Changes in anisotropy during liquefaction and effects on reliquefaction resistance produced by developed anisotropy associated with liquefaction

Modifications de l'anisotropie pendant la liquéfaction et effets sur la résistance à la reliquéfaction produit par l'anisotropie développée lors de la liquéfaction

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ABSTRACT
A distinctive characteristic of the reliquefaction behavior of soils is that there are instances where the phenomenon of a sharp decrease in liquefaction resistance occurs in spite of increases in soil density caused by drainage of water after liquefaction. This fact points to the existence of factors other than density that sway the liquefaction resistance of soils. The current paper demonstrates that, in fact, anisotropy is an important factor influencing liquefaction resistance. This is made clear through the results of systematic triaxial shear tests, which show that the higher the level of developed anisotropy, the lower the liquefaction resistance. In the process of verifying the above, we found that continuous and orderly changes in anisotropy are repeated with dizzying rapidity during liquefaction.

RÉSUMÉ
Les cas de forte diminution de la résistance à la reliquéfaction malgré l'augmentation de la densité liée au drainage des eaux après liquéfaction sont des phénomènes spécifiques connus liés à la reliquéfaction. Ces cas semblent indiquer l'existence de facteurs autres que la densité qui influencent la résistance à la liquéfaction. Notre recherche montre clairement grâce à des essais de cisaillement triaxial systématiques que l'anisotropie est un facteur important de la résistance à la liquéfaction et que cette dernière diminue quand l'anisotropie est élevée. Lors de la vérification de ces résultats, nous avons constaté que les modifications de l'anisotropie se répétaient de manière continue et régulière et ce à une rapidité considérable durant la liquéfaction.

Keywords : sand, liquefaction, reliquefaction, anisotropy, triaxial test

1 INTRODUCTION

When sandy soils liquefy, they inevitably become densified because of the drainage of water that occurs after liquefaction. In general, denser soil is less prone to liquefaction. This means that once liquefaction occurs, the soil should become less prone to liquefaction because of the increase in density. The first researchers to raise their voices against this simple theory were Finn et al. (1970). Through the results of simple and triaxial shear tests, they showed that once sandy soil experiences liquefaction, it can become extremely prone to liquefaction in spite of an increase in density. That is to say, its reliquefaction resistance becomes much lower than its liquefaction resistance. Like many previous studies on reliquefaction, the main aim of this paper is to clear the mechanism of this phenomenon.

To mention the conclusion first, the keyword is anisotropy. Let us explain here, how this paper is structured to demonstrate the connection between reliquefaction resistance and anisotropy. First, using sand specimens made by the air pluviation method, the distinctive effects of initial anisotropy on the monotonic undrained shear behavior and cyclic undrained shear behavior of sand are pointed out. On the basis of the above, we show next that continuous and orderly changes in anisotropy are repeated with dizzying rapidity during liquefaction and that the specimens after liquefaction can exist in various states ranging from severely anisotropic to nearly isotropic. Finally, we show that the differences in the level of development of anisotropy after liquefaction exert a strong influence on reliquefaction behavior.

2 OUTLINE OF EXPERIMENTS

Toyoura sand (density of soil particles ρ_s = 2.646, maximum void ratio e_{max} = 0.985, minimum void ratio e_{min} = 0.639) was used to prepare test specimens. As is well known, Toyoura sand is a sand with a homogeneous grain size.

Specimens with a diameter of 7.5 cm and a height of 15.0 cm were prepared by the air pluviation method for the triaxial shear tests. The targeted relative density of the specimens, other than those mentioned in Fig. 2, was 80%. The actual densities of the specimens in each experiment are mentioned within the corresponding figures showing the experiment results.

All experiments were carried out under a confining pressure of 98.1 kPa and a backpressure of 196 kPa. The B values of the specimens were confirmed to be 0.96 or higher. The following four experimental patterns were used.

