Experimental Study on the Liquefaction Mechanism of Iron Ore Fines Cargoes

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Abstract: The liquefaction of Iron Ore Fines (IOF) during maritime transportation has got more attention in recent years. To study its liquefaction mechanism, the undrained monotonic loading tests on saturated IOF were conducted by using compression tri-axial apparatus. The static liquefaction behaviors of IOF under different densities and confining pressures were investigated. And different phenomenon has been observed on the IOF specimen. For the loose IOF specimen, slight dilate was observed and the phase transformation occurs in its stress-path curve under a high confining pressure. There is no phase transition in the intermediate density IOF sample, which shows more complex behavior. For the dense IOF specimen, a contractive behavior appears firstly then a long dilate starts. In view of these abnormal behaviors, the flow pattern failure mechanism of IOF is discussed, which provides a basis for the safe transportation of this kind of goods.

1. Introduction
Cargo liquefaction has been an arising issue since it is the major reason for numerous bulk carriers' capsizes [1, 2]. Solid bulk cargoes during maritime transportation are subject to compaction due to oscillatory ship motions. Although this kind of solid bulk cargo is usually loaded on the ship under unsaturated conditions, in some cases, due to the lack of understanding of the liquefaction of these materials, for example, the ship capsizing caused by the liquefaction of this kind of cargo under the action of sea waves is inevitable.

The International Maritime Solid Bulk Cargoes (IMSBC) code found that the liquefiable materials have the potential to liquefy due to the proportion of fine particles and moisture they contain [3]. And the only available parameter used to assess the liquefaction potential is the Transportable Moisture Limit (TML). The TML is the maximum gross water content that the liquefiable cargoes may contain without being at risk of liquefying during transportation. Recently, a new test procedure, Modified Proctor/Fagerberg test (MPF test) has been provided to replace the three methods including the Proctor/Fagerberg test (PF test) to determine the TML of IOF. However, whether the liquefaction of the cargo happens or not when its moisture content is lower than its corresponding TML is still unclear. The key parameters affecting the liquefaction process are still questionable. And a further understanding of the mechanism of the flow-type failure is still desired.

Both experimental and numerical methods have been adopted to investigate the mechanism of the flow-type failure of IOF and some results have been obtained. There have been found two common
types of liquefaction, the static liquefaction and dynamic liquefaction [4]. Static liquefaction is caused by increasing the shear stress in a material, usually a monotonic load, until such a point is reached that one point of the material liquefies and propagates rapidly to produce total liquefaction of the material. Dynamic liquefaction occurs when a cyclic or dynamic load is applied to material causing parameters within the material to change and therefore liquefy [5]. Like static liquefaction, dynamic liquefaction propagates throughout the material from a single point to cause total liquefaction of the material. In reality, the liquefaction process is complex and five main potential causes have been identified, including unsafe storage conditions, insufficient loading plan and improper handling of heavy and high density cargo during loading, poor compliance with the testing and certification requirements, the extreme voyage conditions and finally the properties of the liquefiable cargo [6, 7]. Also stated by Lee [8], Munro and Mohajerani [1], apart from the water content, the cargo loading process, the encountering weather condition or sea voyage duration are all the possible causes for the liquefaction. Thus, for the lower part of the cargo in a cargo hold, rather than the cyclic loading, the static shearing loading during or a few hours after the loading operation should be investigated in detail. Compared to the whole voyage of the cargo, its behavior could be regarded as undrained. Owing to the compaction during the loading process and moisture migration, the saturated IOF was firstly chosen and considered. And the behaviors of cargo under excess high static shear load have not been addressed before.

This study aims to investigate the behaviors of IOF under undrained monotonic loading through a tri-axial apparatus corresponding to the conditions of the cargo during its loading process. Different initial densities and confining pressures were considered in the experiments. Based on the stress-strain and stress-path relationships of IOF, whether the IOF is susceptible to flow-type failure is predicted. The results presented in the study could be used as a helpful reference for a proper loading plan of IOF and the future research on this topic.

