Effects of pore water redistribution on post-liquefaction deformation of sands

Effets de la redistribution de l'eau interstitielle sur la déformation du sable aprés la liquéfaction

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ABSTRACT: A unique system is developed for conducting shear tests under any drainage condition, by controlling the amount of water injected into the test specimen as a function of shear strain. The effects of pore water redistribution on the strength and deformation characteristics of sand in liquefied deposits are investigated using this system. It is shown that, when saturated sand dilates due to pore water redistribution, the mobilized shear stress tends to decreases, leading to a large shear strain. The tendency becomes pronounced as the soil density decreases, or as the maximum cyclic shear strain during soil liquefaction or the amount of injected pore water increases. The value of α defined as a ratio between volumetric and shear strains, is an effective indicator to define the effects of drainage condition on post-liquefaction deformation of sands.

RÉSUMÉ: Nous développons un système unique pour conduire le test de cisallement sous n'importe quelle condition de drainage, en contrôlant le montant d'eau injectée dans le spécimen de l'épreuve en tant que fonction de la déformation au cisallment. Ce système permet d'étudier les effets affectés à la résistance et à la déformation du sable du sol liquéfié par la redistribution de l'eau interstitielle. Il en résulte que, lors de la dilatation du sable saturé due à celle-ci, la contrainte de cisallement mobilisée a tendance à diminuer, ce qui cause la déformation au cisallment. Cette tendance devient remarquable au fur et à mesure que la densité de sol se décroît et que la déformation maximum au cisallment ou le montant d'eau injectée augmente. La valeur de α défini comme proportion entre la déformation volumétrique et celle du cisallement est un indicateur efficace, en vue d'évaluer les effets des conditions de drainage sur la transformation du sable après la liquéfaction.

1 INTRODUCTION

The redistribution of pore water pressure induced by soil liquefaction may cause the volume expansion of soil, which in turn causes a further reduction in shear stress to be mobilized, thereby increasing shear strain dramatically. Although most of the delayed failures and lateral flow slides after earthquakes might have been caused by pore water redistribution, neither test procedure nor empirical approach to estimate their strength and deformation properties is currently available. Conventional shear tests performed under undrained conditions are questionable as they not only overestimate the strength but also underestimate the deformation in such a case.

The object of this study is to present a new test system capable of performing shear tests under any arbitrary drainage condition and to examine the effects of pore pressure redistribution on the strength and deformation characteristics of sands in liquefied deposits.

2 TEST APPARATUS AND TEST PROCEDURE

Soil liquefaction that occurs in a soil deposit can cause the migration of excess pore water pressure toward the ground surface as shown in Figure 1. This may cause volumetric expansion, and thereby causes reduction in shear strength in soil elements near the top of the liquefied layer as indicated by Elements I and II in Figure 1. Element II absorbs water from zero excess pore water pressure, while Element I absorbs water from non-zero excess pore water pressure. If a static shear stress exists along the line parallel to the ground surface, the reduction in shear strength may lead to flow-liquefaction.

To simulate the above-mentioned drainage conditions in an element test, the system shown in Figure 2 is attached to the conventional hollow torsion shear test apparatus. By controlling the amount of pore water injected into a specimen as a function of shear strain, this system enables one to determine strength and deformation characteristics of sands under any drainage condition in between undrained and drained conditions. The electro-pneumatic closed-loop system originally developed by Tokima-

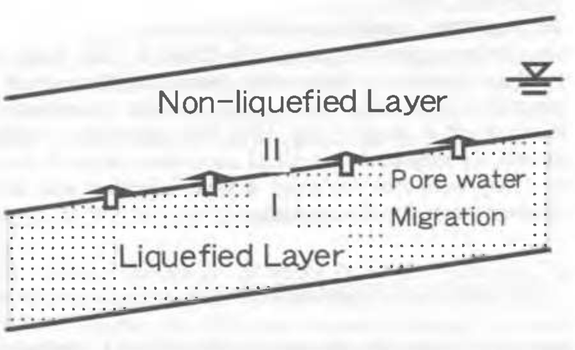

Figure 1. Migration of pore water pressure from liquefied layer.

