RESISTANCE AGAINST LIQUEFACTION OF UNSATURATED TOYOURA SAND AND INAGI SAND

Hailong WANG[1], Junichi KOSEKI[2], Takeshi SATO[3]

ABSTRACT: A series of undrained triaxial tests on saturated and unsaturated sands, Toyoura sand and Inagi sand, were conducted to investigate effects of degree of saturation and fines content on resistance against liquefaction. A specially manufactured triaxial apparatus was employed, on which a control system of confining pressure, measurement systems of volume change and suction of a specimen were equipped. Increase in resistance against liquefaction due to unsaturation was discussed based on current test results and those obtained by other researchers. The effect of fines content on resistance against liquefaction of unsaturated soil was studied by using Inagi sand which contains about 30% fines content. Suction change of unsaturated Inagi sand when being subjected to cyclic loading under undrained condition was observed. Results show fines content may cause some negative effects and result in low increase of resistance against liquefaction for the unsaturated soil.

Key words: Liquefaction, unsaturated soil, fines content, suction.

INTRODUCTION

Unsaturated soil has been one of hot topics in civil engineering and earthquake engineering since it shows much higher resistance against liquefaction comparing to its saturated state, which has been concluded from both laboratory studies (Sherif et al. 1977, Grozic et al. 2000, Bouferra et al. 2007) and field investigations (Okamura et al. 2006a, Kayen et al. 2013). Efforts have been made to reveal factors governing the liquefaction property of unsaturated sands. Representative factors proposed include, degree of saturation, Sr (Yoshimi et al. 1989, Goto et al. 2002), pore pressure coefficient B-value (Yoshimi et al. 1989, Unno et al. 2008), wave velocity in soil (Ishihara et al. 2001, Tsukamoto et al. 2002, Yang 2002, Yang et al. 2004 and Hossain et al. 2013) and potential volumetric strain (Okamura et al. 2006b, Wang and Koseki 2013a & b). As authors surveyed, the potential volumetric strain which is defined as theoretical maximum volumetric strain under applied test conditions produced a very good correlation with increase of the liquefaction resistance for clean sands. Few works have been done on the effect of fines content on liquefaction property of unsaturated soils. Wang and Koseki (2013a & b) show that liquefaction resistance of Inagi sand with considerable fines may be less sensitive to Sr than that of clean sands. Based on previous works, this paper provides new test data on this topic.

TRIAXIAL APPARATUS

A specially manufactured double-cell triaxial apparatus as showed schematically in Fig. 1 was employed to conduct undrained cyclic loading test for saturated and unsaturated materials. A vertical sinusoidal cyclic loading with frequency of 0.1 Hz was precisely applied by a pneumatic loading system. A load cell was installed inside the cell of the apparatus and a LVDT (linear variable differential transformer type displacement transducer) was equipped to measure vertical displacement

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of specimen. PWP (pore water pressure) was recorded by a DPT (differential pressure transducer) in saturated test.

Particularly in unsaturated test, cell pressure was regulated by another pneumatic control system. PAP (pore air pressure) and PWP were monitored by two pressure transducers. The top cap and the PAP transducer were connected by a thin short tube in order to lessen the effect of air in the PAP measurement system. A hydrophobic filter was glued on the surface of the top cap to keep pore water from entering into the PAP measuring system. The membrane filter technique (Nishimura et al. 2012) was introduced to the pedestal instead of the ceramic disk. Considering possible large and non-uniform deformation of unsaturated specimen, a double cell system similar with Ng et al. (2002) was introduced to measure overall volume change of the unsaturated specimen during cyclic loading. The inner cell and a reference tube which were filled with deaired water were connected to a DPT. Volume change of a specimen was obtained by considering change of water level in the inner cell and movement of the top cap. All test data were sampled by a computer program with a sampling time interval of 0.1s during cyclic loading (100 data per cycle).

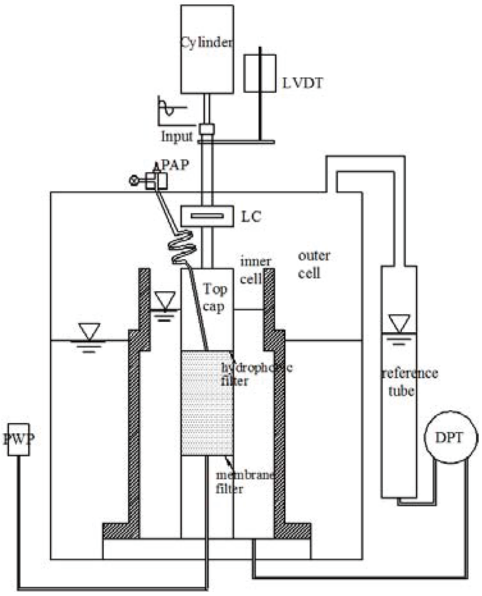

Fig. 1 Triaxial apparatus scheme

TEST MATERIALS

Inagi sand and Toyoura sand passing through 2 mm sieve were tested in this study. Inagi sand consists of 70.5% sand, 18.2% silt and 11.3% clay, classified as SF material according to JGS 0051 (test standard of Japanese Geotechnical Society). Its G_s (specific gravity) is 2.656, and the ρ_{max} and ρ_{min} (maximum and minimum dry densities) are 1.39 g/cm^3 and 1.00 g/cm^3, respectively. The G_s, ρ_{max} and ρ_{min} of Toyoura sand are 2.656, 1.63 g/cm^3 and 1.33 g/cm^3, respectively.

