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Undrained monotonic triaxial loading behaviors of a type
of iron ore fines

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Abstract: Concerning on the static liquefaction properties of an industrial cargo, iron ore fines (IOF), undrained monotonic behaviors of a type of IOF are revealed through conducting triaxial compression tests. It is found that IOF exhibits some similar behaviors as those of common sandy soils, while some very unusual behaviors are also observed. All IOF specimens with compaction degree of 84%-95% and confining pressure of 50 kPa -200 kPa exhibit dilative behavior from the beginning of axial loading until the deviator stresses reached their peaks (q_{pk}). Then the dilative behavior transforms to the contractive one, and the contractive behavior continues until reaching the residual stress without observation of phase transformation and quasi steady state. These behaviors are not usually observed for common sandy soils based on extensive previous works. More studies may be necessary since these unusual behaviors imply that flow failure, similar to the undrained monotonic behavior of very loose sand, may be triggered regardless of density of IOF. In addition, this study also establish the relationships of IOF between its initial conditions, peak stress conditions and residual conditions by employing classical knowledges developed for sandy soils.

Keywords: Iron ore fines; Undrained triaxial test; Static Liquefaction; Steady state; Collapse surface

37 Introduction

38 Iron ore fines (IOF) are transported as a type of bulk cargo for iron making industry. Together
39 with some other cargoes such as nickel ore, sinter feed bauxite etc., they are being concerned by
40 the International Maritime Organization (IMO) and relevant organizations due to accidents and
41 associated life loss caused by reportedly liquefaction of the cargoes during the maritime
42 transportation (Isacson 2010 *a* and *b*; LPC 2011; Gard 2012; Roberts et al. 2013; Chen et al.
43 2014). For safety transportation of IOF at sea, IMO, after the two casualties occurred in 2009
44 (Isacson 2010 *a*), declared that IOF should be regarded as a liquefiable cargo and shipped with a
45 moisture water below the transportable moisture limit (TML), although there was no specific
46 regulation procedure for IOF listed in the International Maritime Solid Bulk Cargoes Code
47 (IMSBC code) (IMO 2010b). Then IMO organized an iron ore technical working group (TWG)
48 with participants of the world's three largest iron ore producers (BHP Billiton, Rio Tinto and
49 Vale) to conduct research, and coordinate recommendation and conclusions about the transport
50 for iron ore fines(IMO 2013 b). Based on the findings of TWG (IMO 2013 b, c, d and e), IMO
51 issued a circular (IMO 2013a), in which IOF containing 10 % or more particles with size less
52 than 1 mm, 50 % or more particles with size less than 10 mm, and less than 35 % goethite
53 content, is categorized to liquefiable cargo. And a new test procedures, Modified
54 Proctor/Fagerberg test (MPF test), is provided to replace the three methods including the
55 Proctor/Fagerberg test (PF test) for determination of TML of IOF because the MPF test seems to
56 be able to produce similar densities of IOF as those for shipping (IMO 2013 b, c, d and e).

57 Fig. 1 schematically illustrates the way to determine TML by MPF and PF tests. MPF and PF
58 tests are essentially the same as the Proctor compaction test but with smaller compaction
59 energies, while gross water content ($=\text{mass of water} / \text{masses of IOF and water}$) rather than the

net water content ($=\text{mass of water} / \text{mass of IOF}$) is used to plot the compaction curve. TML is equal to the gross water content corresponding to the intersecting point of the compaction curve and the 80% degree of saturation line for MPF test, or the 70% degree of saturation line for PF test, namely as can be seen from Fig. 1, TML determined by the MPF test is higher than that of the PF test.

There are very few research results about properties of IOF except reports of TWG. Munro and Mohajerani (2017a and b) discussed the liquefaction potential and stability issue of IOF based on the model tests and traditional consolidated drained triaxial tests. As an independent study, Wang et al. (2014 and 2017b) revealed the soil water characteristic curves of unsaturated IOF, Wang et al. (2016a) revealed the undrained behaviors of saturated and unsaturated IOF subjected to the cyclic triaxial loading, Wang et al. (2016b) revealed some geotechnical properties of two type of IOF, Wang et al (2017a) reported the primary evaluation of liquefaction potential of the IOF heap with considerations of seepage and liquefaction resistance of unsaturated IOF by applying rolling motions.