I. Monotonic undrained shear test (with no liquefaction history)
II. Cyclic undrained shear test (with no liquefaction history) = Liquefaction test
III. Monotonic undrained shear test (with liquefaction history)
IV. Cyclic undrained shear test (with liquefaction history) = Reliquefaction test

Both the monotonic and cyclic undrained shear tests were strain-controlled. The loading rate was 0.12%/min or higher. The stress amplitude was q_{max} = 39.2 kPa for the liquefaction test. Equal deviator stresses were apportioned to the compression and extension sides. The scheme of application of reliquefaction history will be explained later in the appropriate sections of this paper.

3 EFFECT OF INITIAL ANISOTROPY ON MONOTONIC UNDRAINED SHEAR BEHAVIOR

The effect of initial anisotropy on monotonic undrained shear behavior is explained first. The monotonic undrained shear behavior of a specimen that was prepared by the air pluviation method and that had no prior liquefaction history is shown in

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Fig. 1. Since specimens prepared by the air pluviation method exhibit different behavior on the compression and extension sides, it can be confirmed that they possess initial anisotropy, as is well known.

The monotonic undrained shear behavior of Toyoura sand specimens with differing densities prepared by the air pluviation method is shown in Fig. 2. Comparison of the behaviors in Figs. 1 and 2 shows that, in Fig. 1, although the density of the specimen is almost the same on the compression and extension sides, behavior more like that of loose sand has appeared on the extension side rather than on the compression side. In the case of sand, it can be said that the "differences in hardness" that appear in accordance with the direction of shear will materialize as "pseudo-density differences."

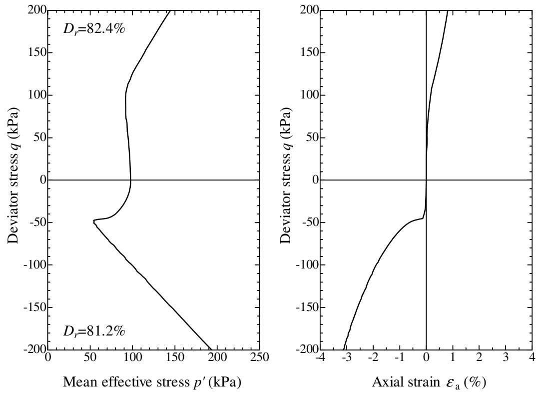

Figure 1. Monotonic undrained shear behavior of sand with initial anisotropy

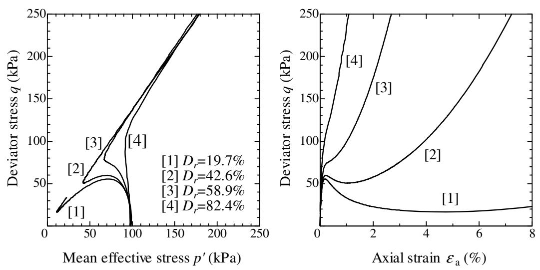

Figure 2. Monotonic compressive undrained shear behavior of sands with densities

4 EFFECT OF INITIAL ANISOTROPY ON LIQUEFACTION BEHAVIOR

The effect of initial anisotropy on liquefaction behavior is discussed next. Figure 3 illustrates the cyclic undrained shear behavior of a sand specimen without prior liquefaction history that was prepared by the air pluviation method. The broken line in the figure denotes the monotonic undrained shear behavior (same as in Fig. 1) of a sand specimen with a similar status. The following two distinctive features of the cyclic undrained shear behavior of specimens prepared by the air pluviation method are evident from this figure.

(1) The effective stress path indicates that, until commencement of the cyclic mobility trace, the mean effective stress decreases significantly on the extension side compared with the compression side. In other words, the pore water pressure increases appreciably on the extension side.
(2) The deviator stress-axial strain relationship shows that strain development is biased towards the extension side during liquefaction.

