range of frequencies. Table's motion can reach up to ±30 deg in rotation and ±0.5 m in translation.

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

A rectangular tank made from non-coloured Perspex of 20 mm thickness to permit direct observation has been used. Its size was 0.23 m × 0.34 m × 0.15 m (width × length × height). The dimensions of the tank were selected to correspond to a Panamax bulk carrier that is excited in roll and sway with maximum frequency (full scale) 0.29 Hz and amplitude range 0.26-17.66 cm (sway)/0-30 deg (roll).

Used materials and procedure of investigation

Sand is 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 1.386t/m^3 and the average diameter, as found from analysis with an optical microscope, was 0.5mm.

Olive pomace on the other hand is by-product of olive processing. The specific gravity was 0.52t/m^3 and the average diameter of particles 4.5mm.

In all tests, the tank was filled with material up to a height of 11.5 cm.Various moisture contents were examined, as detailed in the next paragraphs. For each type of material two series of experiments were performed: one for roll and one for sway oscillations. It should be noted however that the centre of rotation in roll was at the table's height, i.e. at the base of the container; as a matter of fact, material's surface was subjected to a substantial sway in addition to the roll. The excitation was harmonic and the duration of each experiment was 30 s.

In addition, two angle-of-repose tests were performed for the olive pomace, at a moisture level close to 60%. The first test was performed for the unshaken pomace while the second was performed after intensive sway shaking and liquefaction appearance.

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. Specifically, for roll: 0.1 - 3.0 (Hz) / 2.09 - 22.2 (deg) and for sway: 0.6 - 3.0 (Hz) / 0.25 - 17 (cm). The key findings are summarised below. They were basically similar irrespectively of the direction of excitation (roll or sway).

a) 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.

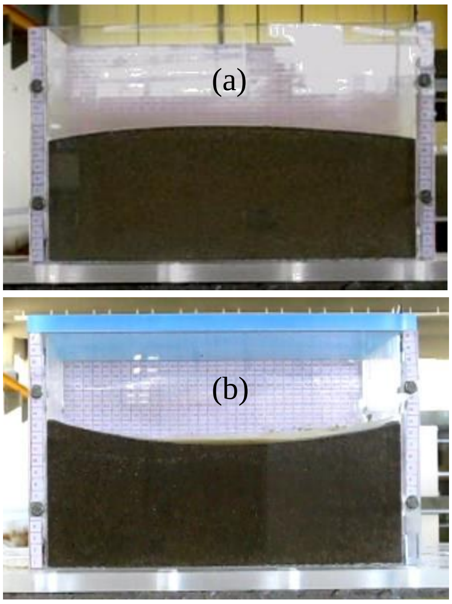

Fig. 2: Sand with MC 27.5% after being excited in roll. a) f=0.15Hz, φ_{max} =4.2deg; b) f=0.5Hz, φ_{max} =13.2deg.

b) Right after the critical moisture content is reached however, two phenomena emerge: for frequencies between 0.1-0.2Hz (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. 2a). For frequencies between 0.4 and 0.8Hz for roll and above 1.2Hz 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. 2b). It is noted that these findings are in good agreement with simulation results presented by Ahmed (2012).

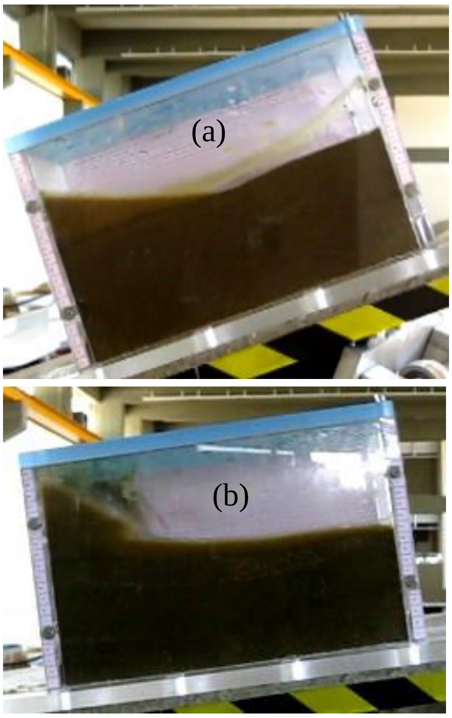

Fig. 3: Sand with MC 40% excited in roll: (α) f=0.1Hz, φ_{max}=22.2deg. The upper water layer is the only part that moves; (b) f=0.8Hz, φ_{max} =9.05deg. At the higher frequency the material below water moves too, albeit sluggishly.