TEST PROCEDURE

All specimens were molded into cylindrical dimensions of 50 mm in diameter and 100 mm in height, and consolidated by either an effective confining stress ($\sigma_0^{'}=\sigma_0$-PWP) of 60kPa for saturated specimens or a net normal stress (σ_0-PAP) of 60kPa for unsaturated specimens. A specimen with B-value $\geqq$0.95 was regarded as fully saturated. For the saturated specimen, pore pressure parameter B-value is normally unity and change of total mean principal stress (p) will not essentially affect effective stress, while for unsaturated specimen, B-value can be much smaller than unity and effective stress will be affected by the change of p significantly. Thus, cell pressure was kept constant during cyclic vertical loading for the saturated test, while sinusoidal cyclic cell pressure was maintained to keep p constant for the unsaturated test. Fully undrained condition was applied during cyclic loading.

Specimen preparation and test procedure for Inagi sand

Pre-wetted Inagi sand with initial water content of around 22% was cured for at least 24 hours before using. For the specimen of the saturated test, the double vacuum method (Tatsuoka 1987, Ampadu and Tatsuoka 1993) was applied for the saturation process; while for the unsaturated specimen, extra water was injected carefully from the top surface of the specimen to achieve desired Sr and then it was cured for at least 12 hours for obtaining an uniform distribution of pore water in the specimen. In this group of test, three sets of tests with average Sr of 100%, 84% and 73% after consolidation were conducted. The average value of Dr (relative density) in this group was 72% after consolidation.

Specimen preparation and test procedure for Toyoura sand

For Toyoura sand, two groups of tests with average Dr of -6% (extremely loose) and 65% (medium dense) after consolidation were considered. In each group, except one set of saturated tests, another set of unsaturated tests, namely, average Sr of 78% for extremely loose condition or 91% for medium dense condition after consolidation was also conducted.

Wet tamping method was introduced to mold the extremely loose specimen following the description of Ishihara (1993). Toyoura sand with initial water content of 5% was carefully tamped in a mold by 10 layers. Then under confining pressure of 20 kPa, carbon dioxide flushing technique and deaired water injection were applied for the saturated specimen. Water injection was applied only under the same confining pressure for the unsaturated specimen until no air bubbles came out from the water collection side. According to this procedure, pore air in the unsaturated specimen was expected to be separated air bubbles and the PAP transducer was disconnected.

In the medium dense group, air pluviation method and carbon dioxide flushing technique were applied to the set of saturated specimens. In order to obtain a relative high Sr in the set of unsaturated tests, pre-wetted Toyoura sand with initial water content of 17.5% was tamped on the pedestal by 5 layers; de-aired water was then injected slowly from the pedestal until certain amount of water drained out from the top cap. Because of technical limitations, measurement systems of PAP and volume change of the specimen during cyclic loading were disconnected. Since wet tamping usually produces a specimen with relative higher liquefaction resistance (Tatsuoka et al. 1982) than that molded by the air pluviation method, this effect should be considered when comparing with results of the saturated test in this group.

TEST RESULTS

In this section, typical results were presented. For comparison purpose, in each group, tests experienced similar number of loading cycles before development of 5% DA (double amplitude of axial strain) were illustrated hereafter. For instance, in the group of medium dense Inagi sand, test results of three specimens with Sr of 100%, 84% and 74% were chosen, which experienced cyclic loading with CSRs (Cyclic Stress Ratio = $\sigma_d/2\sigma'_0$, where, σ_d is single amplitude of cyclic loading, σ_0' is initial confining stress) of 0.149, 0.197 and 0.274, and developed 5% DA at 14th, 13th and 13th cycle, respectively. Similarly, in the group of extremely loose Toyoura sand, specimens with Sr of 100% and 80% were chosen. CSRs of these two tests were 0.065 and 0.210 which caused 5% DA at respectively 53rd and 47th cycle. In the group of medium dense Toyoura sand, specimens with Sr of 100% and 91% were chosen. CSRs of these two tests were 0.147 and 0.327 which caused 5% DA at 32nd and 18th cycle, respectively.

Suction before and during cyclic loading

Fig. 2 shows results (PWP, PAP and suction=PAP-PWP) of unsaturated specimens before cyclic loading in groups of medium dense Inagi sand and extremely loose Toyoura sand. PWP values almost immediately changed to constant negative values after installation of specimens as showed in Fig. 2, which implies good performance of the membrane filter technique (Nishimura et al. 2012) on measuring PWP.