As reported by IMO (2010a), one of the shipping casualties induced by liquefaction of IOF occurred 2 to 3 miles away from the port in a prevailing weather conditions with wind speed of 15 knots and wave height of 2 meters. Thus, rather than the cyclic loading, the static shear loading, for instance, during loading process, seepage process or natural densification process of IOF, may be also responsible for the liquefaction. From this point of view, the undrained behaviors of a type of IOF under monotonic triaxial loading are revealed and compared with typical behaviors of common sandy soils.

82 Typical undrained behaviors of common sandy soils

83 The typical undrained behaviors of common sandy soils have been studied extensively in the past
84 decades (Castro and Poulos 1977; Lindenberg and Koning 1981; Poulos 1981; Been and
85 Jefferies 1985; Sladen et al. 1985; Ishihara 1993; Pitman et al. 1994; Verdugo and Ishihara 1996;
86 Yamamuro and Lade 1997 a and b; Yoshimine and Ishihara 1998; Yoshimine et al. 1999; Yang
87 et al. 2008; Schnaid et al. 2013 among others). Though the fines content, initial shear condition,
88 over-consolidation, sampling method etc. are also effect factors (Ishihara and Okada 1978; Lade
89 and Yamamuro 1997; Vaid and Eliadorani 1998; Sze and Yang 2014), the undrained behaviors
90 of sandy soils are thought to be affected primarily by the density and confining pressure
91 conditions. Fig. 2 (a, b) schematically shows typical undrained behaviors of common sandy soils
92 and Fig. 2 (c, d) indicates the definitions of terminology used in this study. Very loose specimen
93 (e.g. specimen A in Fig. 2) usually behaves contractively from the beginning of loading until
94 reaching the final residual deviator stress (q_s) in the effective stress path plot. In the stress strain
95 relationship plot, specimen A first shows strain hardening until reaching its peak deviator stress
96 (q_{pk}), then strain softening continues until reaching q_s at the steady state (SS). SS is the state of
97 the sand deforming continually, at constant volume and under constant shear stress and confining
98 stress (Ishihara 1993). The behaviors like specimen A may result in flow failure (or flow
99 liquefaction) and induce severe problems since strain develops continuously with a shear stress
100 much smaller peak value (Hanzawa 1980; Marcuson III et al. 1990; Lade 1993; Lade and
101 Yamamuro 1997; Yoshimine 1999; Yamamuro and Covert 2001).

102 Loose ~ medium dense specimen (e.g. specimen B) may also exhibit contractive behavior in the
103 early stage of loading, while it turns to the dilative side at the phase transformation (PT). PT is a
104 point coinciding with the quasi steady state (QSS), where a temporary drop in shear stress takes

place over a limited range of shear strain (Ishihara et al. 1975 and Ishihara 1993). For the medium ~ dense specimen (e.g. specimen C), the initial contractive behavior may turn to dilative one without experiencing strain softening, and for the dense specimen (e.g. specimen D) contractive behavior may not exhibit (Yoshimine et al. 1999). The dilatancy behaviors may change depending on the initial confining pressure, of which usually a low confining pressure impels, and a high confining pressure impedes dilative behavior (Ishihara 1993; Yang et al. 2008).

Fig. 3 shows the undrained behaviors of two specimens of saturated Toyoura sand, a widely used fine sand in laboratory testing, obtained in triaxial tests. The very loose and medium dense specimens behave very similar to specimens A and C in Fig. 2, respectively. It should be noticed that for the triaxial tests in Fig. 3, the very loose specimen was of a void ratio (e) of 1.11 or relative density (D_r) of -33% before the consolidation process. Since it was prepared by the moisture tamping method with ten layers, a negative D_r can be obtained, unfortunately, e after the consolidation process was not measured. On the other hand, the medium dense specimen was prepared by the air pluviation method and e of 0.77 or D_r of 62% was that after the consolidation process.

Test material and program

A type of IOF, with a specific gravity (G_s) of 4.444, a gradation as shown in Fig. 4, was used in this study, which has a similar characteristics with the clayey sand with gravel according to ASTM D2487 (2003). At the time of conducting this study, due to testing device limitation for the MPF or PF test, compaction test with a compaction energy near to the Proctor compaction energy (550 kJ/m³) was conducted following Japanese Industrial Standard (JIS A1210), by

127 which a maximum dry density (ρ_{dmax}) and an optimum water content (w_{opt}) of 2.79 Mg/m³ and
128 12%, respectively were obtained. Munro and Mohajerani (2017a) conducted MPF and Proctor
129 tests on one type of IOF, indicating that ρ_{dmax} and w_{opt} obtained from the MPF test were about 88%
130 and 109% of those obtained from the Proctor test, respectively.