The two features above demonstrate that specimens prepared by the air pluviation method exhibit behavior more similar to that of loose sand on the extension side rather than on the compression side under cyclic undrained shear as well as monotonic undrained shear. In addition, feature (1) indicates that as the anisotropy develops to higher levels, behavior similar to looser sand appears in a certain shear direction, and that, being dependent on this behavior, the liquefaction resistance decreases. Many readers may have realized at this point that in addition to the above, the reliquefaction resistance should also change significantly depending on the level of anisotropy developed in the sand specimen after liquefaction. This is demonstrated later in the latter half of this paper.

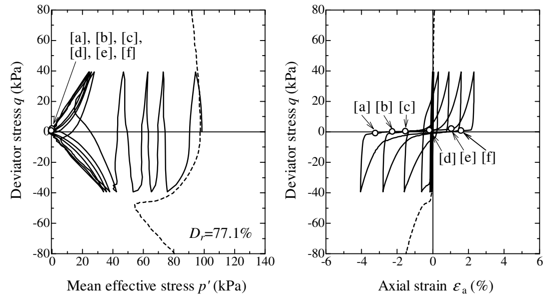

Figure 3. Cyclic undrained shear behavior of sand with initial anisotropy = liquefaction behavior

5 EFFECT OF ANISOTROPY DEVELOPED DURING LIQUEFACTION ON MONOTONIC UNDRAINED SHEAR BEHAVIOR

The state of anisotropy after liquefaction is examined next by studying the monotonic undrained shear behavior of sand that has undergone liquefaction once. Before presenting the experiment results, the process by which the test specimens are subjected to liquefaction history is explained below with reference to Fig. 3.

Step 1: First, specimens made by the air pluviation method are subjected to strain-controlled cyclic undrained shear loading in a manner similar to when specimens are not subjected to liquefaction history so that liquefaction occurs.
Step 2: Next, after confirming that a difference of at least 5% has occurred in the maximum and minimum values of the axial strain, cyclic undrained shear loading is halted at various stages (points [a], [b], [c], [d], [e], and [f] in Fig. 3.).
Step 3: After loosening the loading shaft to allow axial displacement, the drain cock is opened to allow the water to drain off, and the stress state is made to change isotropically; this results in it reaching the same state as that at commencement of cyclic undrained shear loading.
Step 4: After refastening the loading shaft and closing the drain cock, monotonic undrained compression and extension shear tests are performed under strain control. In this step, the standard strain condition is reset with reference to the shape of the specimen at the time of completion of water drainage.

The effects of halting cyclic undrained shear loading at various stages in Step 2 on the state of development of anisotropy after liquefaction are explained below.

5.1 *State of development of anisotropy immediately after unloading (effect of final shear direction)*

First, referring to Fig. 3, the case where cyclic undrained shear loading is halted at the instant the specimen returns to the isotropic stress condition following unloading after the final shear on the extension side (at a position equivalent to point [a] in Fig. 3) is examined. The monotonic undrained shear behavior of the sand specimen that had undergone the above liquefaction history is shown in Fig.4 (the relative densities indicated within Figs. 4, 5 and 6 of the sand specimens that had been subjected to cyclic undrained shear history are those after drainage, i.e., the relative densities during monotonic undrained shear). In contrast to the specimen not subjected to liquefaction history (Fig. 1), behavior similar to that of loose sand has appeared on the compression side, and behavior similar to that of dense sand has appeared on the extension side. From this, it can be understood that because of being subjected to liquefaction history, the anisotropy possessed by the specimen initially is lost completely and new anisotropy develops in an entirely different direction. In addition, the level of the developed anisotropy is higher than that of the initial anisotropy.

Next, referring to Fig. 3, the case where cyclic undrained shear loading is halted at the instant (at a position equivalent to point [f] in Fig. 3) the specimen returns to the isotropic stress condition following unloading after the final shear cycle on the compression side is examined. The monotonic undrained shear behavior of the sand specimen that had undergone the above liquefaction history is shown in Fig. 5. It can be seen that the behaviors in the case of final shear on the extension side (Fig.4) and final shear on the compression side (Fig. 5) are nearly symmetrical. In the case of final shear on the extension side, the behavior on the extension side is similar to that of dense sand, whereas in the case of final shear on the compression side, the behavior of the compression side resembles that of dense sand. In other words, it is clear that the state of anisotropy changes significantly during cyclic undrained shear and is highly developed in the same direction as that of final shear at the instant the effective stress returns to the isotropic state.