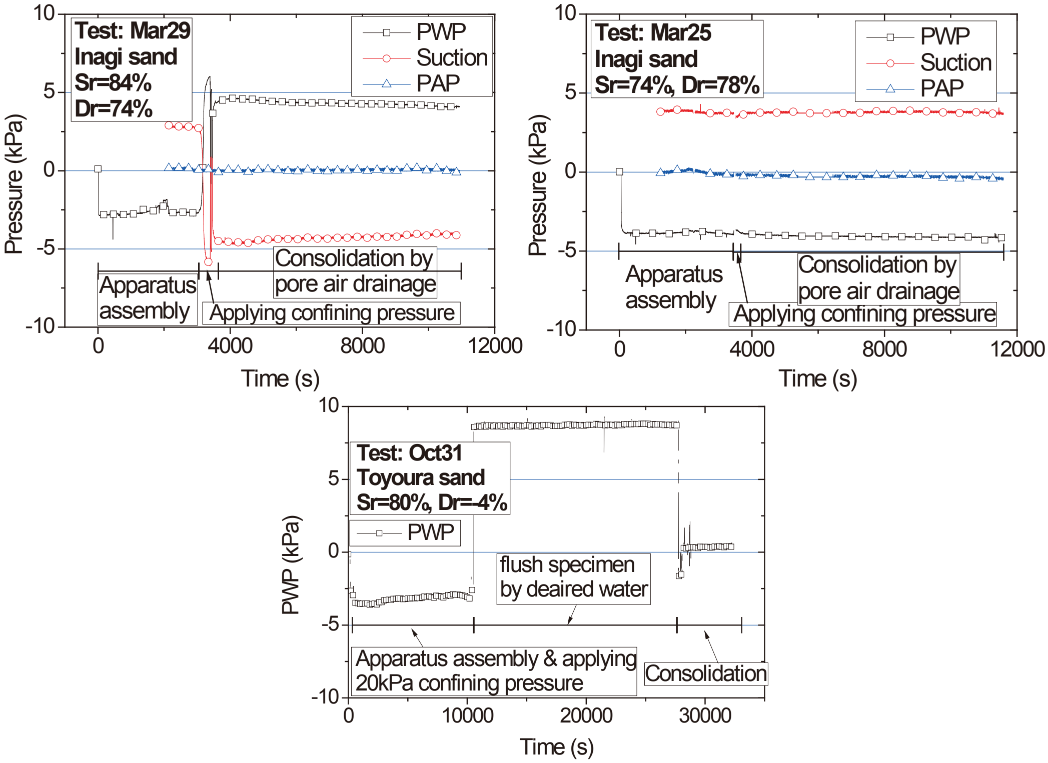

Fig. 2 Pore pressure measurements before cyclic loading, a, Inagi sand with Sr of 84%; b, Inagi sand with Sr of 74% and c, Toyoura sand with Sr of 80%

For the two tests of Inagi sand, suction of the specimen with higher Sr (84%) was lower than the specimen with low Sr (74%) before consolidation, obviously because of difference of initial water content. The significant difference emerged during consolidation, where PWP suddenly rose to a positive value for the specimen with higher Sr, in contrast, it kept almost constant until the end of consolidation for the specimen with lower Sr. This may be caused by formation of different types of pore air in specimens. During consolidation, though for both cases only pore air was allowed to drain out from the drainage path of the top cap which was connected with the PAP measurement system, pore water in the specimen with higher Sr may penetrate the hydrophobic filter and block the pore air drainage path. Pore air in this set of specimens may be air bubbles separated by pore water and soil particles. On the other hand, pore air drainage of the specimen with lower Sr may be unimpeded and suction was not dramatically affected by volume reduction of the specimen during consolidation. Thus, pore air in this set of specimens may be gathered into a whole.

In the case of the extremely loose Toyoura specimen with Sr of 80% as showed in Fig. 2c, PWP was also not affected severely by the specimen molding process, and the final value climbed to the positive side after water flushing. Though PAP could not be measured, pore air was expected to be separated air bubbles similar with the specimen of Inagi sand with higher Sr and PAP was expected to be the same as PWP for the same specimen. In addition, because of the extremely loose condition in this group of tests, the density increased dramatically after consolidation attributed to erosion of the water flushing process and the consolidation process. In the case showed in Fig. 2c, Dr increased from -26% initially to -4% after consolidation, similar scale of volume reduction was also observed in other unsaturated specimens in this group which experienced much shorter duration of water flushing. On the other hand, Dr increased from about -40% initially to -4% after consolidation for saturated cases in this group. These observations imply that unsaturated state may reduce volume change induced by the consolidation process.

