Cyclic shear characteristics of treated sand with colloidal silica grout

Caractéristiques du cisaillement cyclique d'un sable traité avec un mortier de silice colloïdale

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ABSTRACT
A newly permeation grouting technique using a colloidal silica has been developed to prevent the liquefaction of sandy ground beneath existing structures. The aim of the present paper is to study the deformation and the strength characteristics of a treated sand with the colloidal silica. A series of laboratory tests are performed on the treated sand such as monotonic and cyclic torsional shear tests. In the case of cyclic torsional shear test with the treated sand, a relatively large strain is developed in the early stage of loading; however, both the development of shear strain and the decrease of mean effective stress resulted without any collapse and liquefaction. As the results, the remarkable improvement of cyclic shear strength by the colloidal silica treatment can be exhibited. This phenomenon leads to the expansion of dilation region across which it faced the phase transformation line and the failure line.

RÉSUMÉ
Afin de prévenir la liquéfaction de sol sableux présent sous certaines structures existantes, une nouvelle technique de perméabilisation utilisant de la silice colloïdale a été développée. Les objectifs de cette étude sont d'étudier les caractéristiques en déformation et en résistance d'un sol traité avec de la silice colloïdale. Une série de test en laboratoire a été effectuée sur du sable traité tels que des essais de cisaillement en torsion monotones et cycliques. Dans le cas d'un essai de cisaillement en torsion avec un sable traité, des déformations relativement grandes sont développées dans les premières étapes du chargement, cependant, le développement de déformations de cisaillement ainsi que la décroissance de la contrainte moyenne effective apparaissent sans aucun effondrement ni liquéfaction. A partir des résultats, le remarquable développement de la résistance du cisaillement cyclique grâce au traitement par de la silice colloïdale est clairement montré. Ce phénomène conduit à l'expansion de la région de dilatation à travers laquelle il met face à face la droite de la phase de transformation et celle de rupture.

1 INTRODUCTION

A permeating grouting method with a colloidal silica solution is an effective soil improvement technique as a promising countermeasure against liquefaction of ground beneath existing structures (Ohno et al., 2000). It is well known from several former experimental studies (e.g. Yamazaki et al. 1998, Gallagher and Mitchell, 2002) that the silica-treated sand exhibits strong resistance of liquefaction. However, in order to evaluate the seismic performance of treated sandy ground including residual deformations, it is necessary to clear the mechanisms of increasing of cyclic shear strength of the treated sand. The aim of the present paper is to study the cyclic deformation and strength characteristics of treated sand using the high accuracy hollow cylinder torsional shear apparatus. Performing both monotonic and cyclic loading tests, the mechanisms of the increasing of shear strength and the decreasing of deformation of the treated sand are discussed.

2 GROUTING MATERIAL AND SPECIMEN

2.1 *Colloidal silica*

A grouting material used in this study is a kind of colloidal silica, which has been developed by Yonekura and Shimada (1992) and Yonekura (1996) for treatment of liquefiable sand. A long-term stabilization of sand gel treated by the colloidal silica has been demonstrated, which is better than the usual silica grouting material, e.g. a sodium silicate or an acid silica sol (Yonekura, 1996). The colloidal silica used for this testing program is manufactured by ion-exchange for dealkalization. The grouting material is a solution of the colloidal silica, which has 4 wt% silica, an average particle size of 10nm and a low viscosity.

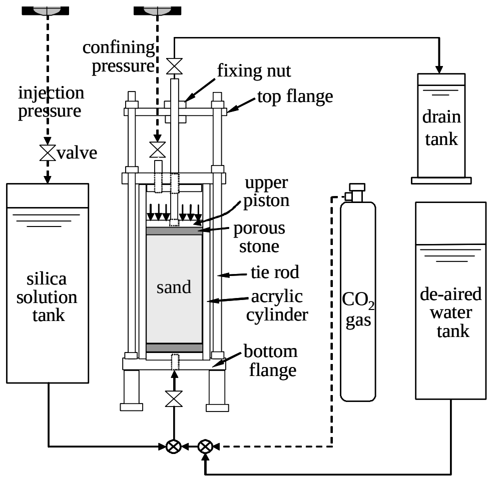
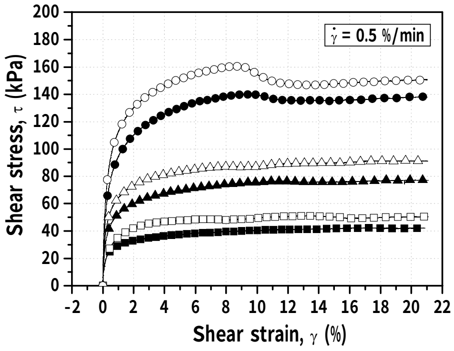