131 Table 1 shows the testing conditions, in which the isotropically consolidated undrained tests
132 (ICU) were mainly conducted, while a few anisotropically consolidated undrained tests (ACU)
133 were also conducted to consider the IOF element subjected to the initial shear stress during the
134 maritime transportation. The compaction degree ($D_c = \rho_d / \rho_{dmax} \times 100\%$, ρ_d : dry density of the
135 specimen) and void ratio (e) are values obtained after the consolidation process.

136 IOF was uniformly pre-mixed with water (initial water content: 12%) and cured for at least 24
137 hours before usage. The specimen with 50 mm in diameter and 100 mm in height was formed by
138 the one dimensional compression method in a split mold, which was essentially the same as the
139 moisture tamping method with one layer (Ishihara 1993; Sze and Yang 2014). In addition, to
140 improve the uniformity of density distribution of the specimen during one dimensional
141 compression, a plastic sheet was pasted in the inner wall of the mold to reduce the friction and
142 tapping energy was applied from the outside wall of the mold while compressing the specimen. It
143 was observed in the trail tests of the undrained cyclic triaxial test that for the specimens prepared
144 by the moisture tamping method with multiple layers, large deformation always first developed
145 from the top part of the specimen, on the other hand, it occurred in the middle part for those
146 prepared by the one dimensional compression method. The double vacuuming method (Ampadu
147 and Tatsuoka 1993) was applied to saturate specimens, by which the pore pressure coefficient $B >$
148 0.95 condition was achieved with the application of the back pressure of 200 kPa.

The volume changes were measured by a double cell system (Wang et al. 2016 c) during the pre-consolidation process and by monitoring the drainage of water from the specimen during the consolidation process. After two hours' consolidation, the monotonic undrained loading with an axial strain rate of 0.1 %/minute was applied in a strain-controlled triaxial system without the application of lubricated ends.

Test results

Isotropically consolidated undrained test (ICU)

Fig. 5 shows the effective stress paths (p' - q) and stress strain relationships (ε_a - q) of ICU specimens with different densities under the initial confining pressure (p_0') of 100kPa, where $p'=(\sigma_a'+2\sigma_r')/3$ and $q=\sigma_a'-\sigma_r'$ (σ_a' : effective axial stress, σ_r' : effective lateral stress). It is seen from the p' - q plot that all specimens dilate from the initial deviator stress (q_0) until reaching q_{pk} . Then the dilative behavior turns to the contractive one until reaching q_s at SS without observation of the PT. The slope of the steady state line (SSL) is $M_s=2.0$. In the ε_a - q plot, deviator stress reaches q_{pk} at ε_a of 1.0%-2.5% and then the strain softening from q_{pk} to q_s is observed without clear observation of the QSS regardless of the density conditions. Note that the residual deviator stress q_s is defined from this section as the minimum q in the range from q_{pk} until the end of the test, and SS is assumed to be the state at residual stress, which are based on the fact that QSS is not very clear for IOF from the results in this study. Regarding the effect of density, the line connecting the initial point (p_0' , q_0) and peak point (p_{pk}' , q_{pk}) of each test is drawn in the subfigure of Fig. 5(a), where p_{pk}' is p' value corresponding to q_{pk} . It is implied that the trend of dilative behavior becomes stronger as the density increases, which is similar to that for common sandy soils.

Figs. 6-8 show the effective stress paths and the stress strain relationships of ICU specimens with similar densities but different p_0' , respectively. Similar to those shown in Fig. 5, all specimens regardless of p_0' exhibit the dilative behavior from q_0 until q_{pk} , and turn to the contractive behavior thereafter until SS. Similar as those shown in Fig. 5, the slope of SSL is $M_s=2.0$ and no clear observation of the PT. Moreover, the strain softening from q_{pk} to q_s is observed without clear observation of the QSS. In the subfigures of p' - q relationships, the lines connecting (p_0', q_0) and (p_{pk}', q_{pk}) were moved to share the same initial points. It is implied that the dilative trend seems to be repressed by the increase in the initial confining pressure, which is also similar to that for common sandy soils.

