Basic study on the anisotropy of sand by using hollow cylindrical torsional shear apparatus

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ABSTRACT

This paper demonstrated an experimental study on the properties and the effects of anisotropy of sand by using a hollow cylindrical shear apparatus. After discussing the effect of initial anisotropy, we experimentally demonstrated the effect of induced anisotropy on undrained shear behavior. The test data of the specimens with prior shear history showed that induced anisotropy derived a pseudo-density change as well as initial anisotropy did. Similar behavior to dense specimens was exhibited when the direction of the second loading was the same as that of the first loading. These experiments captured a developing process of anisotropy. The test data displayed in this study would update our knowledge regarding the anisotropy of sands and lead to the development of a sophisticated constitutive model for soils.

Keywords: torsional shear test; induced anisotropy; sand

1 INTRODUCTION

Figs. 1 and 2 show test results of Toyoura sand obtained with a tri-axial shear apparatus by Yamada et al. (2010). D_r in this figure denotes the relative density of each specimen. Fig. 1 shows monotonic and cyclic undrained shear behaviors of virgin specimens produced by air-pluviation method and Fig. 2 is monotonic undrained shear behaviors of specimens with liquefaction histories. In the later cases, to provide a liquefaction history, first, a liquefaction test was conducted and halted at points from [a] to [e] in Fig. 1, and next, the stress condition was recovered to the initial state [s] by dewatering.

Fig. 2 shows that the monotonic undrained shear behaviors remarkably depend on the halting position of the prior liquefaction test. Through the series of experiments, Yamada et al. (2010) concluded the followings: 1) these results are due to the effects of induced anisotropy, 2) the systematic variation of the induced anisotropy repeatedly occurs during liquefaction. Yamada et al. (2010) also experimentally demonstrated that reliquefaction resistance significantly varies due to the effects of induced anisotropy which occurs during liquefaction.

This experimental study implies that induced anisotropy plays a particularly important role for the complicated mechanical behavior under cyclic loading. Hence, in this study, some experiments were conducted to capture the variation of induced anisotropy under more general stress states by using a hollow cylindrical torsional shear apparatus.

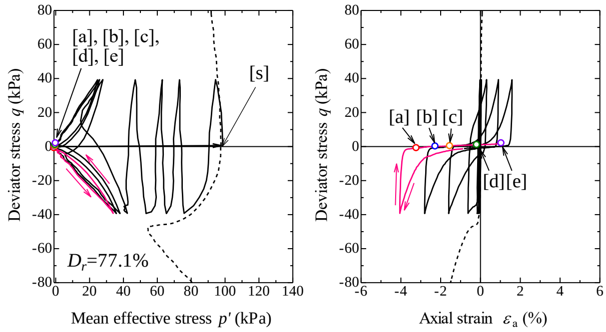

Fig. 1. Liquefaction history (after Yamada et al., 2010).

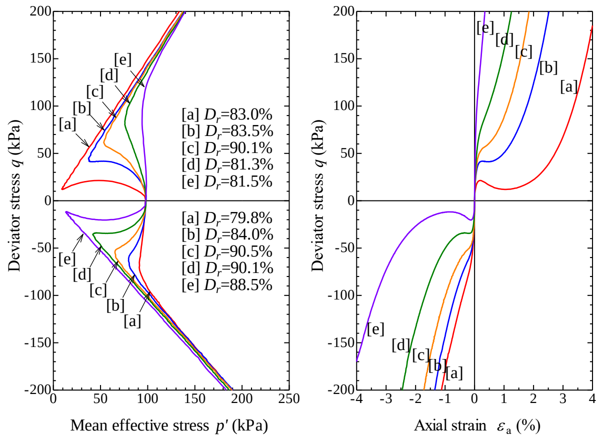

Fig. 2. Monotonic undrained shear behaviors of specimens subjected to liquefaction histories (after Yamada et al., 2010).

