Effects of structure of sandy soil on various mechanical behavior

Effets de la structure du sol sableux sur divers comportements mécaniques

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ABSTRACT: In the present study, the effects of structure of sandy soil on various loading behavior, e.g. static undrained shear strength, stress paths, liquefaction strength etc., are discussed. The sandy soil specimens with different soil structures were produced by air-pluviation or wet-tamping method with different initial water content. A series of triaxial tests both by monotony and cyclic loadings under undrained condition using the artificial structural sand specimen was performed. Furthermore, a series of simple shear tests under monotonic loading was also conducted using the same specimens. Even though the specimens were fully saturated before consolidation, the shear behavior remarkably changes with difference of initial water contents. In the case of monotonic loading of triaxial tests, the highly structural soil characteristics, i.e. significant elastic response in the beginning of loading, the large maximum deviator stress and the rapidly catastrophically failure after peak stress, were observed in large initial water content specimen. The highly structural specimens with large initial water content showed the high liquefaction strength in the cyclic loading of triaxial test.

RÉSUMÉ : Dans la présente étude, les effets de la structure du sol sableux sur divers comportements de chargement, par ex. la résistance au cisaillement statique non drainé, les chemins de contrainte, la résistance à la liquéfaction, etc., sont discutés. Les spécimens de sol sablonneux avec différentes structures de sol ont été produits par la méthode de la pluie d'air ou du tassement humide avec différentes teneurs en eau initiales. Une série d'essais triaxiaux à la fois par monotonie et chargements cycliques dans des conditions non drainées en utilisant l'échantillon de sable structurel artificiel a été réalisée. De plus, une série d'essais de cisaillement simple sous chargement monotone a également été menée en utilisant les mêmes spécimens. Dans le cas du chargement monotone des essais triaxiaux, les caractéristiques hautement structurelles du sol, c'est-à-dire une réponse élastique significative au début du chargement, la grande contrainte de déviation maximale et la rupture rapidement catastrophique après le pic de contrainte, ont été observées dans une grande éprouvette initiale à teneur en eau. Les spécimens hautement structuraux avec une grande teneur en eau initiale ont montré la résistance élevée à la liquéfaction dans le chargement cyclique de l'essai triaxial.

KEYWORDS: soil structure, triaxial test, simple shear test, liquefaction, sandy soil.

1 INTRODUCTION

In conventional and classical soil mechanics, without taking into account the soil structure, the shear strength of soils is considered to be determined by their void ratio. However, it is well known that the difference of soil structure affects their shear behavior despite of the same void ratio. For example, a series of triaxial test was performed using by the gravel-mixed sand specimens that have the same void ratio but considerably different shear behavior by varying the initial water content during specimen preparation (Kodaka et al. 2013). They also showed that the shear behavior difference was able to be explained by changing the soil structure though the numerical simulation using by SYS Cam-clay model. As it is possible to prepare sandy soil specimens that have the same void ratio but considerably different soil structures by the same manner mentioned above, this study demonstrates the effects of soil structure on the mechanical behavior under monotonic and cyclic loading in triaxial tests.

Ishihara (1993) showed that each type of undrained shear behavior of the Toyoura sand specimens, made by various specimen preparation methods, is different from the others. In his study, the void ratios of all the specimens are different due to the initial structure of the sand particles. However, since the specimens in this study are reconstituted using well-graded sand, it is possible for the initial void ratios of all the specimens to be almost the same. This point is quite different from the results of Ishihara's experiment.

Tokimatsu et al. (1986a) pointed out that the liquefaction strength of a clean sand was strongly correlating its elastic shear modulus, and the elastic shear modulus can reflect soil fabric. Tokimatsu et al. (1986b) also showed that the sample disturbance affected the dynamic properties of sand. Therefore, these study suggest the sample disturbance of sand is relating to degradation the soil structure.

A reconstituting structural sand containing some fine fraction is used in this study. This point is different from the mentioned above pioneers' studies targeting to clean sand. However, we can systematically discuss the effects of soil structure of sandy soil on its mechanical behavior by using the artificial structural sand.