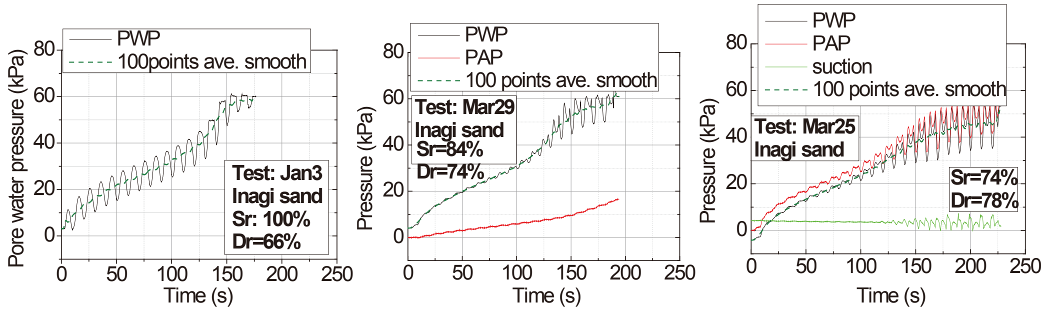

Fig. 3 Pore pressure measurements during cyclic loading of Inagi sand
with Sr of, a, 100%; b, 84% and c, 74%

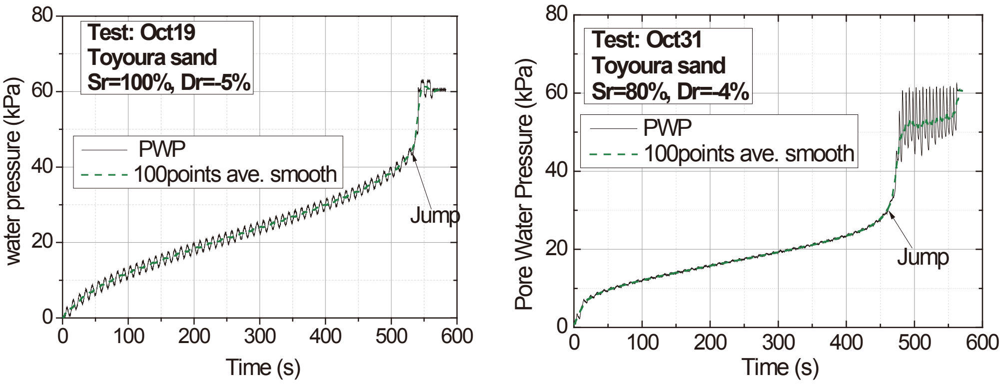

Fig. 4 PWP measurements during cyclic loading of extremely loose Toyoura sand
with Sr of, a, 100% and b, 80%

Figs. 3-4 show results of pore pressure generation of saturated and unsaturated specimens during cyclic loading for medium dense Inagi sand and extremely loose Toyoura sand. The green dash line in each figure depicts the average value of 100 adjacent data of PWP to show a smoother trend of PWP generation. For the saturated test, PWP increased accompanied by large fluctuation, which was induced by alteration of the total mean principal stress (p) during cyclic loading. In contrast, for unsaturated tests pore pressures increased much smoother thanks to effective control of p.

In the group of Inagi sand, development of pore pressures became slower as Sr reduced. For the test with Sr of 84%, PAP was below PWP distantly, which may be induced by invasion of pore water in the PAP measurement system as mentioned before in Fig. 2a. For the specimen with Sr of 74%, PWP and PAP increased synchronously and the suction value kept almost constant until pore pressures increased to around half of the initial effective confining stress. Facts that CSR values were largely different and the numbers of loading cycle before 5% DA were similar among these tests imply that the unsaturated state increased liquefaction resistance of tested soils.

Similar with Inagi sand, PWP of Toyoura sand under extremely loose condition increased to initial confining stress in both saturated and unsaturated cases as showed in Fig. 4 and unsaturated specimen showed much higher resistance against cyclic loading. While, sudden jumps of PWP when it accumulated around half to two thirds of initial confining stress was not clearly observed for specimens of Inagi sand in Fig. 3. This may be explained by the concept of structural collapse which results in a sudden rearrangement of grains and loss of contact points between neighboring grains for the loose specimen (Alarcon and Chameau 1988). For Inagi sand, this kind of sudden rearrangement may not happen during cyclic loading. Interestingly, PWP at the jump point of the saturated test was higher than that of the unsaturated case which was also observed in other tests in this group.

Volumetric strain during cyclic loading

Fig. 5 shows volumetric strain of specimens in groups of Inagi sand and extremely loose Toyoura sand during cyclic loading. Black lines were measured data by the measurement system of the inner cell, red lines were theoretical volumetric strain calculated based on Boyle's law and measured PAP (in case that PAP was not available or problematical, PWP was used as showed in Figs. 5a & c). The fluctuation in the earlier part of measured volumetric strain as showed in Figs. 5a and b was observed in all unsaturated tests in this study except the one showed in Fig. 5c. The fluctuation may be caused by many reasons such as the meniscus effect of water in the inner cell, non-synchronization of pressures in the pressure cell and the reference tube, output delay of the DPT measuring water level of the inner cell and so on. The reference tube and the outer cell were connected to keep pressures the same, while they may not always be precisely the same because cell pressure was controlled to change for the unsaturated test during vertical cyclic loading. The response time of currently used DPT is about 0.3 s, namely the output of the DPT is about 0.3 s later than input signal. Though this error can be dramatically reduced by shifting the time axis of output data when calculating volumetric strain, this way lost effectiveness when water level in the inner cell changed suddenly. For the exception of the data showed in Fig. 5c, vertical strain amplitude and cell pressure change of this test were very small during cyclic loading, which may largely eliminate the fluctuation of measured volumetric strain in the earlier part. In the later stage of cyclic loading, as the PWP was approaching initial confining stress, steep change of water level in the inner cell caused by movement of the top cap and deformation of the specimen was observed. Consequently, the dramatic fluctuation in the later part of measured volumetric strain caused by system errors would not show the real result and have to be abandoned. For the fact that generally the theoretical volumetric strain was smaller than the measured result, on the one hand, system errors as mentioned above may be some of reasons; on the other hand Boyle's law may not be valid since the temperature of pore air may change during loading.