2 OUTLINE OF EXPERIMENTS

The experiments were conducted using a hollow cylindrical torsional shear apparatus. The apparatus can automatically control torque, vertical load, inner pressure, outer pressure and back pressure from a PC.

The test sample was Toyoura silica sand (e_{max} = 0.985 , e_{min} = 0.639). Specimens with an outer diameter of 8cm, an inner diameter of 6cm and a height of 16cm were prepared by the air deposition method. In a part of the experiments, the air rodding method, in which a thin rod was put into a specimen to decay depositional planes, was applied. The mean stress p, the intermediate principal stress coefficient $b = (e_{max}-e) / (e_{max}-e_{min})$ and the maximum stress angle α were kept constant during the shear process. p was set to 196kPa in all tests. b was set to 0.50 except the tests related to intermediate stress. α was set as shown in Fig. 3. Membrane correction was applied to all tests.

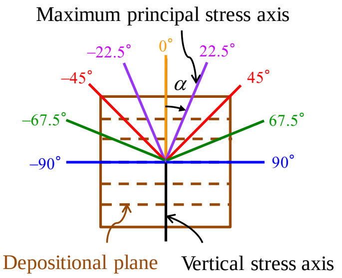

Fig. 3. Maximum principal stress angle α.

3 EXPERIMENTS WITHOUT PRIOR SHEAR HISTORY

First, the effects of density, the direction of principal stress and intermediate principal stress on undrained shear behavior will be discussed using specimens without prior shear history.

3.1 The effect of density

Monotonic undrained shear tests were conducted to the air deposited specimens under b = 0.50 and α = 45.0deg. The typical undrained shear behaviors were obtained as shown in Fig. 4.

3.2 The effect of the direction of principal stress

Fig. 5 shows undrained shear behaviors of air deposited specimens with a relative density of about 60% under b = 0.50 and α = 0.0-90.0. Behavior more like loose sand appeared as α increased. In other words, the behavior resembles more like dense sand with increasing the angle between the loading direction and the depositional planes. Common characteristics can be seen in the experiments by Nakata et al. (1998) and Yoshimine et al. (1998). This tendency is attributed to the initial anisotropy produced during the specimen preparation process. To proof this insight, a similar series of tests were performed to the specimens made with air rodding method. The relative density of the specimens was also about 60%. Fig. 6 shows the experimental results. Since the difference seen in Fig. 5 is not confirmed, the tendency pointed out in Fig. 5 is definitely due to the effect of initial anisotropy.

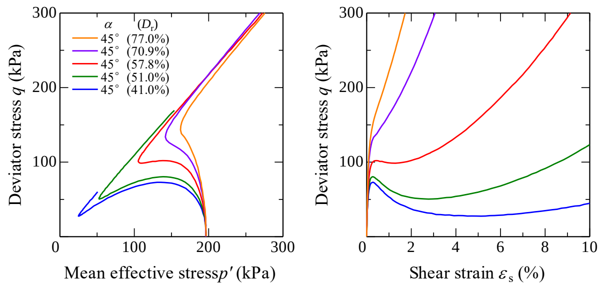

Fig. 4. The effect of density (air deposited specimens).

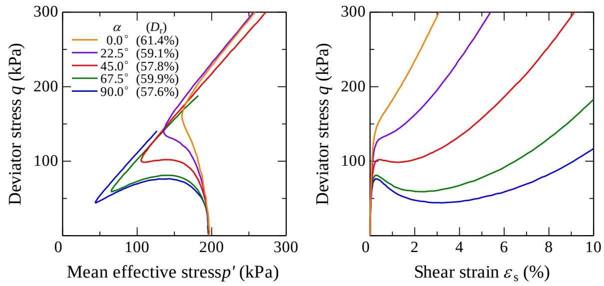

Fig. 5. The effect of the principal stress direction (air deposited specimens).