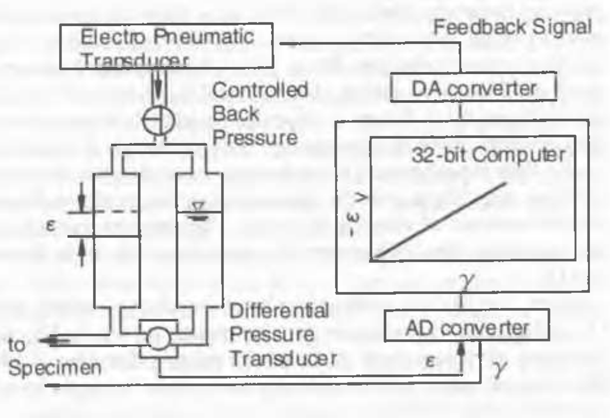

Figure 2. Controlling system for pore water absorption.

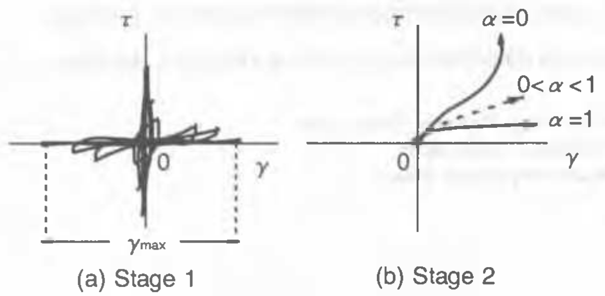

Figure 3. Test stages in Series I.

tsu & Nakamura (1986) was modified and used to inject pore water into the test specimen.

The drainage condition is defined and controlled by the strain ratio between the volumetric strain and the shear strain defined as:

$$\varepsilon_v/\gamma = \alpha \cdot (\varepsilon_v/\gamma)_{drain} = \beta \quad (1)$$

in which $(\varepsilon_v/\gamma)_{drain}$ is the strain ratio at failure under drained conditions, and α and β are controlling parameters. $\alpha=0$ and 1 correspond to undrained and drained conditions, respectively, and $0<\alpha<1$ corresponds to partially drained conditions in between the two.

Toyoura sand was used in the tests. The specimens were prepared with an air-pluviation method, by which the sand was continuously poured into a specimen mold from a constant height. The relative densities of the specimen used were about 45%, 65% and 85%. The back pressure after consolidation and the initial effective confining pressure were 200 kPa and 100 kPa, respectively.

Two series of tests hereby called Series I and II, were performed. Series I simulate the drainage conditions in Element I, while Series II those in Element II. The specimens in Series I were initially subjected to a cyclic shear stress ratio of 0.2-0.3 under undrained conditions until the double amplitude shear strain reaches either 0.5, 5, or 10% (Stage 1, Fig. 3(a)). They were then subjected to shear stress from zero shear strain at a strain rate of 0.2%/min, with α being equal to a constant value between 0 and 1 (Stage 2, Fig. 3(b)). The specimens in Series II were initially subjected to an initial static shear stress of 10 or 20 kPa. They were then subjected to water injection with the applied shear stress remaining constant.

3 TEST RESULTS FROM SERIES I

Figure 4 compares the test results from Series I conducted on specimens with different densities and drainage conditions. The maximum double amplitude shear strain in Stage 1 was 0.5% for all the results shown. When $\alpha=0$, the shear stress increases with increasing shear strain at all densities. As α increases from zero, the shear strain induced by a given shear stress increases, e.g., the shear stress mobilized for a given shear strain decreases. Such a trend becomes obvious from a small α, as the soil density is low (Figure 4(a)). When α becomes equal to 1, a large shear strain develops without showing any strength, which is associated with flow liquefaction. Of particularly interest is the fact that such flow takes place even for dense sand on the condition that a sufficient amount of water is injected. The required volumetric strain to induce flow failure may be characterized by β in Equation (1).