Up to now, it has been thought that particulate materials such as soil possess two separate types of anisotropy. The first is inherent anisotropy, which is the anisotropy acquired during sedimentation. The other is induced anisotropy, which is the anisotropy that develops along with the stress history that causes plastic deformation of soil. However, with respect to the point that the hardness changes that occur according to the loading direction appear as a pseudo-density differences, there is no dissimilarity between so called inherent anisotropy and induced anisotropy. The results obtained here tell us that, in the case of sand, there is no intrinsic difference between the two types of anisotropy and that what has been referred to as inherent anisotropy until now is nothing more than a form of induced anisotropy. Based on this point of view, this paper refers to induced anisotropy as simply anisotropy. In addition, the anisotropy acquired at the time of specimen preparation is referred to as initial anisotropy, in the sense that it is the initial state of induced anisotropy.

5.2 *Changes in anisotropy during liquefaction*

It is evident from Figs. 4 and 5 that the anisotropy changes appreciably during the cyclic mobility trace. In order to examine how such changes in anisotropy progress during the half-cycle between points [a] and [f] in Fig. 3, the liquefaction test was halted at positions equivalent to points [a], [b], [c], [d], and [e] in Fig. 3. The experimental procedure was identical to the one carried out previously. The monotonic undrained shear behavior of the sand specimen that had been subjected to liquefaction history is illustrated in Fig. 6. At first glance, Fig. 6 resembles Fig. 2, which illustrated the undrained shear behavior of sand with differing densities. However, in the test results shown in Fig. 6, there is no appreciable difference in the relative densities. A closer look at the figure shows that as the halting point moves from [a] to [e], the behavior on the compression side gradually comes to resemble that of dense sand. In contrast, the behavior on the extension side tends to gradually become similar to that of loose sand. These behaviors indicates that the anisotropy that was prominent at point [a] in Fig. 3 disappears gradually, and the sand becomes temporarily isotropic near point [c]. As liquefaction continues further, the anisotropy starts to develop on the compression side, and at point [e], it has developed to the same level as that seen when the liquefaction was halted at point [a]. Such changes in anisotropy are believed to occur repeatedly in a dizzying manner during liquefaction.

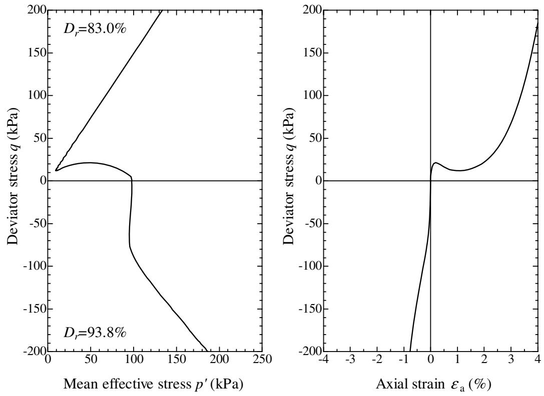

Figure 4. Monotonic undrained shear behavior of sand subjected to liquefaction history (In the case where cyclic undrained shear loading is halted at a position equivalent to point [a] in Fig. 3)

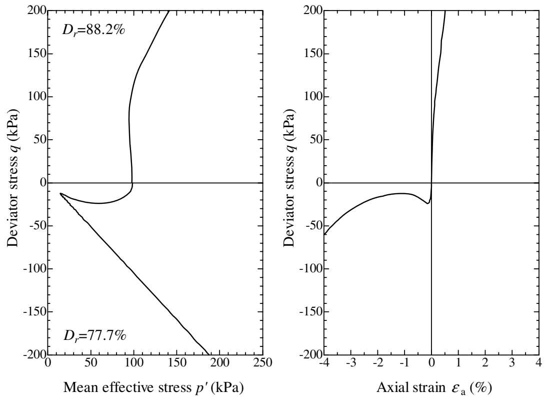

Figure 5. Monotonic undrained shear behavior of sand subjected to liquefaction history (In the case where cyclic undrained shear loading is halted at a position equivalent to point [f] in Fig. 3)