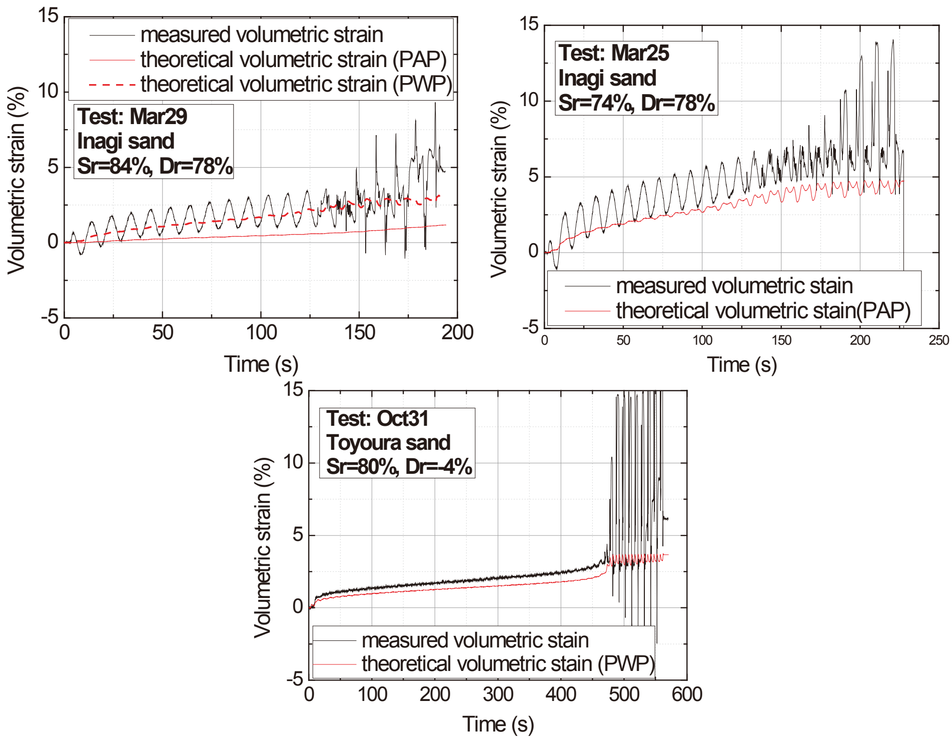

Fig. 5 Volumetric strain of unsaturated Inagi sand with Sr of,
a, 84%, b, 74% and c, Toyoura sand with Sr of 80%

Stress strain relationship and effective stress path

Since PAP could not be measured in some tests, the term effective stress (p-PWP) were used in figures of this section. Stress strain relationships and effective stress paths of typical tests in Inagi sand group were plotted in Figs. 6-7. These three specimens experienced similar numbers of loading cycles before 5% DA developed and CSR values increased as Sr decreased. Clearly, the resistance against cyclic loading increased as Sr decreased. It is worth noticing that the axial strain developed more progressively with the reduction of Sr as showed in Fig. 6. The concepts of liquefaction and/or cyclic mobility were often defined differently by researchers (Castro 1975, Seed 1979 and Tokimatsu et al. 1983). To illustrate the difference between these concepts is out of the scope of this paper, while these concepts can be borrowed to illustrate the difference among current test results. The saturated specimen behaved close to liquefaction (Castro 1975)/flow type liquefaction (Ishihara 1993) where axial strain developed suddenly and infinitely under low unrecoverable shear stress when axial strain accumulated to some extent. One the other hand, unsaturated specimen behaved like cyclic mobility (Castro 1975) / initial liquefaction (Seed and Lee 1966) where axial strain developed gently and the effective stress touched 0 kPa transiently or only approached 0 kPa. The pore air performed like a cushion, deforming itself to reduce pore pressure generation.