Figure 5 shows the relationship between relative density and β to induce flow liquefaction for the results shown in Fig. 4. The values of β vary from 0.1 to 0.3 for relative densities of 45-85%. This indicates that the induced shear strain is one order of magnitude greater than the volumetric strain occurring in loose

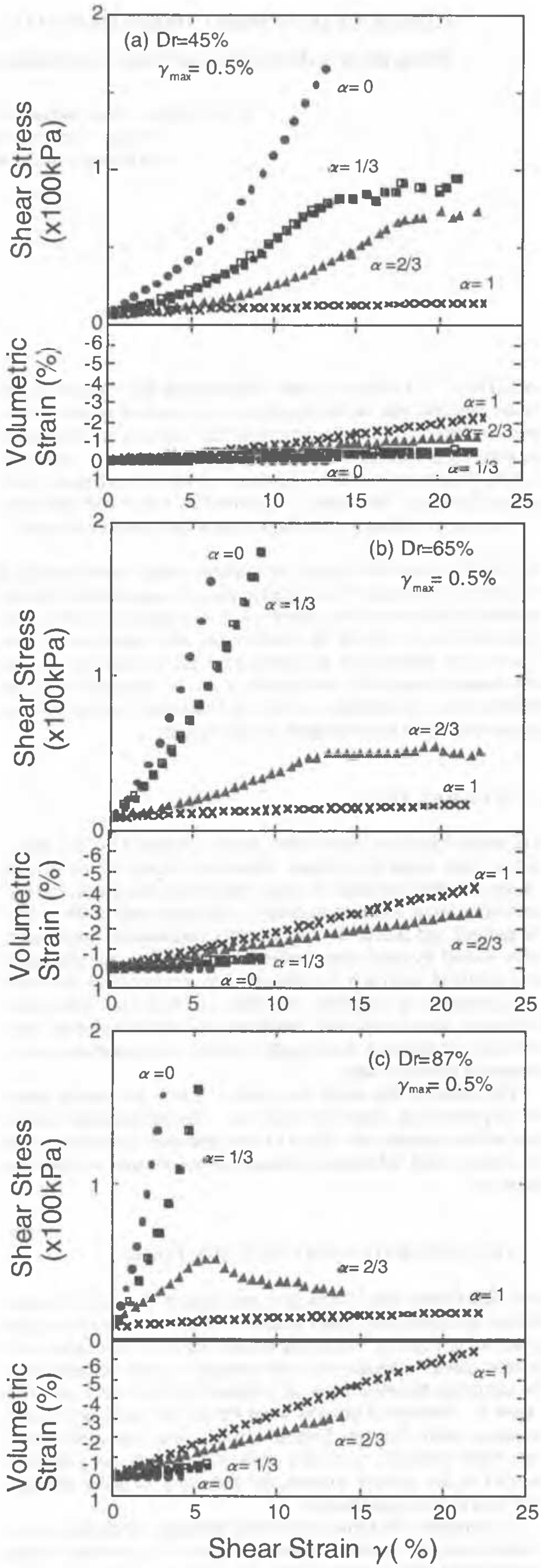

Figure 4. Result of shear tests with different α for liquefied sands with different strain histories.

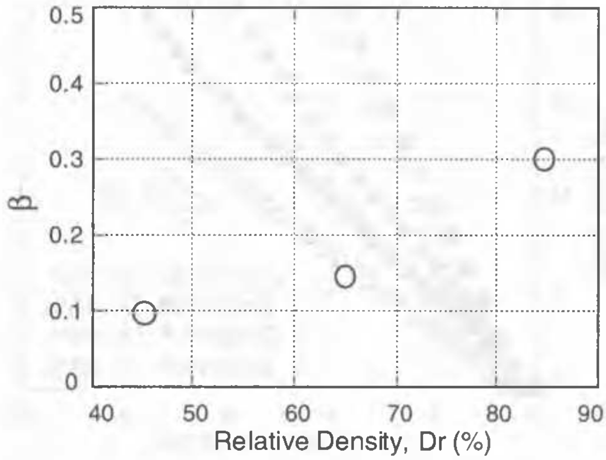

Figure 5. Relation between Dr and β in Test Series A.