2. Methodology and testing procedure
Owing to the massive weight of the shipped IOF cargo, by using the high pressure tri-axial apparatus, a similar situation corresponding to the loading process could be attained. And a good understanding of undrained IOF behaviors under such pressures could be got.

The grain size distribution of IOF is shown in Fig. 1. It contains about 18.6% of gravel, 58.9% sand and about 22.5% non-plastic fine content. The Gs of IOF is between 4.4-4.5. An average of 4.444 was chosen and applied for all Gs related calculation throughout this study. According to method A stated in [9], the compaction test was conducted to estimate the \( \rho_{d,\text{max}} \) and \( w_{\text{opt}} \). Corresponding to the water content of IOF in real condition [1], the values varies from 8-13% were chosen in the compaction tests. And the degree of compaction \( (D_c) \) is used to describe the density of the specimens. The physical properties of the IOF are summarized in Table. 1.

![Figure 1. Particle size distribution of IOF.](image-url)
Table 1. Physical properties of IOF.

| Items  | value | Items  | value |
|--------|-------|--------|-------|
| Gravel (%) | 18.6 | $D_{50}$ (mm) | 0.17 |
| Sand (%) | 58.9 | $D_{50}$ (mm) | 1.1 |
| $F_c$ (%) | 22.5 | $D_{60}$ (mm) | 2.2 |
| $G_s$ | 4.444 | $\rho_{d\max}$ (kg/m$^3$) | 2760 |
| $w_{opt}$ (%) | 12 | | |

The IOF material was mixed properly, oven-dried and then mixed with the optimum water content ($w_{opt} \approx 11.5\%-12\%$). Moist tamping method [10] was used to prepare the specimen and different degrees of compaction was obtained. The volume change of the specimens during consolidation could be calculated through the volume of drained water collected in a burette by a differential pressure transducer (DPT). To obtain the saturated specimen, the double-vacuum method [10] is used to obtain full saturation condition of the materials. Through the increment of the cell pressure the corresponding value of pore water pressure ($PWP$) could be recorded. When the volume change of the specimen is stabilized the consolidation is considered to be completed. Finally, the load is applied. The load is governed by an axial strain target (e.g. 40%). After finishing, the pressure in the cell is reduced gradually. The water is removed and the apparatus is unassembled. The specimen is carefully retrieved for sieve analysis. All the tests were conducted on the IOF with a strain-controlled tri-axial apparatus with a maximum 3 MPa confining pressure [11, 12].

3. Undrained behaviour of IOF

All the tests were consolidated undrained. Loading rate was set to 0.1 mm/min and the axial strain was used to control the termination of the tests. All the tests conditions and obtained parameters are summarized in Table 2.

Table 2. Summaries of the test conditions and obtained parameters.

| $e_f$ | $\rho_d$ (g/cm$^3$) | $D_c$ (%) | $\sigma_c$ (MPa) | $q_{peak}$ (MPa) | $p'_{peak}$ (MPa) | $q_{res}$ (MPa) | $p'_{res}$ (MPa) |
|-------|-------------------|-----------|-----------------|-----------------|-----------------|----------------|----------------|
| 1.002 | 2.22              | 80.4      | 0.2             | 0.115           | 0.111           | 0.088          | 0.056          |
| 0.996 | 2.23              | 80.7      | 0.2             | 0.108           | 0.112           | 0.053          | 0.031          |
| 0.969 | 2.26              | 81.7      | 0.5             | 0.263           | 0.216           | 0.207          | 0.138          |
| 0.889 | 2.35              | 85.2      | 1.0             | 0.878           | 0.551           | 0.813          | 0.524          |
| 0.833 | 2.42              | 87.7      | 2.0             | 1.469           | 0.892           | 1.335          | 0.836          |
| 0.792 | 2.45              | 89.8      | 0.2             | 0.433           | 0.234           | 0.275          | 0.157          |
| 0.754 | 2.53              | 91.8      | 0.5             | 0.770           | 0.438           | 0.466          | 0.278          |
| 0.682 | 2.64              | 95.7      | 0.2             | 1.481           | 0.861           | 1.198          | 0.763          |
| 0.651 | 2.69              | 97.5      | 1.0             | 2.398           | 1.402           | 2.301          | 1.386          |
| 0.647 | 2.70              | 97.8      | 2.0             | 3.225           | 1.872           | 2.891          | 1.790          |