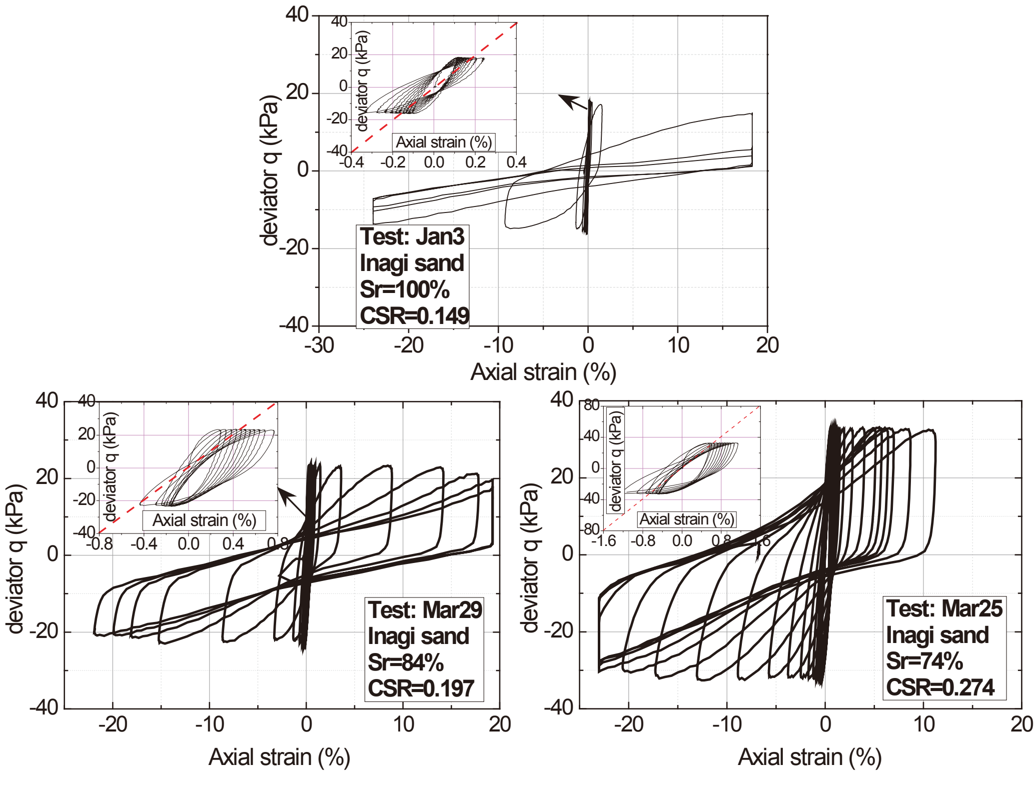

Fig. 6 Stress strain relationship of Inagi sand, a, Sr=100%, b, Sr=84% and c, Sr=74%

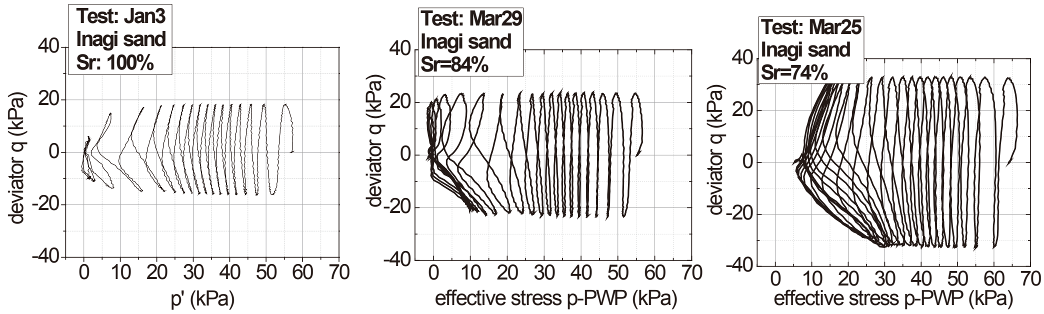

Fig. 7 Effective stress path of Inagi sand, a, Sr=100%, b, Sr=84% and c, Sr=74%

Similar plots for Toyoura sand with extremely loose condition and medium dense condition were depicted in Figs. 8-9. Significant differences in stress strain relationship and effective stress path between Inagi sand and Toyoura sand was not observed, while the sudden loss of effective stress near the end of test for saturated Toyoura sand was clearer than that of Inagi sand as showed in figures of effective stress path.