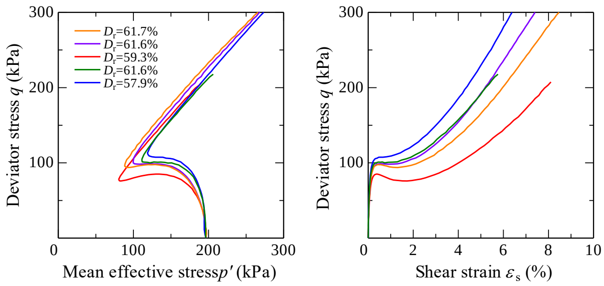

Fig. 6. The effect of the principal stress direction (air rodding specimens).

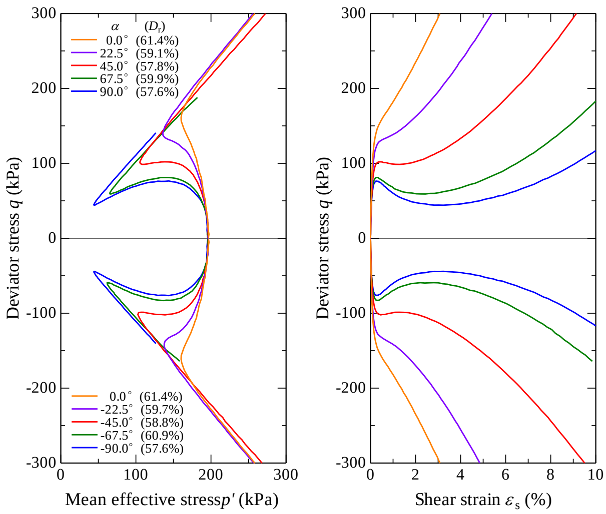

Fig. 7. The effect of the direction of principal stress (air deposited specimens).

For the following discussions, the experimental data in the cases that α takes negative value was supplemented. Fig, 7 shows undrained shear behaviors of air deposited specimens in all principal stress directions shown in Fig. 3. (Note: The sign of q is assigned according to that of α. The data in the case of α = 0.0deg was drawn in both upper and lower side. The data in the case of α = -90.0deg is as same as that in the case of α = -90.0deg.) Almost symmetrical behaviors appeared as shown in Fig. 7. This figure consolidates that the difference according to the principal stress angle is attributed to the existence of initial anisotropy.

3.3 The effect of intermediate principal stress

Fig. 8 shows the undrained shear behaviors of air deposited specimens with a relative density of 60% under b = 0.50-1.00 and α = 0.0deg. The effective stress path like loose sand appeared as b increased. As shown in Fig. 9, the intermediate principal stress applied specimens along the depositional plane. Therefore, the above-mentioned characteristics are attributed to the initial anisotropy. The well-known effect of intermediate principal stress on failure angle also appeared in Fig. 8. As shown in Fig.10, the failure angle of the experiments indicated the similar value of Lade-Duncan (1975) failure criterion.

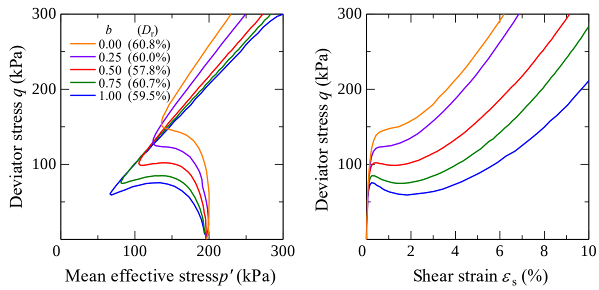

Fig. 8. The effect of intermediate principal stress (air deposited specimens).

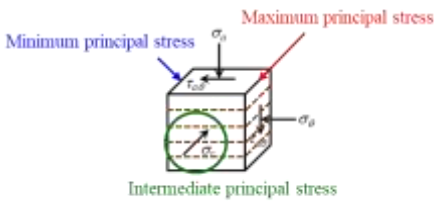

Fig. 9. Applied direction of intermediate principal stress.