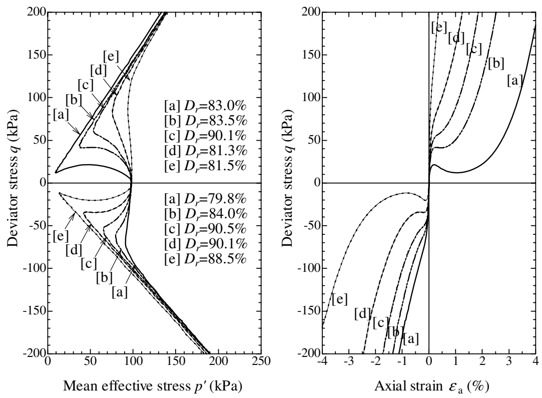

Figure 6. Monotonic undrained shear behavior of sand subjected to liquefaction history (In the case where cyclic undrained shear loading is halted at positions equivalent to points [a] to [e] in Fig. 3)

6 EFFECT OF ANISOTROPY DEVELOPED DURING LIQUEFACTION ON RELIQUEFACTION BEHAVIOR

The relationship between the state of anisotropy developed during liquefaction and the ease of occurrence of reliquefaction is described next. In a manner similar to the previous experiment, the liquefaction tests were halted at positions corresponding to points [a] to [e] in Fig. 3. This was followed by application of cyclic undrained shear instead of monotonic undrained shear. The behaviors of the specimens with respect to each of the above halting positions during the second cyclic undrained shear tests, that is to say, the reliquefaction behaviors, are presented in Fig. 7 (the relative densities before and after drainage are denoted within the figures). The broken lines in these figures represent the monotonic undrained behaviors after halting the liquefaction tests almost at the same positions (pertinent data extracted from Fig. 6).

By comparing the cyclic undrained shear behavior and monotonic undrained shear behavior shown in each figure, it can be understood quickly that the ease of liquefaction has been influenced by the state of development of anisotropy. In addition, by comparing the cyclic undrained shear behaviors with one another, it can be easily understood that the more developed the state of development of anisotropy is, the greater the ease of liquefaction. Furthermore, comparison of the results of the above tests halted at positions corresponding to points [a] and [e] with the cyclic undrained shear behavior of sand without prior liquefaction history (Fig. 3) shows that the resistance to liquefaction has become significantly lower than that before experiencing liquefaction history, in spite of the increased density. The reason for this is that the state of anisotropy is clearly more highly developed than before liquefaction in the case of halting at positions corresponding to points [a] and [e]. As you have probably already realized, the decrease in liquefaction resistance with increasing levels of developed anisotropy is due to the fact that the specimen can latently exhibit behavior resembling looser sand. In the same manner in which initial anisotropy affects cyclic undrained shear behavior, the resistance to liquefaction is swayed significantly by behavior that is similar to loose sand. It can be seen from the above that anisotropy surpasses even density as the factor that holds the key to liquefaction resistance.

On the other hand, the amount of strain growth per cycle is smaller during the 2nd liquefaction test (Fig. 7) than in the 1st liquefaction test (Fig. 3). It can be said that density is the more important factor with respect to the deformation that occurs during liquefaction.

7 CONCLUSION

In the current study, triaxial tests were carried out to examine the changes in anisotropy taking place during liquefaction and to investigate the effects of the anisotropy developed during liquefaction on reliquefaction behavior. The main conclusions obtained in this study are outlined below.