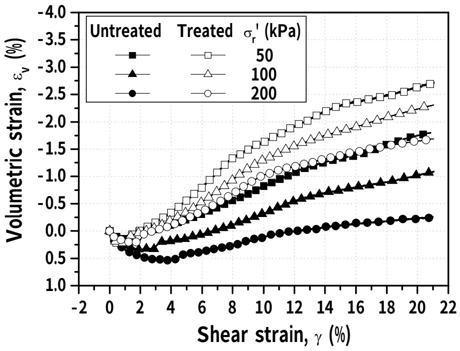
Figure 1. Treated sand preparation apparatus permeating a colloidal silica solution.

2.2 *Treated sand specimen preparation*

The sand used in the testing program is Toyoura sand, which is poorly graded sand, i.e. average grain size, D_{50}=0.2mm, and coefficient of uniformity, U_c=1.6. To make a reproducible specimen, we have developed an apparatus for making of the treated sand specimen as shown in Figure 1. The following preparation method for the treated sand specimen was adopted. Dry Toyoura sand was pluviated into the acrylic mold to be D_r=40%, and then the prescribed confining pressure was applied by air pressure through the upper piston. To saturate the specimen,



(a) Stress – strain relations



(b) Volumetric Strain – shear strain relations

Figure 2. Drained torsional shear test results.

CO_2 gas and then de-aired water was injected into the specimen from the bottom of the mold. The grouting material gradually permeated the saturated sand from the bottom of the mold by exchange of de-aired water for grouting material. The specimens were placed in a constant temperature room (20 ^{o}C) to cure for four weeks maintaining to apply the confining pressure by compressed air.

3 TESTING APPARATUS

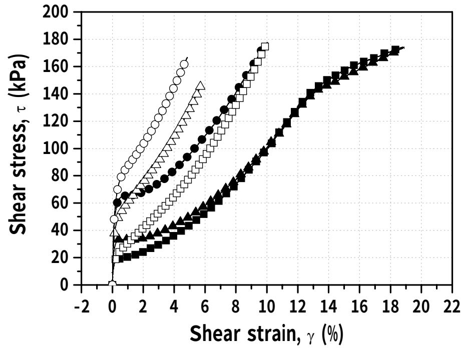
A hollow cylinder torsional shear apparatus is used in the present study. Aaxial load and torque are simultaneously and individually applied on the hollow cylinder specimen by two servo mortars on constant loading rates. Each loading device has an electromagnetic clutch, which can let the loading direction turn for an instant. Owing to this device, the precise cyclic loading without any play can be applied during the cyclic tests. Axial load and confined pressure are automatically controlled by a personal computer during the test procedure including the consolidation stage before the shear loading. The hollow cylinder specimen is 100mm of height and 100 & 60 mm of outer & inner diameters.

4 TEST RESULTS

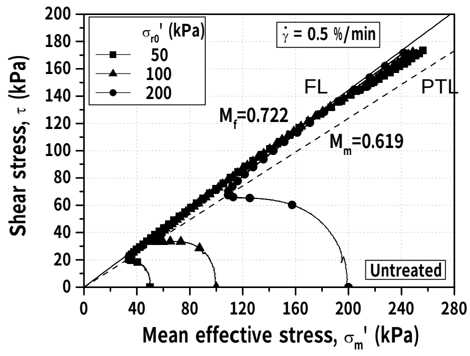
4.1 *Monotonic loading test*

Figure 2 shows the test results of monotonic drained torsional shear test. By comparing between the untreated and the treated sands under the same confining pressure, it is clear that the treated sand demonstrates large shear stresses and significant characteristics of dilatancy.