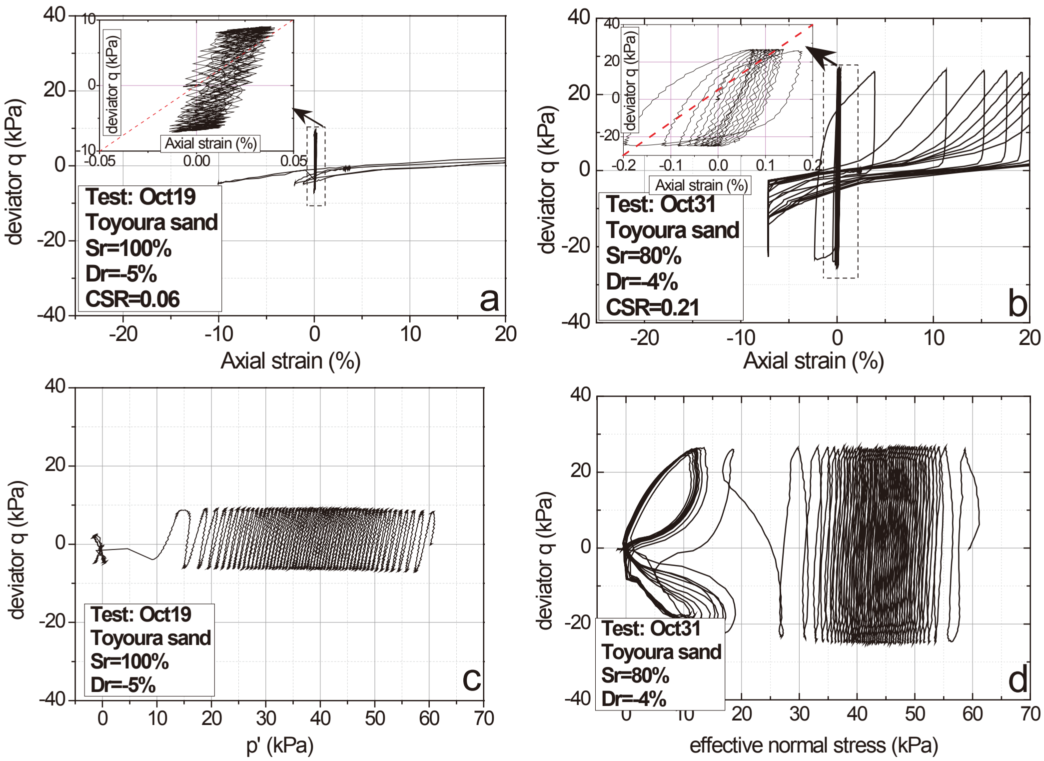

Fig. 8 Stress strain relationship and stress path of extremely loose Toyoura sand

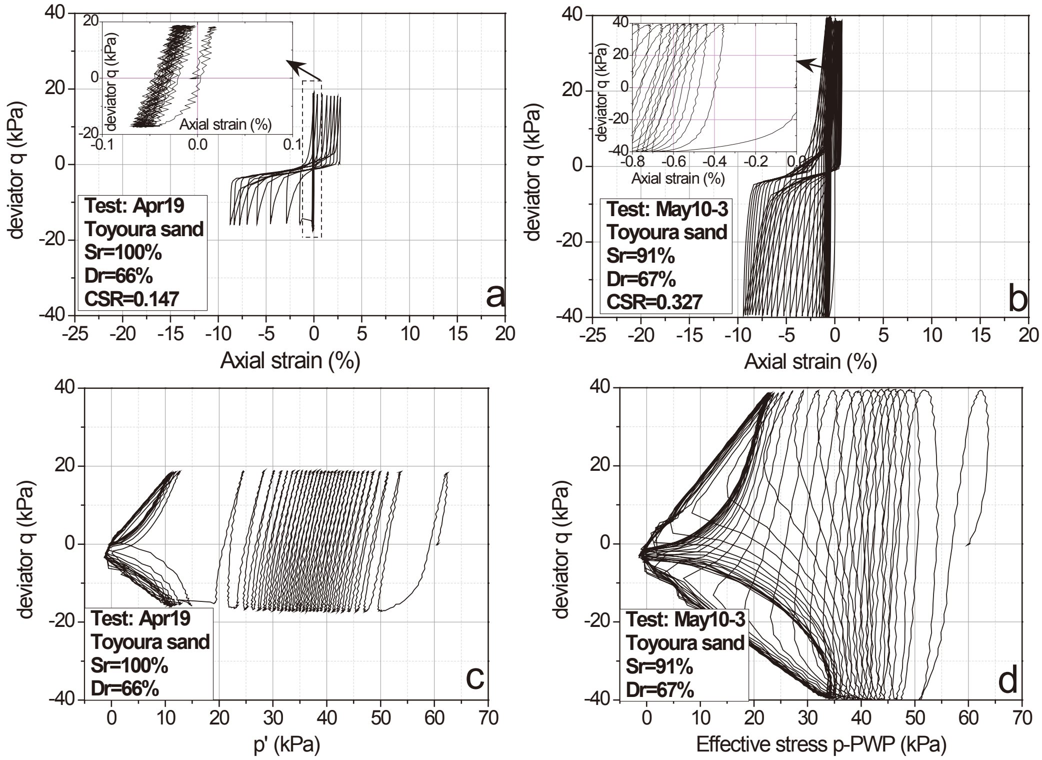

Fig. 9 Stress strain relationship and stress path of medium dense Toyoura sand

Resistance against liquefaction

Fig. 10 depicts the relationship between number of cycles and CSR to cause double amplitude of axial strain, DA, of 5% (DA=5%). The resistance against cyclic loading of soils increased because of unsaturation. Here, the CSR value that causes DA=5% at 20th cycle is defined as CRR (cyclic resistance ratio) as showed in text boxes in each figure. The liquefaction resistance curves were roughly parallel for tests in the same group, which makes it easier to define the increase of resistance induced by decrease in Sr. The factor of saturation condition (K_s) is defined as a ratio of CRR for the unsaturated condition with respect to the saturated condition (CRR_{Uns}/CRR_{Sat}) in the same group of tests. Okamura (2006b) proposed an empirical equation $K_s=\log(6500\varepsilon_v^*+10)$ to correlate K_s with potential volumetric strain ε_v^*, which can be expressed as

$$\varepsilon_v{}^* = \frac{\sigma_c'}{p_0 + \sigma_c'}(1 - S_r)n$$

where σ_c': effective confining stress, p_0: absolute pressure of pore air before cyclic loading, Sr: degree of saturation, n: porosity. By introducing this parameter, previous experimental data by other researchers, results in this study as well as the proposed empirical equation were summarized in Fig. 11.