Anisotropically consolidated undrained test (ACU)

Fig. 9 plots the effective stress paths and stress strain relationships of ACU specimens with various q_0 . The behaviors of specimens with the $q_0>0$ condition are very similar to those of the specimen with $q_0=0$ condition. However, it seems that q_{pk} and q_s first increase and then decrease with the increase in q_0 . The lines connecting the initial and peak points of the stress paths are shown in the subfigure of Fig. 9 (a), which suggest that the dilative behavior become stronger as the increase in q_0 . The stronger dilative behaviour induced by the increase in q_0 may be one of the reasons that result in the increase in q_{pk} and q_s , while, q_{pk} and q_s may reduce as the initial stress condition (p_0', q_0) approaches the failure envelope.

Discussions

Unusual behaviors of IOF compared to common sandy soils

As a new material in Geotechnical Engineering, the granular material IOF exhibits similar behaviors as those of common sandy soils, such as those under effects of density and confining

pressure, while some very interesting unusual behaviors are found from this study. By comparing Figs. 5-8 with the typical behaviors of common sandy soils shown in Fig. 2, the unusual undrained behaviors of IOF for tested specimens, as schematically illustrated in Fig. 10, can be summarized as the following three points:

1. IOF specimens exhibit dilative behavior from q_0 to q_{pk} , while common sandy soils generally behave contractively in this stage except for relatively dense specimens (e.g. specimen D in Fig. 10).

2. The dilative behavior of IOF transforms to the contractive behavior from q_{pk} , while for common sandy soils, once they turn to the dilative behavior, it generally continues until reaching the SS.

3. The deviator stress of IOF reduces (i.e., strain softening develops) from q_{pk} to q_s without clear observation of the QSS and PT, while these kinds of behaviors from q_{pk} to q_s are normally observed only for very loose specimens of common sandy soils (e.g. specimen A in Fig. 10).

The first point may relate to the specimen preparation method (i.e., the one dimensional compression method), by which even the loosest specimen ($D_c=84\%$) may be initially overconsolidated. This inference may be supported by similar observations of specimens formed by the moisture tamping method (Høeg et al. 2000; Djafar Henni et al. 2011; Zhao and Zhang 2014; Mahmoudi et al. 2016). Ishihara and Okada (1978) also showed that the contractive behavior can be impeded by increasing the overconsolidation ratio.

The rest of two points may also relate to the gradation of IOF with U_c of 106. The skeleton of the IOF specimens may be initially constituted by relatively large particles. When the deviator stress reaches q_{pk} , the contacts between relatively large particles may transform to small particles, by

which the contractive behavior and the strain softening may be induced. This interpretation may be supported by Hara et al. (2004), which studied the effect of U_c on the undrained monotonic behaviors of gravelly soils. They found that shear stress of the material with higher U_c was prone to drop with the development of shear strain.

In addition, test results on Toyoura sand specimens as shows in Fig. 3, which were conducted by using the same apparatus with similar testing procedures, imply that the triaxial apparatus would not be the reason resulting in the unusual behaviors of IOF. Nevertheless, the unusual behaviors of IOF observed in this study cannot be fully explained and are worth further researches. As can be seen from Fig. 10, IOF regardless of its density may deform continuously under a smaller shear loading than peak shear strength like specimen A in Fig. 10. As mentioned in “Typical undrained behaviors of common sandy soils” section, specimen A may result in flow failure (or flow liquefaction). Even in a good weather condition, deformation of IOF may develop locally and gradually during loading or shipping due to stress conditions and material properties. Therefore, once the shear stress exceeds the peak shear strength of IOF, sudden and large deformation (or flow failure) may be triggered locally or globally, which may induce casualties

Steady state line and collapse surface of IOF

Fig. 11 plots the SSL of IOF in the p' - q and p' - e spaces based on the test results in this study. In the p' - q space, SSL is of a slope of $M_s=2.0$ which corresponds to an angle of internal friction of $\phi_s=48.6^\circ$ according to the Mohr-Coulomb failure criterion. The data obtained by Munro and Mohajerani (2017 b) from consolidated drained triaxial tests (CD tests) of 9 samples of one type of IOF are also plotted in solid stars. It seems that the IOF from this study and that from Munro and Mohajerani (2017 b) have similar SSLs. The SSLs of common sandy soils obtained by other researchers are plotted in dash lines, which imply that M_s of IOF is significantly higher than

those of common sandy soils. It is seemed from literature reviews that the M_s of a sandy material may closely relate to its gradation characteristics, such as the fines content, gravel content, uniformity, etc..