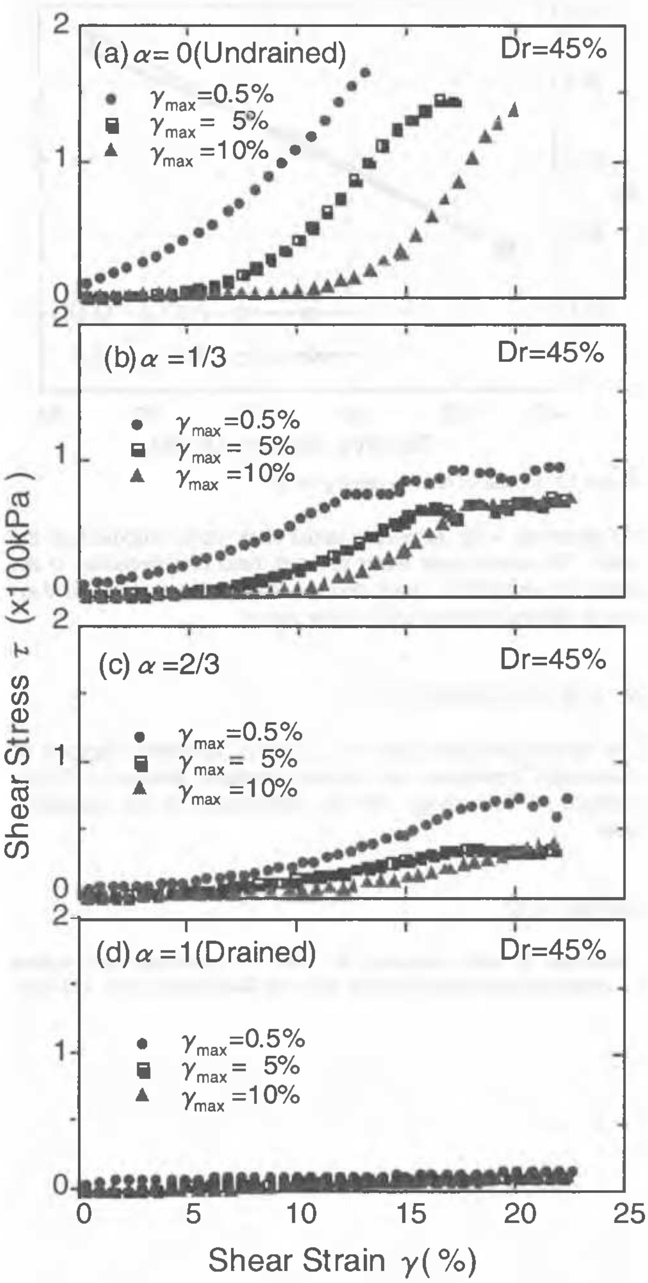

Figure 6. Result of Series I with different drainage conditions after liquefaction.

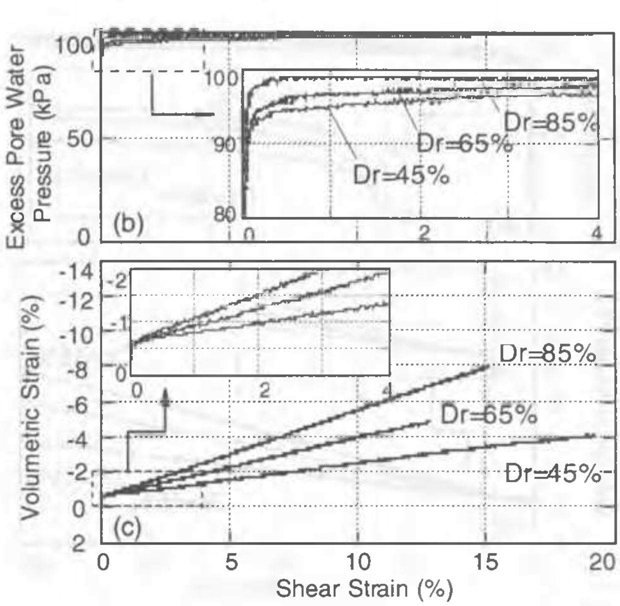

Figure 7. Results of Series II with initial shear stress ratio of 0.05.

