ABSTRACT

Accidents and life loss caused serious concern on the liquefaction problem of some solid bulk cargoes such as iron ore fines during transportation at sea. To understand the liquefaction property of a type of iron ore fines, a series of tests, e.g. SEM observation, monotonic loading triaxial test, cyclic loading triaxial test etc. were conducted. Test results show that this unusual material possesses some special properties, for instance, much higher specific gravity ($G_s=4.444$) as compared to common materials in geotechnical engineering. SEM observation unveils that the tested iron ore fines has a multi-layer, micro-porous structure which may affect its water retention ability under unsaturated states. The result from the undrained monotonic loading test indicates an angle of internal friction of 45.6° according to the Mohr-Coulomb failure criterion. Interestingly, the peak strength and the residual strength were achieved at values of axial strain of approximately 2.5% and 13%, respectively, regardless of confining pressure among three undrained monotonic loading tests. The undrained response of tested iron ore fines to cyclic loading shows similar characteristics as those of common sands and the liquefaction resistance of this material defined based on the relationship between cyclic stress ratio (CSR) and number of cycle is not significantly affected by change of confining pressure.

Keywords: iron ore fines, laboratory test, undrained strength

1 INTRODUCTION

In 2009 two vessels, the ‘Asian Forest’ and the ‘Black Rose’, capsized and sank following liquefaction of iron ore fines cargoes which they had loaded in the Indian ports of Mangalore and Paradip (Isacson, 2010a). In October and November 2010, three vessels, the ‘Jian Fu star’, the ‘Nasco Diamond’ and the ‘Hong Wei’ sank during the carriage of nickel ore from Indonesia to China with a loss of forty four seafarers, which were very possibly induced by cargo liquefaction (Isacson, 2010b). Several vessels had also experienced cargo liquefaction problems after loading bauxite in the Amazon region in northern Brazil (Gard, 2012). These accidents caused serious concern of P&I Clubs and their members because of accidents and losses mentioned above. Extensive discussions have been made about it on 15th-18th sessions of sub-committee of DSC (Dangerous goods, Solid cargoes and Containers). Recently, the sub-committee of DSC proposed to add a new entry in IMSBC Code for iron ore fines which will be applied to iron ore with $D_{10} < 1$ mm and $D_{50} < 10$ mm ($D_{10}$ and $D_{50}$ denote particle sizes passed by 10% and 50% of a material by weight, respectively) (DSC, 2013). Except reports which support discussions for sub-committee of DSC, very few works related to liquefaction of iron ore fines are available. Atkinson and Taylor (1994), Taylor and Atkinson (1998) and Laue (1998) reported the behavior of iron concentrates, which is a similar type of cargo with iron ore fines, subjected to conditions during a

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voyage. In this paper, results from a series of laboratory tests are presented to study geotechnical properties of a type of iron ore fines (IOF, hereafter) focusing on its undrained strength.

2 MATERIAL

Figs. 1 and 2 show respectively the overall view and a typical close view of relatively large particles of the tested IOF. Large particles of the tested IOF are normally covered by dull brownish-yellow fines and shows a multi-layer structure like shale. In Fig. 2, a rather smooth surface of the top layer was observed from the top view; while some substance with the similar color as fines seems to be sandwiched among layers as can be seen from the lateral view. The gradation of the tested IOF (Fig. 3) shows all particles passed 9.5mm sieve. It is classified as SFG material containing 33.5% gravel, 42.9% sand, 17.1% silt and 6.5% clay according to the test standard of Japanese Geotechnical Society (JGS 0051-2000). Non-plastic fines content is about 24%.

Iron ore is normally rich in iron oxides which increases its self-weight. Fig. 4 shows measured values of specific gravity ($G_s$) with an average value of 4.444 from seven tests, which is much larger than common materials encountered in geotechnical engineering. In addition, $G_s$ values of IOF distributed in between 4.4 and 4.5 which are much more scattered than those of common materials according to authors’ test experience on other materials. This may be caused by the fact that iron ore is usually a mixture of many natural mineral components, e.g. hematite, goethite etc. which may possess different properties and cause fluctuation of $G_s$ among tests. Fig. 5 shows the results of compaction test of the tested IOF, which was conducted by applying compaction energy of 550 kJ/m$^3$ according to methodA of JIS A-1201:1990 (JIS: Japan Industrial Standard). Three sets of new material were prepared and they were used two times for each in the test. The maximum dry density of 2.79 g/cm$^3$ was obtained with an optimum water content of about 12%, under which state the Sr (degree of saturation) is around 90%.
3 SEM IMAGES

SEM (Scanning Electron Microscope) observation was conducted to reveal the detail information of the tested IOF. Figs. 6a & 6b and Figs. 6c & 6d show typical views of relatively large particles of tested IOF from respectively the top view and lateral view (the view directions are shown in Fig. 2). In addition, observation for fines content was also included (Figs. 3e & 3f). The dash line boxes in Figs. 6a, 6c and 6e indicate the observation scope of Photos 6b, 6d and 6f, respectively. Fig. 6a also shows smooth surfaces of the top layers and triangle crystal structures were observed on the surfaces (e.g. red dash box in Fig. 6b); on the other hand, many micro pores distribute on the lateral side of IOF particle and the size of pores seems not uniform (Figs. 6c and 6d). Though it is not known whether these pores are connected to each other into a network or not, it should somehow affect some properties of IOF, e.g. water retention ability, G, etc. The micro pore is not visible for fines content under current magnifications and the shape of fines looks rather spherical (Fig. 6e and 6f).