In the e - p' space, SSL of IOF can be written as

$$e = 1.09 - 0.17 \log_{10} (p_s' / p_{\text{ref}}) \quad \text{Eqn. 1}$$

where p_{ref} is a reference value for normalization (=1 kPa herein). Comparing with common sandy soils, it can be seen that SSL of IOF is much steeper in the e - p' space except for the silt (i.e. silty sand with Fc of 100%) from Kwa and Airey (2017). Note that SSLs of Kwa and Airey (2017) were strictly speaking critical state lines (CSLs) since they were obtained by drained tests, while SSLs were those obtained by undrained tests (Sladen et al. 1985). And it is interesting that even for the same materials CSLs were difference depending on the density conditions. In addition, for common sandy soil specimens with initial condition at the right hand side of SSL, p' usually goes to the left hand side to reach SS or to reach QSS then to SS during shearing, and those with initial condition at the left hand side of SSL, p' usually goes to the right hand side directly reaching SS. While, for IOF, it is shown that even for initial condition at the left hand side of SSL, p' always goes to the right hand side to reach peak state and then comes back to SS.

Been and Jefferies (1985) proposed the state parameter ψ based on a large number of undrained test of Kogyuk sand. The state parameter ψ was defined as the void ratio difference between the initial state and the steady state conditions at the same mean effective stress. They stated that the same sand tested under very different combinations of void ratio and mean effective stress, behaves similarly if test conditions assure an equal ψ . For a comparison, Fig. 12 plots the relationship between the state parameter and the normalized peak strength of IOF and

reproduction of the test results on Kogyuk sand in Been and Jefferies (1985). It is shown that the relationship is unique with some scattering for each of the tested materials.

Regarding the peak point (p_{pk}', q_{pk}) , Sladen et al. (1985) and Alarcon-Guzman et al. (1988) discussed and applied the concept of collapse surface. They stated that all points of (p_{pk}', q_{pk}) normalized by their corresponding residual confining pressures (p_s') lie on a unique line in the p' - q space regardless of the e and p_0' . This line was the projection of the collapse surface in the e - p' - q space. By doing the same process, Fig. 13 (a) plots the results for IOF together with those for common sandy soils. The collapse surface of IOF in the p' - q space can be written as:

$$\frac{q_{pk}}{p_s'} = M_L \left(\frac{p_{pk}'}{p_s'} - 1 \right) + M_s \quad \text{Eqn. 2}$$

It can be seen that the slope M_L of collapse surface of IOF in the p' - q space is 1.5, which is much larger than those of common sandy soils.

In addition, Fig. 13 (b) plots the collapse surface in the p' - e space, from which p_{pk}'/p_s' is connected to D_c (%) as follows:

$$\frac{p_{pk}'}{p_s'} = \frac{0.2 D_c}{D_c - 81.8} \quad \text{Eqn. 3}$$

From Figs. 11-13 and Eqns. 1-3, it can be seen that the initial conditions (e.g., e or D_c), peak conditions (e.g. p'_{pk} and q_{pk}) and the residual conditions (e.g. p'_s and q_s) can be connected by the classical knowledges developed for sandy soils. While as indicated in Fig. 10, there are some unusual behaviors for IOF, which may need more studies both experimentally and numerically in order to properly evaluate the liquefaction potential of IOF.

Conclusions

To properly evaluate the static liquefaction potential of IOF, undrained behaviors of a type of IOF were studied by conducting the isotropically and anisotropically consolidated undrained triaxial shear tests for specimens with the degree of compaction ranging from 83.8% to 95.0% or the initial confining pressure ranging from 50 kPa to 200 kPa. It is found that IOF exhibits similar behaviors as those of common sandy soils, such as those under effects of density and confining pressure, while some unusual behaviors were also observed as follows.

1. All IOF specimens exhibited dilative behavior from the beginning of the axial loading until the deviator stresses reached their peaks. While for common sandy soils, the contractive behavior was generally observed in the initial shear stage.

2. The dilative behavior of all IOF specimens transforms to the contractive behavior from the peak deviator stress, while for common sandy soils, once they behave dilatantly, it generally continues until reaching the steady state.

3. Following the contractive behavior, the deviator stress of IOF reduces (i.e., strain softening develops) from the peak deviator stress to the residual deviator stress. During this reduction process, the quasi steady state and phase transformation were not clearly observed. While coexistence of the reduction process of deviator stress and the absence of quasi steady state and phase transformation state is normally observed only for very loose specimens of common sandy soils.