2 TEST CONDITIONS

The test sample was a combination of Mikawa silica sand No. 4 and No. 6 and silt-rich Noma sand mixed in proportions of 3:1:3 by mass. Figure 1 shows the grain size distribution for the mixed sample used in the tests. The figure also shows the results for actual levee sand (sand collected at the Kitajima Levee on the Chitose River), and the grain size of the mixed sample was artificially adjusted to resemble this natural sand, including the fine fraction content.

Table 1 tabulates the specifications of each specimen used in the triaxial test. The specimens used in the monotonic and cyclic loading were prepared so that their void ratios were almost the same, as indicated in Table 1.

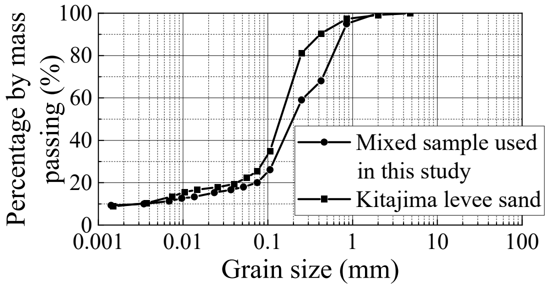


Figure 1. Grain size distribution of the test sample.

Table 1. Specifications of each specimen used in the triaxial test.

Test conditions	Initial water content, w_0 [%]	Initial effective confining pressure [kPa]	Void ratios after consolidation
Monotonic loading	0	50	0.637
		100	0.614
		150	0.608
	5	50	0.679
		100	0.645
		150	0.651
	10	50	0.659
		100_no1	0.656
		100_no2	0.645
		150	0.638
Cyclic loading	0	100	0.622
	5		0.614
	10		0.624

In this test, specimens with the same dry density (i.e., void ratio) but different soil structures were prepared using the mixed sample with exactly the same grain size and three different initial water contents during preparation of 0%, 5%, and 10%. Specifically, in the cases of 5% and 10% initial water content, distilled water was added to the mixed sample in the dry state until the prescribed water content was reached, and the sample was stirred thoroughly until uniform. Specimens 50 mm in diameter and 100 mm in height were prepared by compacting the mixed sample in five layers in a mold until it reached the prescribed density. Because the unsaturated specimens prepared in this way were self-supporting after demolding, they were carefully covered with a rubber sleeve and then set up in the triaxial testing apparatus. In the case of 0% initial water content (i.e., dry sand), a two-piece split mold covered with a rubber sleeve was set up in the triaxial testing apparatus, and the specimen was prepared using the sample in the dry state by the air pluviation method. After applying a confining pressure by negative pore pressure to the specimen covered with the rubber membrane, the specimen was removed from the two-piece split mold and the test was conducted. Although all of the specimens were prepared in a dry or unsaturated state during sample preparation, after being installed in the triaxial testing apparatus, they were fully saturated using a double vacuum pressure method.

Figure 2 shows optical microscopy images of the surface for the three types of specimens prepared by varying the initial water content. The specimens with initial water contents of 5% and 10% were self-supporting in the unsaturated state and the surfaces were observed directly. However, in the case of 0% initial water content, the specimen was prepared inside a transparent acrylic cylinder with an inner diameter of 50 mm by the air pluviation method, using the same procedure as for the actual tested specimens, and was then observed through the acrylic cylinder. In Figure 2, grains of various sizes appear tightly packed in the specimen with an initial water content of 0%. In the specimen with an initial water content of 5%, the fine fraction is aggregated and dotted throughout in a particle-like manner. In the specimen with an initial water content of 10%, as aggregation of the fine fraction progressed, aggregates containing a large amount of water become attached to large sand particles, and the gaps between the particles become larger. This shows that the soil structure of the specimen formed by the wet tamping or air pluviation changes dramatically as a result of varying the initial water content. Figure 2 also shows that the higher the initial water content, the larger the apparent gaps between particles, and therefore, it can be inferred intuitively that the particles are difficult to pack together in this case. Consequently, the higher the initial water content, the greater the number of times the specimen needed to be tamped down and the greater the amount of compaction energy required during the tamping in order to achieve the same dry density.