Fig. 6. SEM images for large particles and fines content of the tested IOF.
4 UNDRAINED TRIAXIAL TESTS

Undrained monotonic loading tests and cyclic loading tests were conducted to investigate undrained behavior of the tested IOF. The process of making a specimen is the same for both tests. Pre-wetted IOF with about 12% water content was cured for at least 24 hours before utilization. A specimen was molded into cylindrical dimensions of 50 mm in diameter and 100 mm in height and saturated by double vaccumng method. A specimen with B-value ≥0.95 was regarded as fully saturated.

4.1 Undrained monotonic loading test

A triaxial apparatus with a strain control axial loading system was employed for this type of test. The strain rate was about 0.1%/min. Confining pressures \( \sigma_0' \) varied from 50 kPa to 200 kPa. The compaction degree, \( D_c \) ranged from 92.8% to 95.0%, which was defined as dry density of a specimen after consolidation normalized by maximum dry density (2.79 g/cm\(^3\), Fig. 3). Tests were terminated either when a specimen achieved steady state where the specimen deformed under constant deviator stress and effective stress or when axial strain of a specimen surpassed a certain value, say 20%.

Fig. 4 shows stress paths and stress strain relationships of all three tests. The peak strength of the tested IOF increased with the increase of initial confining pressure and strain softening behavior was observed after exhibiting the peak strength. Interestingly, the values of axial strain at which the peak strength was achieved are similar (axial strain =2.5%) for these three different tests; moreover the residual strength was also achieved at similar axial strain, approximately starting from 13%. By fitting the peak shear strength of three tests as shown the dash line in Fig. 4a, the angle of internal friction of 45.6° was obtained according to the Mohr-Coulomb failure criterion.

4.2 Undrained cyclic loading test

Another triaxial apparatus with a stress control axial loading system was employed to conduct undrained cyclic loading tests. Vertical sinusoidal cyclic loading with frequency of 0.1 Hz was applied by a pneumatic double action cylinder. Two sets of tests with initial confining pressure of 50 kPa and 100 kPa were conducted. The average compaction degree of specimens in this series of tests is 92.4%. Figs. 5-6 show time histories of deviator stress \( q \), pore pressures generation and axial strain, stress strain relationship and effective stress path of typical tests with initial confining pressure of 50 kPa and 100 kPa, respectively. The PWP (excess Pore Water Pressure) increased gradually under cyclic loading and approached initial confining pressure in the last several cycles. Axial strain accumulated mostly in extension side after each loading cycle except the last few cycles where relatively large deformation developed. Generally, the undrained responses to cyclic loading for this material show similar pattern with common sands. The red dash lines shown in effective stress paths in Figs. 5-6 are failure envelops calculated according to the angle of internal friction obtained from the monotonic loading test (Fig. 4a) and the Mohr-Coulomb failure criterion. The failure envelop of specimen under cyclic loading seems coincident initially with that of undrained monotonic loading when effective stress (\( p' \)) first reached 0 kPa, while it enlarged as cyclic loading continuously applied thereafter.

Fig. 4 Responses of IOF in undrained monotonic loading test, a) stress paths; b) stress strain relationships
Fig. 5 Responses of IOF to cyclic loading under initial confining pressure of 50 kPa, time histories of (a) deviator stress, (b) pore water pressure, (c) axial strain; (d) stress strain relationship and (e) effective stress path

Fig. 6 Responses of IOF to cyclic loading under initial confining pressure of 100 kPa, time histories of (a) deviator stress, (b) pore water pressure, (c) axial strain; (d) stress strain relationship and (e) effective stress path

Fig. 7 shows the relationship between CSR (Cyclic Stress Ratio=$\sigma_d/2\sigma_0'$, where $\sigma_d$ is single amplitude of cyclic loading) and number of cycle which caused 5% axial strain of double amplitude. This relationship is usually used to estimate the resistance against liquefaction of a material. As shown, relationships obtained from two sets of tests with various confining pressure are not significantly different from each other, namely the relationship in Fig. 7 well normalized the effect of confining pressure on liquefaction resistance for this material.

Fig. 7 Relationship between CSR and No of cycle of IOF

5 CONCLUSION

Geotechnical properties of a special material, iron ore fines, was reported in this paper. Test results show this type of iron ore fines possesses much higher $G_s$ value. Relatively large particles of this material show a multi-layer, micro-porous structure and fines content is of rather spherical shape. The angle of internal friction obtained from undrained monotonic loading tests with different confining pressure is about $45.6^\circ$ and this
angle is roughly coincident with results from undrained cyclic loading tests. The pattern of undrained responses to cyclic loading for this material are similar with common sands. The liquefaction resistance of this type of iron ore fines defined based on the relationship between CSR and number of cycle is not significantly affected by confining pressure. These properties need to be compared with those of common geo-materials.

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