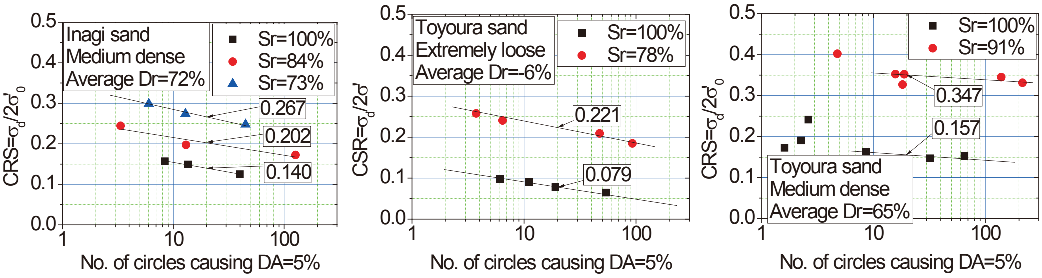

Fig. 10 Relationship between number of cycles and CSR for
a, medium dense Inagi sand; b, extremely loose Toyoura sand; c, medium dense Toyoura sand

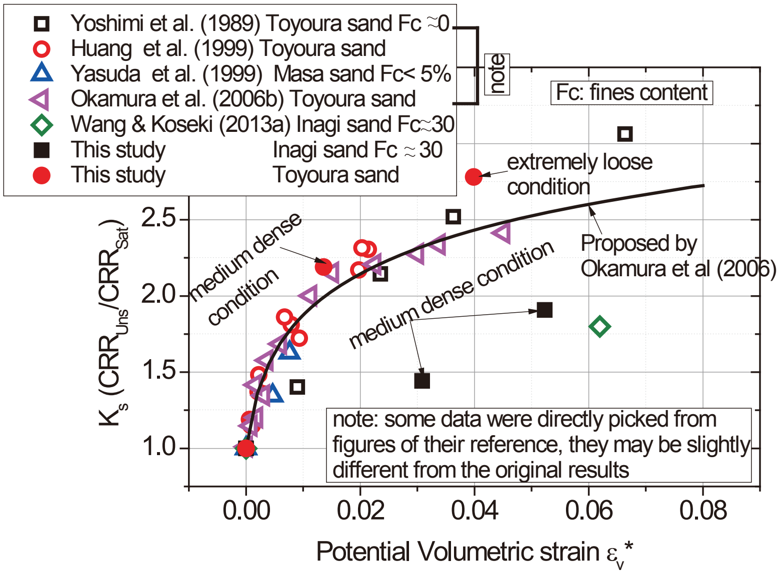

Fig. 11 Relationship between potential volumetric strain and factor of saturation condition

Fig. 11 shows that test result of medium dense Toyoura sand matched with data of other researchers, while extremely loose specimen of Toyoura sand shows even higher resistance increase. Although there is no other data under such extreme condition except the one in this study, from the overall trend of data of clean sands which shows divergence as ε_v^* increases, the relationship proposed by Okamura (2006b) may not fully explain results for clean sands.

Another feature of Fig. 11 is results of Inagi sand distributed beneath those of clean sands which contain no or very few fines content. Interestingly, fines content, which can generally retain more suction than sand particles in unsaturated condition and consequently bring more strength to soils, would increase more resistance against liquefaction. The maximum suction measured in this study was about 4kPa (Fig.2b, medium dense Inagi sand). This value may be too small to increase soil strength significantly, while there should be some other reasons which induce minor increase of liquefaction resistance of unsaturated soil containing fines.

Fundamentally, soil structure collapses and void ratio of soil skeleton reduces during undrained cyclic shear loading (Martin et al. 1975), because of which the effective stress transfers to pore water pressure and unrecoverable excess pore water pressure is generated. The volume shrinkage of soil skeleton induced by shear stress may be different among materials and consequently the increase of pore pressures may be different. In other words, the higher the volume change of soil skeleton induced by shear stress is, the less sensitive to Sr the resistance against liquefaction of material becomes.

Potential volumetric strain ε_v^* expresses possible maximum volumetric stain, while the deformation property of materials may be also important to the resistance against liquefaction.

CONCLUSIONS

Results of fully undrained cyclic loading test on unsaturated Inagi sand and Toyoura sand to investigate liquefaction property of unsaturated soil were reported in this paper. The relationship between the factor of saturation condition (K_s=CRR_{Uns}/CRR_{Sat}), which indicates increase of resistance against liquefaction of unsaturated soil, and potential volumetric strain was not unique for materials containing different amount of fines. K_s of Inagi sand with about 30% fines shows lower value than that of Toyoura sand. In order to find a better parameter to correlate with K_s, the stress strain behavior of different types of soils may need to be considered.

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