(a) Initial water content of 0%, w_0=0%

(b) Initial water content of 5%, w_0=5%

(c) Initial water content of 10%, w_0=10%

Figure 2. Observed surface of specimens via optical microscopy.

We have already confirmed by observation of the other specimens after fully saturation that the soil structures observed in the unsaturated state, such as those in Figure 2, were preserved after the specimens were fully saturated. Furthermore, to explain the notable differences in mechanical behavior of the specimens

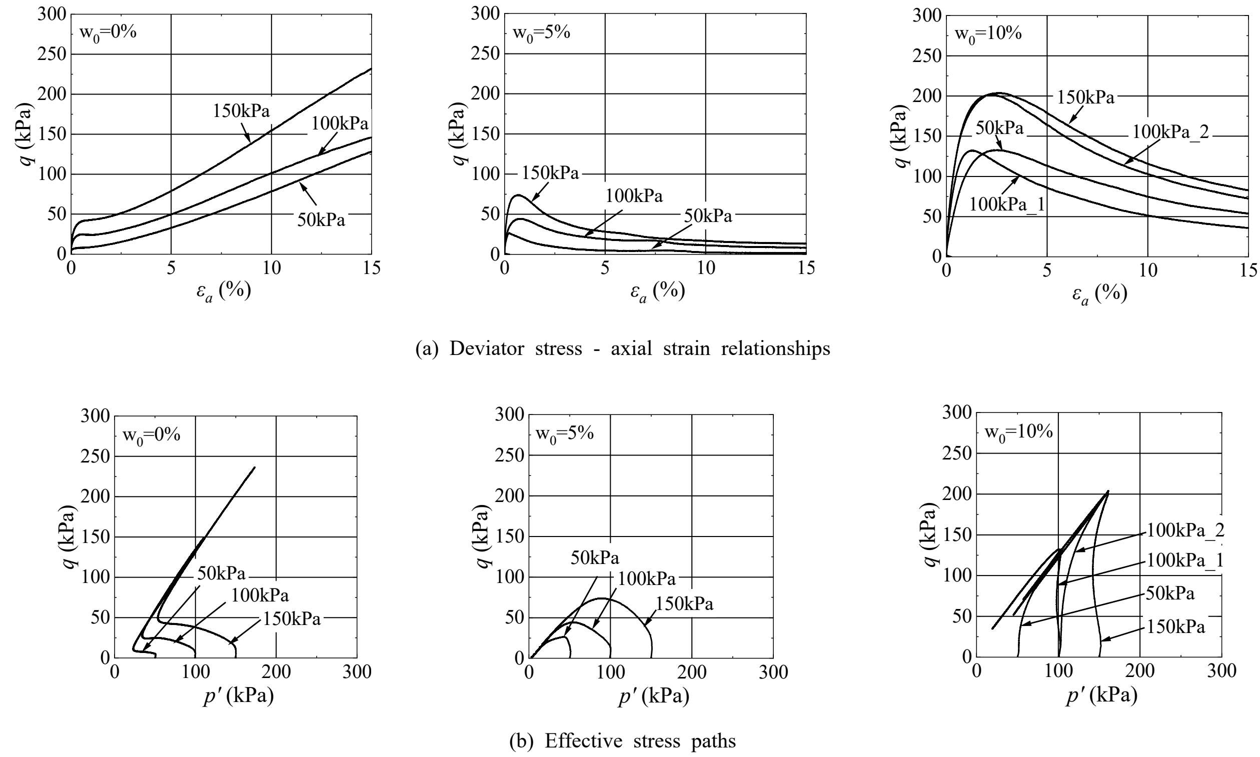


Figure 3. Test results of triaxial test under monotonic loading condition.

in the test results discussed later, it is appropriate to consider that these soil structures were present even after the specimens were fully saturated.