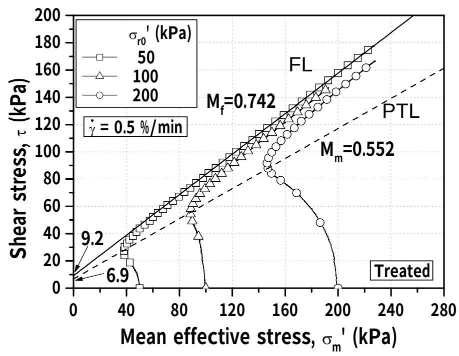
The undrained torsional shear test under a monotonic loading condition has been also performed. The stress - strain relations



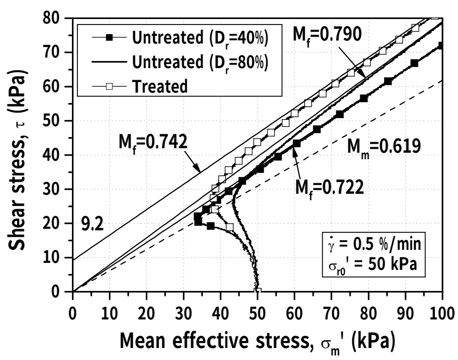
(a) Stress – strain relations



(b) Effective stress paths (untreated sand)



(c) Effective stress paths (untreated sand)



(d) Effective stress paths (comparison)

Figure 3. Undrained torsional shear test results.

and the effective stress paths of untreated and treated sand specimens are shown in Figures 3. The considerable increases of shear stress can be observed in the case of treated sand.

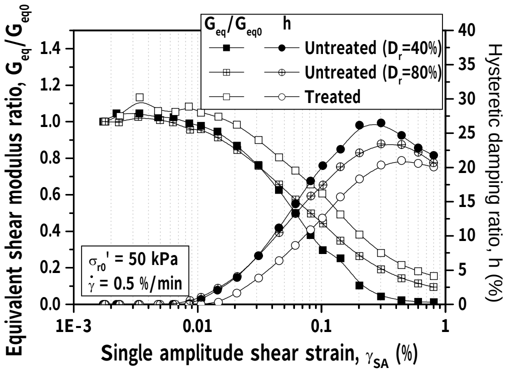


Figure 4. Cyclic loading test results to determine the deformation properties.

As shown in Figure 3 (b) and (c), the inclination of failure line (FL), M_f, slightly increases and the position of failure line moves to upper by the colloidal silica treatment. The intercept of failure line occurs due to the cohesive properties of treated sand. On the other hand, the inclination of phase transformation line (PTL), M_m, decreases by the treatment. As a result, the dilation region, which is between failure line and phase transformation line, is expanded by the colloidal silica treatment. In this region, the sand exhibits the stable undrained shear behavior due to the constraint of dilation.

Figure3 (d) illustrates the effective stress path of the untreated dense sand (D_r=80%) together with the results of untreated and treated sand specimen as shown in the above figures. Both of the failure line and the phase transformation line of the dense sand specimen pass through the origin. Although the inclination of failure line of the dense sand is larger than that of others, the inclination of phase transformation line is almost same as that of untreated loose sand. The undrained shear behavior of the treated sand specimens is quite different from that of the untreated dense sand.

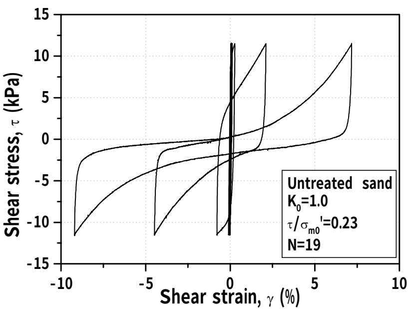
4.2 *Cyclic loading test*

Figure 4 shows the results of the cyclic torsional shear test to determine the deformation properties of specimens. The equivalent shear modulus ratio of the treated sand demonstrates high rigidity even for the high level of shear strain.