4. Relationships between the initial conditions (e.g., e or D_c), peak conditions (e.g. p'_{pk} and q_{pk}) and the residual conditions (e.g. p'_s and q_s) are established by employing classical knowledges developed for sandy soils. It is also suggested that for IOF, the slopes of the steady state line and

the collapse surface in p' - q and/or p' - e spaces are much steeper than those of common sandy soils.

The above behaviors may be partly explained by the specimen preparation method and gradation of IOF, while, since IOF specimens regardless of density exhibit flow failure type behavior, further studies may be very necessary.

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Legend

Table 1 Testing conditions

- Fig. 1 Schematic illustration of method to determine TML
- Fig. 2 Schematic drawing of typical undrained behaviors of sandy soils
- Fig. 3 Undrained behaviors of Toyoura sand (a) effective stress path, (b) axial strain and deviator stress relationship
- Fig. 4 Gradation curve of IOF
- Fig. 5 Undrained behaviors of IOF under $p_0' = 100 \text{ kPa}$ (a) effective stress path, (b) axial strain and deviator stress relationship
- Fig. 6 Undrained behaviors of IOF with D_c of 95% (a) effective stress path, (b) axial strain and deviator stress relationship
- Fig. 7 Undrained behaviors of IOF with D_c of 92% (a) effective stress path, (b) axial strain and deviator stress relationship
- Fig. 8 Undrained behaviors of IOF with D_c of 87% (a) effective stress path, (b) axial strain and deviator stress relationship
- Fig. 9 Undrained behaviors of IOF with D_c of 92% and various pre-shear stresses (a) effective stress path, (b) axial strain and deviator stress relationship
- Fig. 10 Schematic comparison of undrained behaviors between common sandy soils and IOF (a-b) effective stress paths and stress strain relationships of common sandy soils, (c-d) effective stress paths and stress strain relationships of IOF
- Fig. 11 Steady state condition of IOF (a) p' - q space; (b) p' - e space
- Fig. 12 Relationship between state parameter and normalized peak strength
- Fig. 13 Collapse surface in (a) p' - q space; (b) p' - e space

Table 1 Testing conditions

Testing items	Compaction degree <i>D_c</i> (%)	Void ratio <i>e</i>	Initial confining pressure <i>p</i> ₀ ' (kPa)	Intimal shear stress <i>q</i> ₀ (kPa)
Isotropic Consolidated Undrained Test (ICU)	95.0	0.679	200	0
	94.9	0.682	100	0
	92.0	0.734	50	0
	91.2	0.751	100	0
	87.3	0.829	100	0
	87.5	0.825	60	0
	83.8	0.905	100	0
Anisotropic Consolidated Undrained Test (ACU)	93.1	0.715	100	17
	92.1	0.732	100	59
	92.8	0.719	100	121

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Fig. 1 Schematic illustration of method to determine TML

Fig. 2 Schematic drawing of typical undrained behaviors of sandy soils

Fig. 3 Undrained behaviors of Toyoura sand

(a) effective stress path, (b) axial strain and deviator stress relationship

Fig. 4 Gradation curve of IOF

Fig. 5 Undrained behaviors of IOF under $p_0' = 100 \text{ kPa}$

(a) effective stress path, (b) axial strain and deviator stress relationship

Fig. 6 Undrained behaviors of IOF with D_c of 95%

(a) effective stress path, (b) axial strain and deviator stress relationship

Fig. 7 Undrained behaviors of IOF with D_c of 92%

(a) effective stress path, (b) axial strain and deviator stress relationship

Fig. 8 Undrained behaviors of IOF with D_c of 87%

(a) effective stress path, (b) axial strain and deviator stress relationship

Fig. 9 Undrained behaviors of IOF with D_c of 92% and various pre-shear stresses
(a) effective stress path, (b) axial strain and deviator stress relationship

Fig. 10 Schematic comparison of undrained behaviors between common sandy soils and IOF
 (a-b) effective stress paths and stress strain relationships of common sandy soils, (c-d) effective stress paths and stress strain relationships of IOF

Fig. 11 Steady state condition of IOF (a) p' - q space; (b) p' - e space

Fig. 12 Relationship between state parameter and normalized peak strength

Fig. 13 Collapse surface in (a) p' - q space; (b) p' - e space