In this study, consolidated undrained shear tests were conducted on the specimens. Monotonic and cyclic loading was performed in the triaxial test. In the monotonic loading test, three different initial effective confining pressures of 50, 100, and 150 kPa were used, as indicated in Table 1, and the specimens were sheared at an axial strain rate of 0.1%/min. In the cyclic loading test, the initial effective confining pressure was 100 kPa, and the specimens were loaded with three different deviator stress amplitudes at a frequency 0.1 Hz.

3 TRIAXIAL TEST RESULTS

Figure 3 shows the results of the triaxial test under monotonic loading for the specimens prepared at the three different initial water contents. The top row shows the relationship between deviator stress $q=\sigma_1-\sigma_3$ and axial strain ε_a, while the bottom row shows the effective stress path diagrams, i.e. the relationship between q and mean effective stress p'. The left-hand side, center, and right-hand side show the test results for specimens with 0%, 5%, and 10% initial water content, in that order.

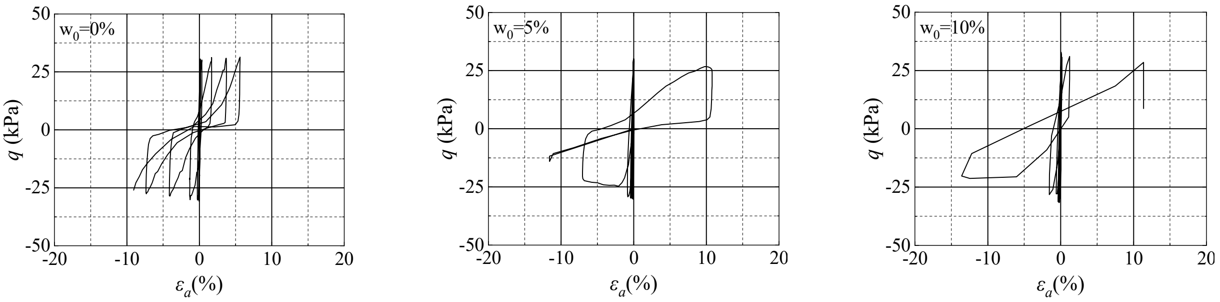
Focusing on the effective stress path in the case of an initial water content of 0%, the specimens undergo rapid plastic compression and reach the phase transformation state in the early stage of shearing. Subsequently, deviator stress increases greatly until the end of shearing due to the confinement of positive dilatancy. At an initial water content of 5%, the specimens exhibit plastic compression similar to the 0% specimens, but show relatively high stiffness compared to the 0% specimens until the peak deviator stress. However, the specimens abruptly demonstrate softening behavior after the peak and show a final state similar to static liquefaction toward the origin. At an initial water content of 10%, the effective stress paths are similar to an elastic response, rising vertically in the early stage of shearing compared to the 0% and 5% specimens, and the specimens reach extremely large deviator stresses. However, after reaching a peak, the specimens show rapid strain softening and undergo notable brittle collapse.

As the initial water content increases from 0% to 5% to 10%, an elastic response in the early stage of shearing becomes clearly apparent and brittle strain softening after the peak load also becomes pronounced. This is considered to be because matrix suction according the initial water content during the specimen preparation causes the coarse and fine fractions to form a "strong" structure. This kind of structure does not form in the specimens with an initial water content of 0%, and those specimens therefore demonstrate significant plastic compression from the early stage of shearing, despite having the smallest void ratio. However, after phase transformation, the specimens with an initial water content of 0% exhibit significant heavy overconsolidation characteristics due to the confinement of positive dilatancy, and then deviator stress considerable increases. This increase in deviator stress occurs as a result of fully undrained conditions that do not typically materialize under the natural condition, and it is important to note that it does not directly indicate that strength of the soil is large.