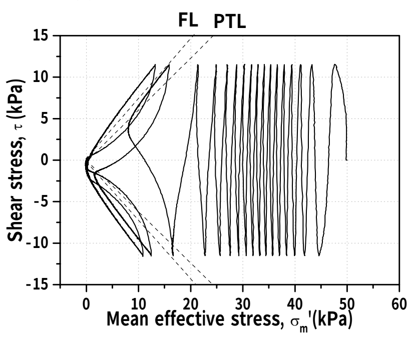
The results of the conventional undrained cyclic torsional shear tests of untreated sand specimens are illustrate in Figure 5. In that case, cyclic stress ratio, τ / σ'_{m0}, is 0.23. Untreated sand developed very little shear strain before the effective stress state reached to the phase transformation line (PTL), which is measured by monotonic loading tests under undrained condition. However, once the effective stress state reached to the phase transformation line, large strains occurred rapidly and the untreated sand liquefied completely within a few additional cycles. On the other hand, different deformation characteristics are distinctly observed in the treated sand as shown in Figure 6, in which cyclic stress ratio is relatively large; τ / σ'_{m0} = 0.600. In that case, a relatively large strain was developed in the early stage of loading, however, both the development of shear strain and the decrease of mean effective stress resulted without any collapse and liquefaction. Furthermore, during the cyclic loading the phase transformation lines of untreated sand move to the inside, which are the same position of untreated sand. On the other hand, the positions of failure lines do not so change. Figure 7 shows the test results of untreated dense sand. The typical cyclic mobility can be observed in that case.

5 DISCUSSION

From the stress – strain relations as shown in Figures 5, 6 and 7, three typical differences between the untreated sand and the treated sand can be listed. The first difference point is the tangential shear modulus for the small level of the mean effective stress. The second one is the characteristics of development of shear strain during the cyclic loading. The last is the movement of the phase transformation line during the cyclic loading.

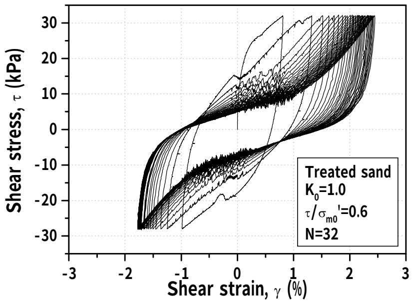


(a) Stress – strain relations

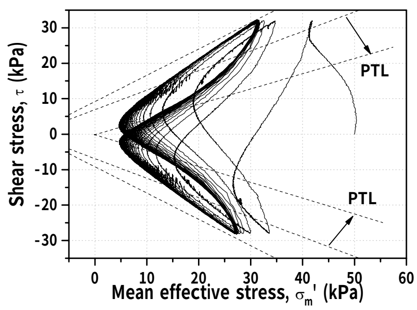


(b) Effective stress path

Figure 5. Undrained cyclic loading test result of untreated sand.

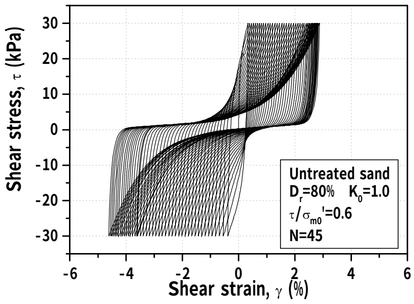


(a) Stress – strain relations

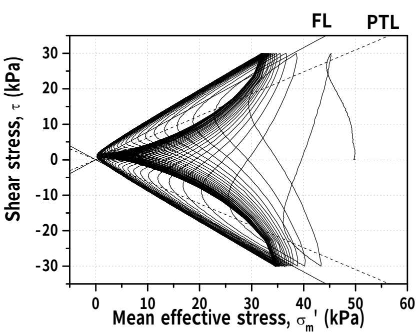


(b) Effective stress path

Figure 6. Undrained cyclic loading test result of treated sand.



(a) Stress – strain relations



(b) Effective stress path

Figure 7. Undrained cyclic loading test result of untreated sand.

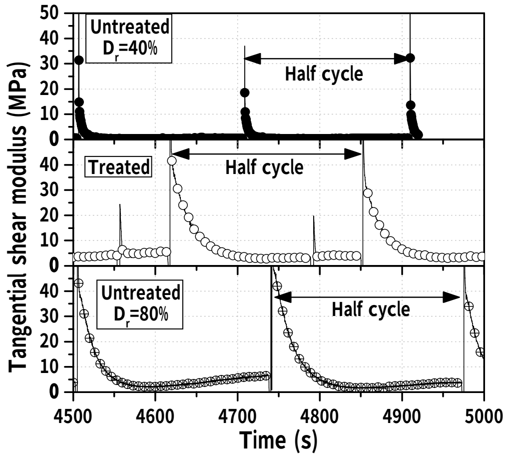


Figure 8. Reduction of the tangential shear modulus during cyclic loading.