3.1. Steady state

Based on all the tests that have been conducted, the actual steady state was only observed on samples from loose group under relatively low confining stress ($\sigma_c = 0.2$ MPa). The stress-strain, stress-path and EPWP-strain relationship of two tests with an initial confining stress of 0.2 MPa are shown in Fig. 2. Based on the test results, it can be seen that at the beginning of loading the samples slightly dilate before they turn into an extreme contraction, which is different from the behaviors of loose sand soils. The shear stress is increasing with the increase of the axial strain and it reaches the peak point at around 1.5-2.0% axial strain. Then it drops down, stabilizes and becomes almost constant when the axial strain is 20%. On the other hand, the effective stress tends to decrease from the very beginning of
loading, keeps on decreasing and finally reaches steady state when the axial strain is 20%. While, a positive pore water pressure is generating inside the specimens, due to the extreme contraction behavior of the specimen, and keeps on increasing and becomes almost constant when the specimen reaches its steady state. When a loose IOF specimen is subjected to a low confining stress, the steady state could be reached and the static liquefaction occurs accordingly.

Figure 2. Stress-strain, stress-path and EPWP-strain of samples which had reached the steady state.

3.2. Quasi-Steady state
When a loose sand sample is initially loaded with relatively high confining stress, the strength will drop down and attain a minimum strength, then increases again and reaches the steady state [13]. This minimum strength is regarded as the quasi steady state point. Therefore, this behavior is called quasi steady state (QSS).

Figure 3. Stress-strain, stress-path and EPWP-strain of samples which exhibited quasi steady state.

Fig. 3 shows two IOF samples from dense group, with a degree of consolidation of (Dc = 89.8% & 91.8%) and confining stress of (σc = 0.2 MPa & σc = 0.5 MPa), respectively. The deviator stress in both samples reached the peak point at around 2% axial strain, then, strain softening takes place. While on the p’-q plane, and corresponding to the same range, the specimen showed a contractive behavior then started to dilate up to the peak point, and lastly started to contract again. In the case of σc = 0.2 MPa and based on stress-path curve, it is seen that the specimen reached a minimum strength value then started to increase again. Similar behavior can be anticipated in the case of σc = 0.5 MPa.

3.3. Transitional state
All other tests that did not fit in either “steady state” or “quasi steady state” were labeled as “transitional state”. The stress-strain, stress-path and EPWP-strain relationships of three tests belong to loose group are shown in Fig. 4.
Deviator stress (kPa)
Axial strain (%)
\( \sigma_c = 0.5 \text{MPa}, D_c = 81.7\% \)
\( \sigma_c = 1.0 \text{MPa}, D_c = 85.2\% \)
\( \sigma_c = 2.0 \text{MPa}, D_c = 87.8\% \)

Deviator stress (kPa)
Mean effective stress (kPa)
\( \sigma_c = 2.0 \text{MPa}, D_c = 97.8\% \)
\( \sigma_c = 1.0 \text{MPa}, D_c = 97.5\% \)
\( \sigma_c = 0.2 \text{MPa}, D_c = 95.7\% \)

Deviator stress (kPa)
Axial strain (%)
\( \sigma_c = 2.0 \text{MPa}, D_c = 97.8\% \)
\( \sigma_c = 1.0 \text{MPa}, D_c = 97.5\% \)
\( \sigma_c = 0.2 \text{MPa}, D_c = 95.7\% \)

**Figure 4.** Stress-strain, stress-path and EPWP-strain for loose group samples in transitional state.

The 0.5 MPa confining stress is behaving exactly the same as the 0.2 MPa tests (see Fig. 2) with one exception that the 0.5 MPa test did not reach steady state yet, as seen from the Fig. 4, the shear stress is still decreasing. On the other hand, the other two tests presented in Fig. 4, namely 1.0 MPa and 2.0 MPa, show a different behavior. First, these samples belong to loose group and by looking at the degree of compaction after consolidation (85.2% and 87.1%), it is clear that a large change of volume took place and the specimens became much denser. Therefore, the peak strength is much higher in comparison with the other tests, and it is not achieved at a very early axial strain but at about 15%. From the stress-path both tests show little positive dilatancy after loading, then they exhibit a large contraction until a certain point when there is a transformation to a long dilation. Finally, after reaching the peak shear strength, the samples start to contract again until reaching about 40% axial strain, where the tests were terminated.