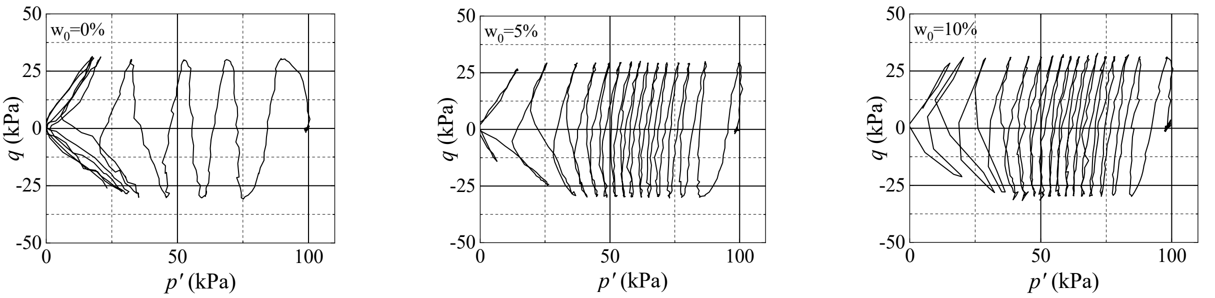
Based on the above, the more developed the soil structure in the sandy soil, the more the soil is characterized by a large elastic response and a high shear resistance in the small strain range, and rapid brittle failure occurs with the collapse of the soil structure.

Figure 4 shows the results of the triaxial test under cyclic loading. The top row shows the relationship between deviator stress and axial strain, while the bottom row shows the effective stress path diagrams. The left-hand side, center, and right-hand side show the test results for specimens with 0%, 5%, and 10% initial water content, in that order. These diagrams show only the test results corresponding to a cyclic stress amplitude ratio of 0.15 at a maximum deviator stress of 30 kPa for each of the specimens.

At an initial water content of 5% and 10%, the decrease in effective stress in each cyclic loading is small and the axial strain is also extremely small. However, as soon as the effective stress approaches zero and liquefaction occurs, a large axial strain is



(a) Deviator stress - axial strain relationships



(b) Effective stress paths

Figure 4. Test results of triaxial test under cyclic loading condition.

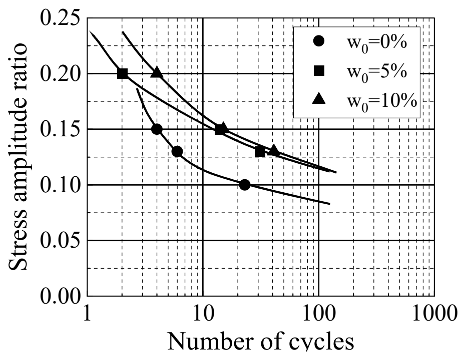


Figure 5. Liquefaction strength curves

observed. This is the same as the tendency for brittle failure in monotonic loading. At an initial water content of 0%, the decrease in effective stress in each cyclic loading is large from the early stage of shearing, and a relatively large axial strain is produced from the loading onset.

Figure 5 shows the liquefaction strength curves including the test results at other stress amplitude ratios. Due to the differences in initial behavior during cyclic loading, the liquefaction strength of specimens prepared with an initial water content of 0%, i.e. dry sand, is clearly low compared to specimens prepared with an initial water content of 5% and 10%. In other words, specimens that form soil structures have higher liquefaction strengths.

In the past, the difference in liquefaction strength between naturally deposited sand that was undisturbed and sand that had been reconstituted at the in situ density was discussed based on the level of disturbance (Tokimatsu et al. 1986b, Kiyota et al. 2009). As a result, the common understanding is that it is difficult to accurately predict liquefaction strength in field without performing liquefaction tests using high-quality undisturbed frozen samples. This test results in this study suggests that disturbance of soil is closely related to soil structure in sandy soils. If we clarified the formation mechanism of the soil structure and artificially reproduced the soil structure by regarding disturbance as a deterioration in the soil structure, it would be possible to obtain the high quality test results from reconstituted specimens using disturbed samples collected using an inexpensive method.