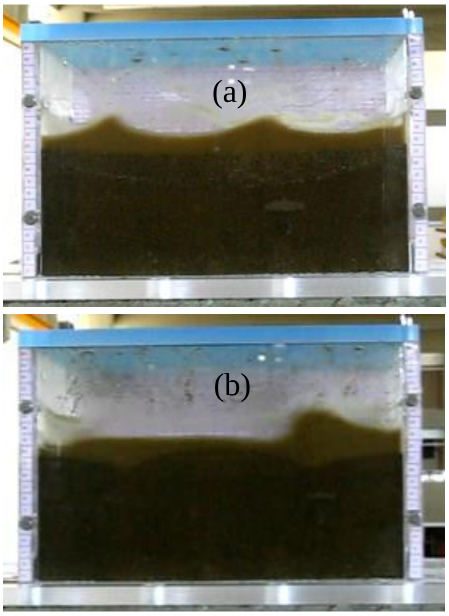

Fig. 4: Sand with MC 40% excited in high frequency - small amplitude sway. (a) f=2.5Hz, a=2.37cm; (b) f=1.4Hz, a =4.3cm.

c) 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. 3a). 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. 3b). For higher excitation frequency the water layer enters a resonance area and moves following the corresponding natural mode (Figs. 4a and 4b). At the same time, the material underneath the water layer rearranges itself.

d) 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 frequencies where liquefaction first appears.

Results for olive pomace

The olive pomace used for our experiments was supplied from two different olive mills in Greece (one in Corfu and one in Kalamata). We worked with samples of "dry" and "wet" olive pomace, having moisture content that is commonly found when such a material is transported by sea. The focus of our 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. For the wet olive pomace however, two phenomena should be noted:

- Moisture diffusion from specific areas of moisture concentration (black areas inside the material appearing in Figs. 5a and 5b) 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 (2011) for a heavier material (wet nickel ore).

- Excitation at frequencies above 1.0Hz leads to noticeable shift of a portion of material to the sides of the container.

To examine the change in the semi-static behaviour of the olive pomace before and after liquefaction occurrence, comparative tilting tests were conducted.

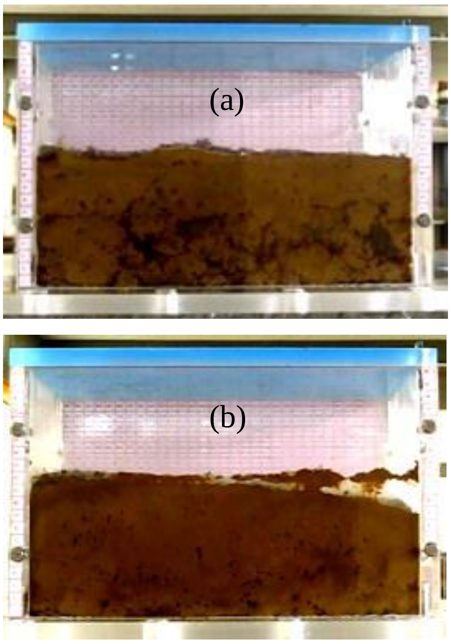

Fig. 5: Wet olive pomace (a) before; and (b) after the application of sway excitation (*f*=2.2Hz, *A*=4.3cm). Moisture's diffusion is apparent (the black spots in the first picture have become moisture layers in the second). Also, there is some shift of material after liquefaction occurred.

In accordance to the tilting box test method prescribed in IMBSC (IMO 2012), the tank was tilted with rate 0.3deg/s. Due to physical limits (container's height) the tilting stopped when 30 deg 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 deg). However, due to the moisture, 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.

STABILITY ANALYSIS

The computer code "AVEVA Marine" was used to investigate how cargo liquefaction can affect the static stability of a bulk carrier. Ship's main dimensions are presented in Table 2. Different cases of cargo's specific gravity (heavy and light cargoes) and cargo's distribution were examined.

Table 2: Ship's Main Dimensions

Ship's Main Dimensions	
Length Overall (L_{OA})	290.049m
Breadth Mld (B)	44.600m
Depth Mld (D)	25.700m
Design Draft (T)	18.000m
Deadweight (DWT)	172000t

As heavy cargoes were selected nickel ore (1.7-3.0t/m^3), iron ore (1.2-3.5t/m^3), sand (1.0-2.0t/m^3) and bauxite (1.2-1.4t/m^3). In the "light" cargo category (<1.0t/m^3) 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 (IACS 1997). Nevertheless, heavy cargoes, such as iron ore, are sometimes loaded homogeneously.

Heavy Cargoes

In case of alternate loading of heavy cargoes, with specific gravity 1.6 and 3.6t/m^3, as the cargo becomes heavier the loss of stability after liquefaction becomes greater (Figs. 6,7).