1) During liquefaction, continuous and orderly changes in anisotropy are repeated with dizzying rapidity. Because of this, the anisotropy exists in various states of development when liquefaction ends. Furthermore, the developed anisotropy remains without fading off even after drainage.
2) As the level of developed anisotropy increases, liquefaction is facilitated because behavior resembling that of looser sand is exhibited when sand is subjected to shear in a certain direction.
3) In cases where, because of being subjected to liquefaction history, the anisotropy has developed to appreciably higher levels than before liquefaction, the sand exhibits behavior resembling that of extremely loose sand in spite of increased density. As a result, its liquefaction resistance decreases significantly.

Please refer to our paper (Yamada et al. 2009) if you need further discussion on this topic.

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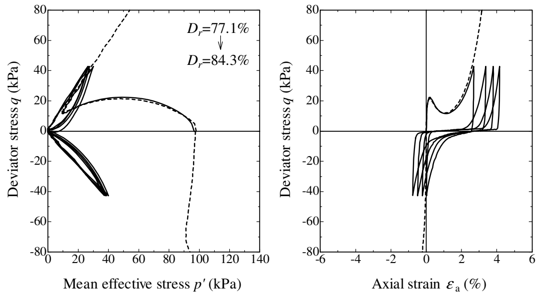
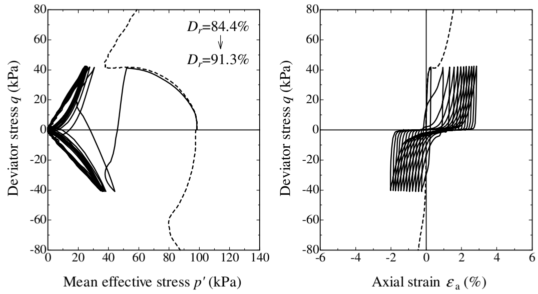
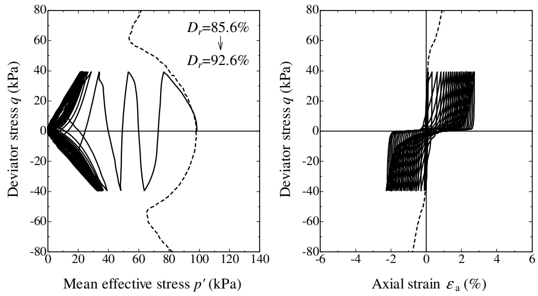


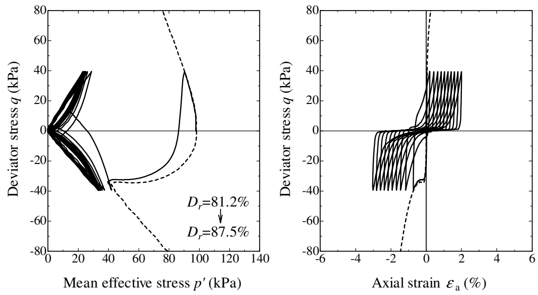
(a) In the case where the first cyclic undrained shear loading is halted at position equivalent to point [a] in Fig. 3



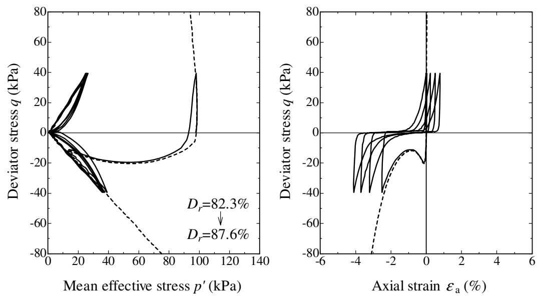
(b) In the case where the first cyclic undrained shear loading is halted at position equivalent to point [b] in Fig. 3



(c) In the case where the first cyclic undrained shear loading is halted at position equivalent to point [c] in Fig. 3



(d) In the case where the first cyclic undrained shear loading is halted at position equivalent to point [d] in Fig. 3



(e) In the case where the first cyclic undrained shear loading is halted at position equivalent to point [e] in Fig. 3

Figure 7. Cyclic undrained shear behavior of sand that has been subjected to liquefaction history = reliquefaction behavior