sand with Dr=45%, i.e., a small amount of volume expansion may lead to a large shear strain. The required volumetric strain to induce the same shear strain for a sand with Dr=85%, by contrast, is three times greater. This means that the smaller the relative density, the larger becomes the shear strain for a given volumetric strain.

Figure 6 shows the results of Stage 2 test on sand specimens with Dr=45%, after they were subjected to a shear strain of 0.5, 5, or 10% at Stage 1. The trend in which the shear strain increases under almost zero shear stress becomes pronounced as the maximum shear strain applied at Stage 1 increases. When the shear stress begins to increase, the increment ratio of shear strain against shear stress is almost the same, irrespective of the maximum shear strain at Stage 1 for the same value of α. In addition, the larger the value of α, the smaller becomes the shear stress for a given shear strain. This means that the threshold strain below which the shear stress is almost zero depends not only on the maximum shear strain developed under undrained cyclic loading but also on the volume of water injected into the specimen.

4 TEST RESULTS FROM SERIS II

Figure 7 shows the results of Series II for the specimens with three different densities but with the same initial shear stress ratio of 0.05. Despite the difference in relative density, the excess pore pressure ratios of all the specimens increase to about 0.9 when the volumetric strain reaches 0.5 %. The shear strain does not seem to increase in this process. The shear strain, however, increases abruptly when the volumetric strain exceeds 0.5%. The excess pore pressure ratio is over 0.95 and becomes closer to 1 as the relative density of the specimen increases. This indicates that the critical excess pore pressure ratio inducing flow failure increases with increasing relative density. It is interesting to note that the volumetric strain in this process is linearly proportional to the shear strain. In addition, the slope angle between the two decreases with decreasing relative density. This indicates that the volumetric strain leading to a certain shear strain decreases with decreasing relative density.

Figure 8 shows the results of Series II for the specimens with an initial shear stress ratio of 0.1. The pore pressure ratio and volumetric strain, at which the shear strain begins to increase abruptly, are 0.85 and 0.3%. These values are less than those of the specimens with an initial shear stress ratio of 0.05. This means that the volumetric strain and excess pore pressure ratio

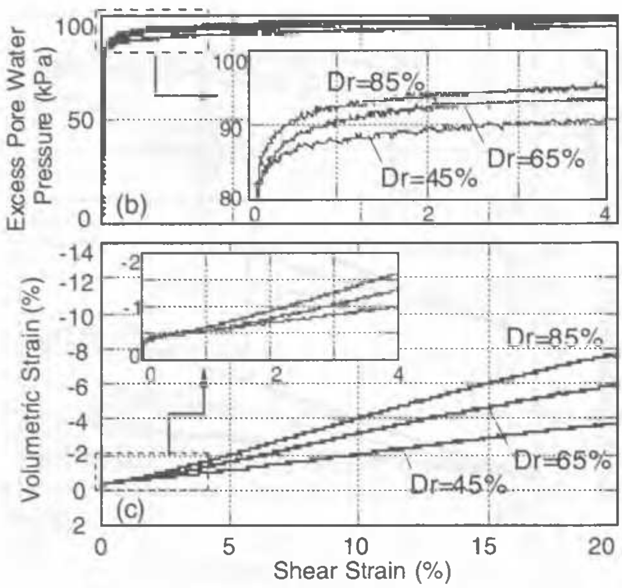

Figure 8. Results of Test Series II with initial shear stress ratio of 0.10.

that are required to induce flow liquefaction decrease with increasing initial shear stress.