**Figure 5.** Stress-strain, stress-path and EPWP-strain for loose group samples in transitional state.

Three samples from dense group sheared with initial confining stress of 0.2 MPa, 1.0 MPa and 2.0 MPa can be seen in Fig. 5. Stress-path of each curve starts with a very limited dilation, then contraction, then a long dilation again and finally they contract after reaching the peak and head to the expected steady state zone. One observation is that the denser the initial state the higher the shear strength becomes. As the peak deviator stress in the denser specimen was almost 2.5-3.0 times larger than that in the looser ones (see Fig. 2). Apart from that, the first contraction behavior is larger in the loose specimen, which is a common trend in clear sands [14] or even sands with fines [15]. As for the sample with relatively low confining stress (0.2 MPa), the contractive behavior right after loading is rather limited, then a perfect dilation appears until reaching the peak point at which the strength drops and head for the assumed steady state zone. This suggests that the higher the confining stress the more contraction appears in both loose and dense groups. In Fig. 5, the EPWP increased in response to the start of loading then reached a peak value at an axial strain of about 2-3%, which is reflected on the stress-strain by a change from rapid increase in the deviator stress to a steadier one. Then the EPWP starts to decrease, goes even to negative zone in the case of 0.2 MPa, allowing the effective stress to increase constantly with a large dilation behavior until reaching the peak point.

Based on the three categories were established, steady state, quasi steady state and finally the transitional state and summaries of the tests are given in Table 3.
Table 3. Summaries of saturated IOF behaviors under undrained monotonic loading.

| Definition/Failure                      | Conditions                             |
|----------------------------------------|----------------------------------------|
| Steady state / Static liquefaction     | $D_c \text{ initial} = (73\%-75\%) \& \sigma_c = 0.2 \text{ MPa}$ |
| Quasi steady state / Limited liquefaction | $D_c \text{ initial} = (89\%-90\%) \& \sigma_c = (0.2-0.5) \text{ MPa}$ |
| Transitional state / Dilation          | $D_c \text{ initial} = (73\%-75\% \& 95\%) \& \sigma_c = (1-2) \text{ MPa}$ |

4. Conclusions
To investigate the liquefaction behaviors of IOF corresponding to the conditions at the lower part of a cargo hold during or a few hours after the loading process, a series of consolidated undrained monotonic loading tri-axial tests were conducted on saturated IOF. Different initial degrees of compaction and a wide range of initial confining pressures were considered in the tests. Based on the test results, conclusions can be made as follows.

1. The loose IOF specimen reached steady state under a low initial density and confining pressure. However, slight dilate phenomenon was observed in the stress-path curve of the loose IOF specimen at the beginning of loading. Furthermore, the PT phenomenon appears in its stress-path curve under a high confining pressure.

2. For the medium dense IOF specimen, more complicated behaviors occurred in its stress-path curve. It showed a contractive behavior at first, then started to dilate up to the peak point and lastly started to contract again. The PT phenomenon was not observed in its stress-path curve compared to the behaviors of sand soils.

3. For the dense IOF specimen, it also showed a contractive behavior at first then a long dilate starts different with the dense sand soils which only dilate without the contract. Also the PT phenomenon was observed in the stress-path curve of dense IOF specimen. And with increase of the initial confining pressure, the peak shear strength also increases.

Apart from the saturated behaviors of IOF under monotonic loading, further study should emphasis on the unsaturated IOF and different conditions, for example, the cyclic loading.

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