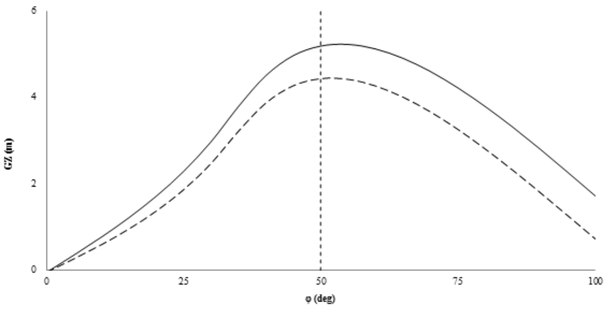

Fig.6: Effect on GZ of liquefaction for alternate loading of cargo having specific gravity 1.6t/m^3 - before (solid line) and after (dashed) liquefaction.

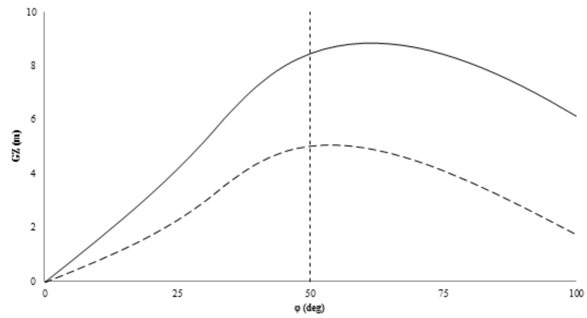

Fig.7: Effect on GZ of liquefaction for alternate loading of cargo having specific gravity 3.6t/m^3 - before (solid line) and after (dashed) liquefaction.

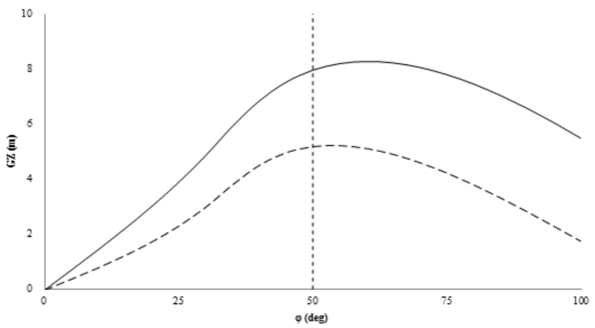

Fig.8: GZ curves for homogeneously loaded cargo of specific gravity 1.6t/m^3 – before (solid line) and after (dashed) liquefaction.

In the case of homogeneous cargo loading with specific gravity 1.6t/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.

Light Cargoes

For light cargoes (0.77t/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 (Figure 9a), after liquefaction stability drops (Figure 9b).

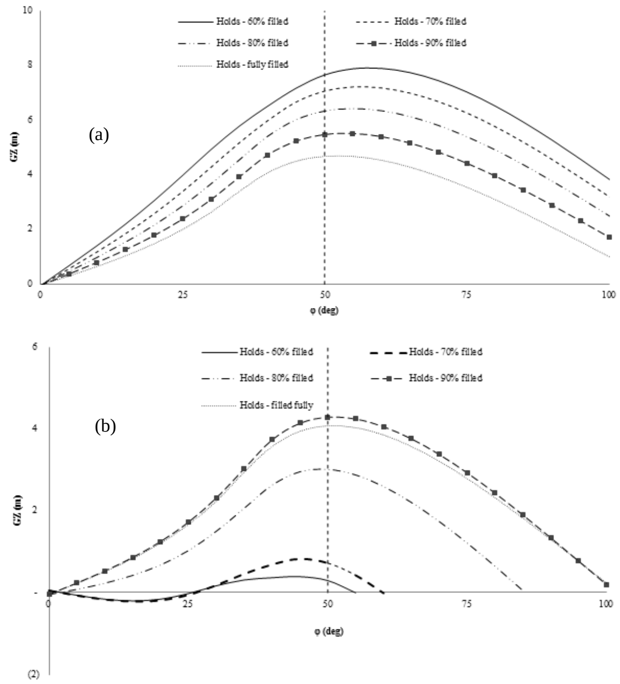

Fig. 9: GZ curves for examined light cargoes a) before and b) after liquefaction (homogeneous loading).