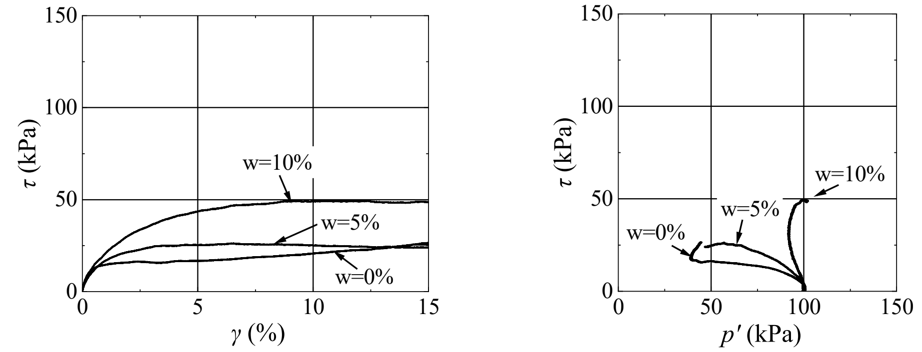
4 SIMPLE SHEAR TEST RESULTS

Table 2 indicates the specifications of specimens used in the simple shear test. As in the triaxial test, specimens were prepared with three different initial water contents. However, the specimens in the simple shear test were cylinders of 60 mm in diameter and 30 mm in height, and they were prepared in three layers. After the specimens had been fully saturated using a double vacuum method, they were consolidated isotropically to an initial effective stress of 100 kPa. Then, a simple shear test under undrained condition was performed by loading monotonically the upper pedestal horizontally at a constant displacement rate with the lower pedestal still in place.

Table 2. Specifications of each specimen used in the simple shear test.

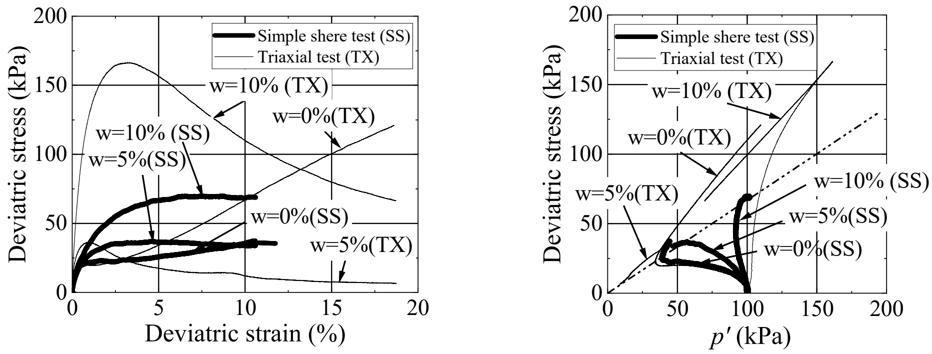
Test conditions	Initial water content, w_0 [%]	Initial effective confining pressure [kPa]	Void ratios after consolidation
Monotonic loading	0	100	0.637
	5		0.636
	10		0.636

Figure 6 shows the effective stress paths and shear stress–shear strain relationships obtained from the simple shear test. The kind of strain softening observed in the triaxial test results is not found, but for all of the specimens regardless of initial water content,