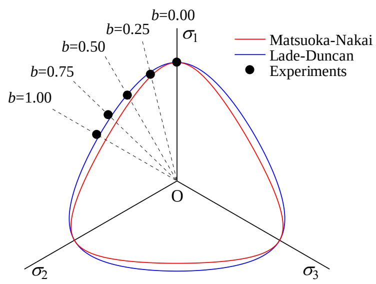

Fig. 10. Comparison with Matsuoka-Nakai (1974) and Lade-Duncan (1975) failure criterions.

4 EXPERIMENTS WITH PRIOR SHEAR HISTORY

Next, the effects of induced anisotropy on undrained shear behavior will be discussed to capture the changing process of induced anisotropy.

4.1 Undrained shear behavior of the specimen with different magnitude of prior shear history

Shear histories shown in Fig. 11 were applied to the air deposited specimens with the relative density of 60% under b = 0.50, α = 45.0deg. The level of prior shear history was varied. After the prior shears were halted before/on/after reaching the phase transition point, shear stress was unloaded and pore water pressure released by opening a drainage cock. Fig. 12 shows undrained shear behaviors of the specimens subjected to the loading histories under b = 0.50, α =±45deg.

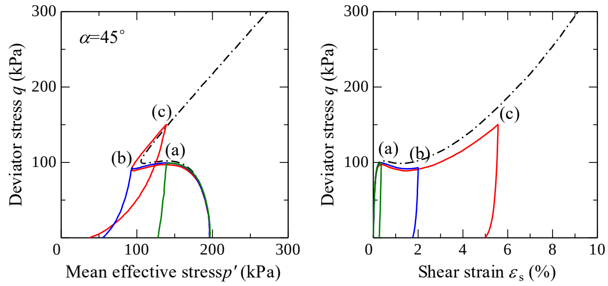

Fig. 11. Shear histories.

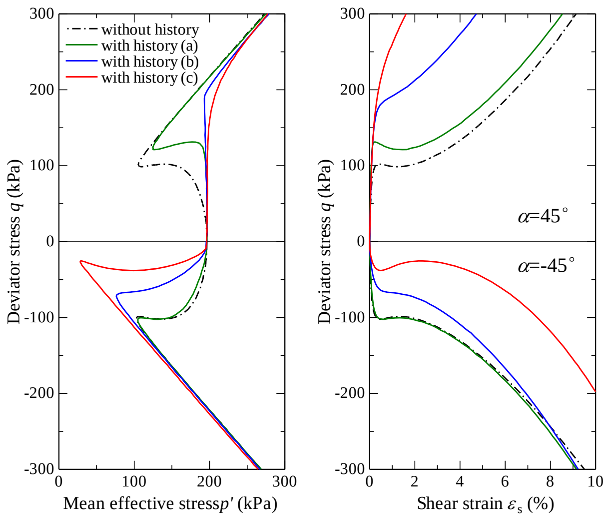

Fig. 12. The erect of the magnitude of prior shear history.

In the case that the prior shear was halted at point (a), although almost elastic behavior appeared in initial when loading direction was as same as that of prior loading, little difference was appeared compared with the case with no shear history when loading direction was normal to that of prior loading. As the level of prior loading history increases, the difference depending on the shear direction in undrained shear behavior becomes to appear significantly. In the case that the prior shear was halted at point (c), while behavior like quite dense sand appeared when α = +45deg, behavior like quite loose sand appeared when α = -45deg. These experiments captured a developing process of induced anisotropy.