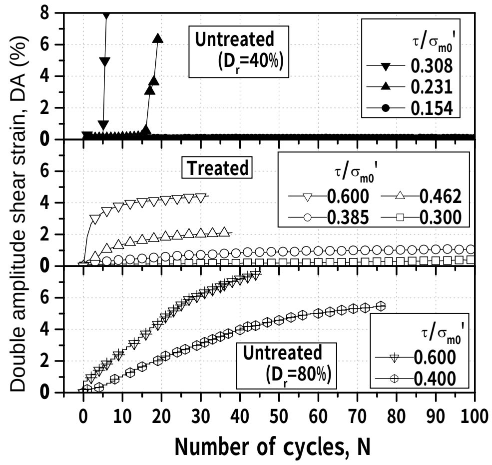


Figure 9. Developments of shear strain during cyclic loading.

Figure 8 illustrates the reduction of the tangential shear modulus during the cyclic loading. The modulus were calculated from the hysteresis loops at 0.8% of single amplitude strain, which were obtained by the cyclic deformation test as shown in Figure 4. The rigidity of the untreated sand rapidly reduces to be almost zero with increasing the number of cycles for the relative high level of shear strain. On the other hand, the treated sand keeps the small value of rigidity, which is not zero, even for the high level of strain due to the ductile and cohesive properties of sand gel.

Figure 9 exhibits the development of shear strain with increasing number of cycles with the other test results of cyclic stress ratio. The untreated sand exhibits the rapid development of share strain. In the case of the treated sand, the relative large shear strain develops from the initial loading stages and converges on the finite value in the early stage of loading. In untreated dense sand case, the shear strain develops in a constant increment with increasing the number of cycles. The convergence of shear strain of treated sand is caused by the expansion of the dilation region due to the movement of phase transformation line as shown in Figure 6.

Figure 10 shows the cyclic strength curves, which includes all experimental results performed in the present study. In these curves, the number of cycles is adopted as the number at DA=1% because of the little development of shear strain for treated sand. It is found that there is a great influence of the colloidal silica treatment on the cyclic shear resistance.

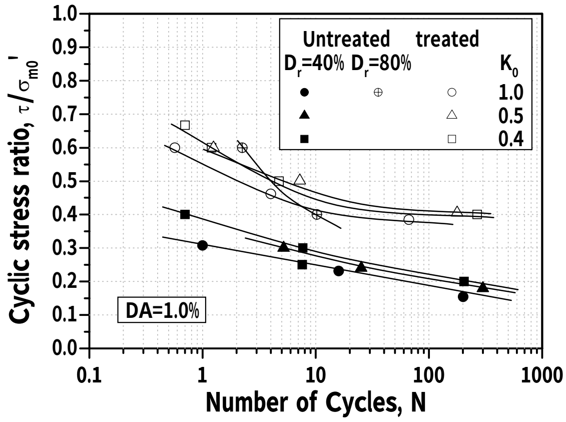


Figure 10. Reduction of the cyclic stress ratio with increasing the number of cycles.

6 CONCLUSIONS

In order to study the deformation and the strength characteristics of the treated sand with the colloidal silica, a series of laboratory tests has been performed on the treated sand such as monotonic and cyclic torsional shear tests. In the case of cyclic torsional shear test with the treated sand, a relatively large strain is developed in the early stage of loading; however, both the development of shear strain and the decrease of mean effective stress resulted without any collapse and liquefaction. As the results, the remarkable improvement of cyclic shear strength by the colloidal silica treatment can be exhibited. This phenomenon leads to the expansion of dilation region across which it faced the phase transformation line and the failure line. When the performance based design for the silica-treated ground are carried out, it is necessary for the dynamic deformation analysis to produce the appropriate constitutive model for the treated sand based on the test results (Oka et al. 2003).

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