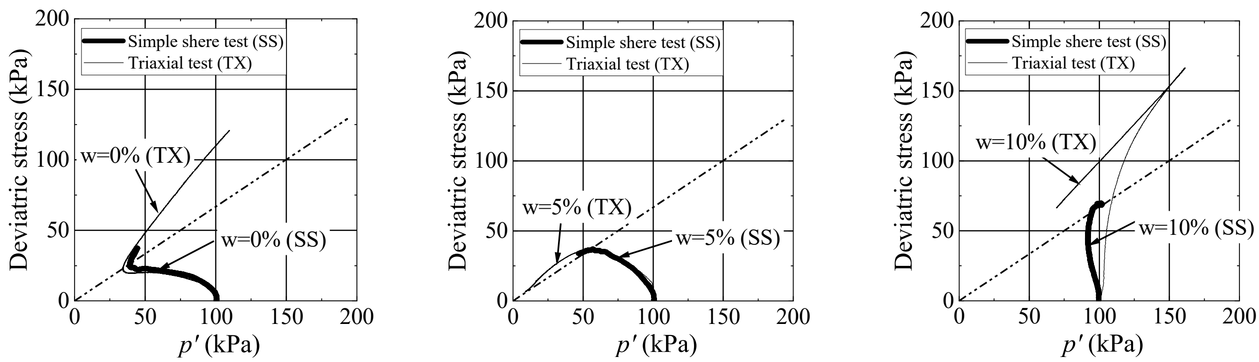


(a) Shear stress - shear strain relationships (b) Effective stress paths

Figure 6. Simple shear test results.



(a) Deviatoric stress - deviatoric strain relationships (b) Effective stress paths



(b)-1 Effective stress paths (w_0=0%) (b)-2 Effective stress paths (w_0=5%) (b)-3 Effective stress paths (w_0=10%)

Figure 7. Results of triaxial test and simple shear test

the behavior before phase transformation resembles that in the triaxial test. Specifically, the higher the initial water content of the specimen, the more the effective stress path rises vertically in the early stage of shearing, and these specimens can be considered to be highly structured.

Because the shear modes differ greatly in the triaxial and simple shear tests, the results of both tests are required to compare using the same parameters. That is, the results are reorganized as shown in Figure 7 by calculating both the second invariant of the deviatoric stress tensor, here called "deviatoric stress" for convenience, for vertical axis and the second invariant of the deviatoric strain tensor, likewise called "deviatoric strain", for horizontal axis. Looking at the effective stress paths in Figure 7, in addition to the phase transformation lines roughly coinciding, the phase transformation points also coincide to a surprising extent in the specimens with initial water contents of 0% and 5%, despite the different shear modes in the triaxial and simple shear tests. In the specimens with an initial water content of 10%, the fact that the effective stress path rises vertically and the specimen exhibits elastic behavior in the early stage of shearing is the same, but the maximum shear stress is far larger in the triaxial test. This test result for specimens with an initial water content of 10% is consistent with the finding that the remarkable strain softening of sensitive clays with notable soil structures is a phenomenon observed only in triaxial tests (Kodaka et al. 2011). Additionally, at all initial water contents, the effective stress path after phase transformation differs considerably in both tests. Specifically, in the triaxial test, a degree of strain softening is apparent in specimens possessing notable soil structures with initial water contents of 5% and 10%, while a degree of strain hardening is apparent in specimens possessing poor soil structures with an initial water content of

0%. Because the shear modes differ greatly, it is thought that major differences appear in the shear stress, which is a response value, due to a loss in homogeneity in the specimens, particularly in the latter half of shearing. At present, it is not possible to draw a simple conclusion as to which test is appropriate.

5 CONCLUSIONS

Specimens with different soil structures were prepared by varying the initial water content during their preparation, and triaxial and simple shear tests were conducted. The results were compared, focusing on the effective stress paths. In the triaxial test, it was shown that the shear behavior differed greatly, under not only for monotonic loading but also for cyclic loading. Because the matrix suction that occurs between soil particles varies depending on the water content during specimen preparation, it is thought that as the water content increased, the fine fraction coagulated around the coarse particles and formed a soil structure. This was confirmed by optical microscopy. Additionally, it was inferred from the results of the cyclic loading test that this soil structure and the sample disturbance are closely related, and this suggests that it is possible to prepare artificial quasi undisturbed samples by understanding the soil structures of natural sand deposits. Further, it was shown that despite the shear modes differing greatly in the triaxial test and the simple shear test, the paths up until phase transformation are relatively consistent. The phenomenon of high maximum shear stress and subsequent large strain softening observed in the specimens with an initial water content of 10%, which had superior soil structures, was observed in the triaxial test only.

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