4.2 The effect of principal stress direction on undrained shear behavior of the specimen with prior shear history

The same prior shear history as shown in Fig11 at halting point (c) was applied in this section. Fig. 13 shows undrained shear behaviors of specimens with the prior shear history. Loading direction was varied as shown in Fig. 3. The relative densities D_r shown in the figure are the value during the second loading. The results shown in Fig. 13 are irregular unlike the results shown in Fig. 7. Upon receiving Fig.13, another maximum principal stress angle α^* shown in Fig. 14 were introduced. α^* is defined to the angle from the direction of the prior shear history. Although spacing between each line was not uniform, results were ordered regularly like Fig. 7. The data shown in broken lines were supplemented into the wide space. Behavior more like dense sand appeared as α^* decreased. This tendency means that induced anisotropy developed to the direction of prior loading history. In addition, with respect to the point that the “differences in stiffness” that occur according to the prior shear history appear as “differences in pseudo-density” differences, there is no dissimilarity between the anisotropy acquired during deposition and that developed by the stress history. In other words, the anisotropy that the air deposited specimen has should be considered as an initial state of the induced anisotropy. Moreover, asymmetric behaviors appeared in Fig. 15. This means that the effect of initial anisotropy remained at the beginning of the second shear. If greater shear history is applied, more symmetrical behaviors would appear. Therefore, Fig. 15 also captured a developing process of induced anisotropy.

5 CONCLUSION

This paper provided the basic experiments related to anisotropy. The results contain the data that captured the changing process of anisotropy.

We are currently attributing the development of a sophisticated constitutive model and will attempt to simulate the experiments.

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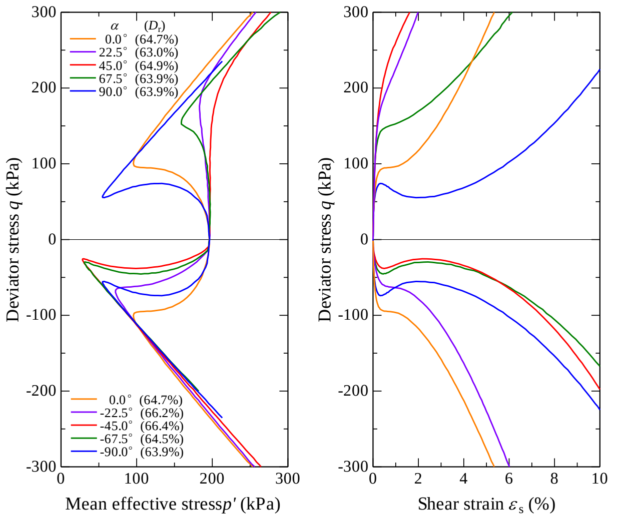

Fig. 13. The effect of the principal stress direction on undrained shear behavior of the specimen with prior shear history (ordered by α).

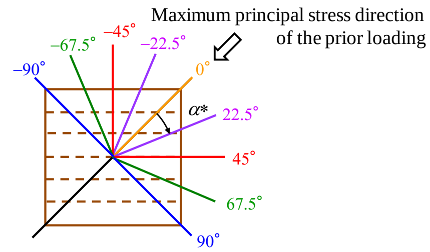

Fig. 14. Maximum principal stress angle α^* from the prior loading direction.

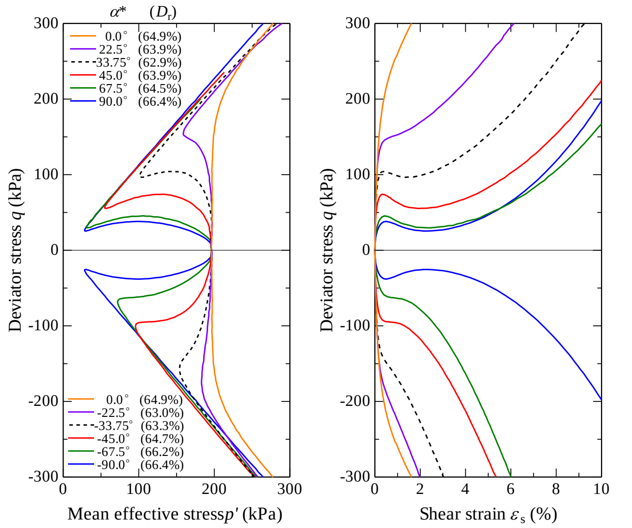

Fig. 15. The effect of the principal stress direction on undrained shear behavior of the specimen with prior shear history (reordered by α^*).