To examine the effects of initial shear stress on the relation between volumetric and shear strains, the test results from Series II are summarized in Figure 9. The figure confirms that there exists linear relationship between the two strains, which appears independent of the initial shear stress ratio but dependent on the relative density. Namely, the volumetric strain causing a shear strain of 20% is about 4% for Dr=45%, while it is 8% or more for Dr=85%.

Figure 10 summarizes the relationship between relative density and β computed from Equation (1). The figure confirms that the value of β increases with increasing relative density, irrespective of the initial shear stress. This means that the shear strain induced by water absorption is more than five times the induced volumetric strain for Dr=45% but reduces to about twice the volumetric strain for Dr=85%. The trend is consistent with that observed in Figure 5, except for the absolute values of β which become doubled.

5 CONCLUSIONS

The following conclusions may be made based on the results from two series of tests.

(1) The proposed system is capable of estimating strength and deformation characteristics of sands under any arbitrary drainage condition. The proposed value of α is an effective indicator to define a drainage condition in between fully undrained and drained conditions.

(2) Even dilative medium dense sand may lose its shear strength and undergo flow failure if a sufficient amount of pore water is absorbed. Such pore water absorption is believed to be one of the major causes of liquefaction-induced flow slides in dilative sands.

(3) If liquefied sand dilates due to pore water migration from the lower liquefied layer, the mobilized shear stress tends to decreases, leading to a large shear strain. The tendency becomes pronounced as the soil density decreases or as the maximum cyclic shear strain during soil liquefaction or the amount of injected pore water increases.

(4) If nonliquefied sand subjected to initial shear stress dilates by only 0.3-0.5 % due to pore water migration from the lower liquefied layer, the shear strain tends to increases, irrespective of soil density. The threshold volumetric strain inducing flow failure decreases with increasing initial shear stress imposed on the sand. The excess pore water pressure ratio corresponding to the threshold volumetric strain decreases with decreasing soil density or increasing initial static shear stress.

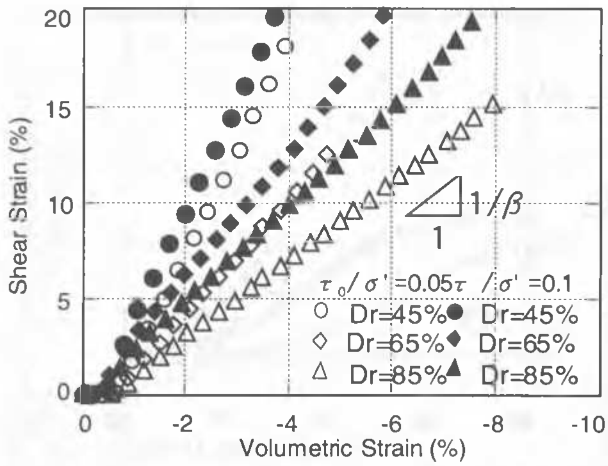

Figure 9. Relation between shear and volumetric strains.

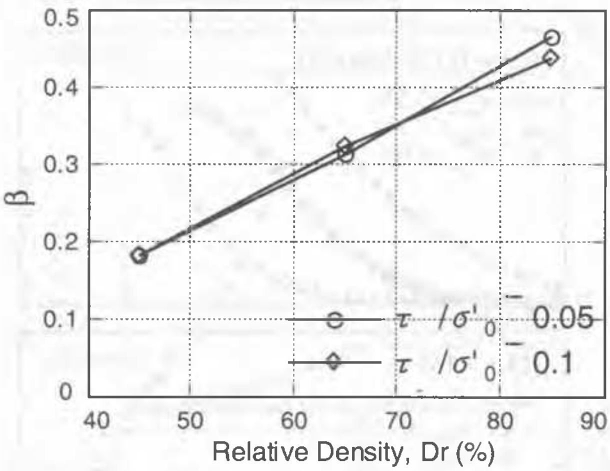

Figure 10. Effects of relative density on β.

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Tokimatsu, K. and Nakamura, K. 1986. A liquefaction test without membraine penetration effects, *Soils and Foundations*, 26-4, 127-138.