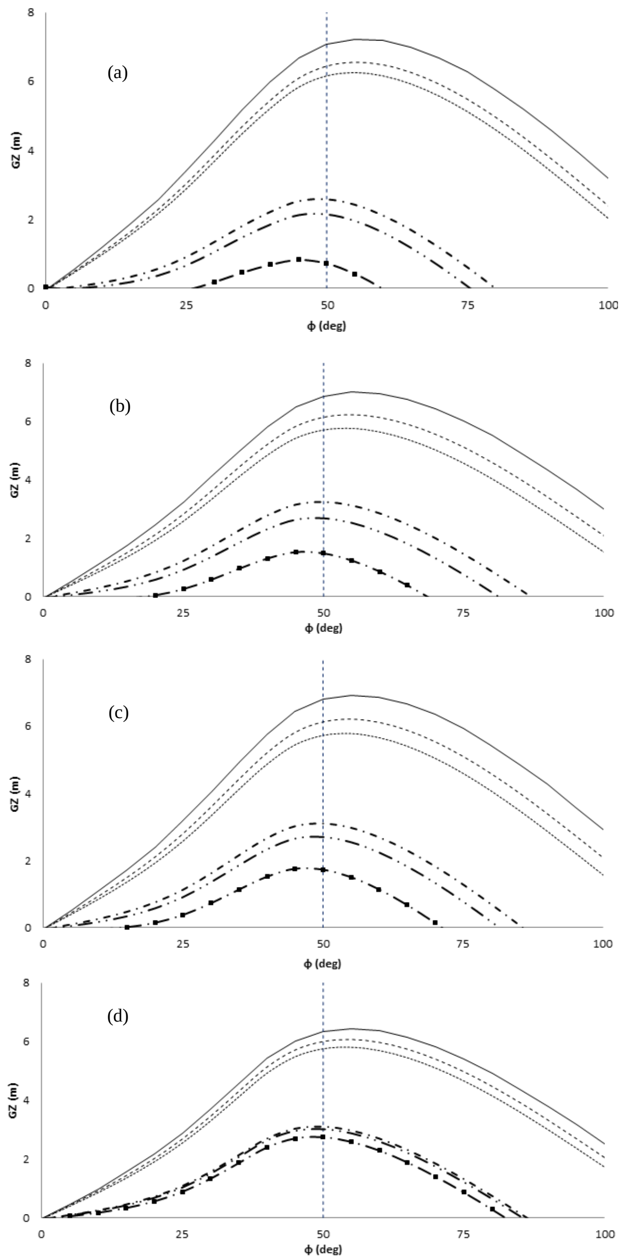

Fig. 10: GZ curves for examined light cargoes - before and after liquefaction. Different cargo distributions, corresponding to homogeneous loading of (a) 70%; (b) 73%; (c) 74%; and (d) 80% filled holds. Alternating loading before (solid) and after (dot-dashed), Homogenous loading before (dashed) and after (double dot-long dashed) and inhomogenous loading before (dotted) and after (square) liquefaction.

Greatest reduction occurs for 60% to 70% filling of the holds, producing a lolling phenomenon.

Several other cases of cargo quantity and distribution were investigated whose results are summarised in Figure 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 & 6 and complete filling of all others. When liquefaction occured under inhomogeneous loading as described above, there was little reduction of stability. For the cases of 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.

CONCLUSIONS

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 behaviour. The olive pomace seems to be more dangerous as the whole volume of material tends, after liquefaction, to behave like a fluid.

Static stability calculations, confirm that alternate or inhomogeneous loading is safer, with little reduction of stability.

A next step in our research would be the experimental examination of heavier materials (nickel and iron ore). Also, measurements of pressure at tank side walls, due to material's motion, are under way.

REFERENCES

Ahmed, M., FNI, 2012. *The Nautical Institute Seminar on Cargo Liquefaction - Hazards and Developments*, The Nautical Institute London Branch, London 3rd December 2012 presentations.

Castro, G., 1969. *Liquefaction of Sands*, Ph.D. Thesis, Harvard Soil Mechanics Series N81. Harvard University, Cambridge MA.

The Swedish Club (2012), *Carriage of Nickel Ore and Iron Ore Fines*, Detailed Bulletin.

International Association of Classification Societies (IACS) (1997), *Bulk carriers, Guidance and Information on Bulk Cargo Loading and Discharging to Reduce the Likelihood of Over - stressing the Hull Structure,* IACS publishing.

International Association of Dry Cargo Shipowners (INTERCARGO), *Benchmarking Bulk Carriers 2011-12.*

International Maritime Organization (IMO) (2012), "*Solid Bulk Cargoes Code [IMSB Code 268(85)]*", IMO publishing, ISBN: 978-92-801-1535-2.

Jonas, M., 2012. *liquefaction of mineral ores- IMSBC Code regulations and test methods,* Bulletin 2012 Volume 107 (2), pp. 22 - 30.

Jian-Ping, W., 2011. *A Study on Sfe Operation of Nickel Ore.* Opatija, International Conference IMLA 19.

Popek, M., 2010. *The Influence of Organic Polymer on Parameters Determining Ability to Liquefaction of Mineral Concentrates. International Journal on Marine Navigation and Safety of Sea Transportation* 4 (4), pp. 435-440.

Terzaghi, K., &. Peck B R, 1948, *Soil Mechanics in Engineering Practice*, John Wiley and Sons, New York.

Xenaki, V.C. & Athanasopoulos, G.A., 2003. *Liquefaction resistance of sand–silt mixtures: an experimental investigation of the effect of fines*. Soil Dynamics and Earthquake Engineering, 23, pp. 183 - 194.