Cyclic shear tests on a colloidal silica treated sand

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1. Introduction

Colloidal silica is a water-glass based solution, which contains suspended silica (SiO_2) particles. It is commonly used in permeation grouting as a method of ground improvement to correct existing or anticipated foundation problems. It has been reported (e.g. Kodaka et al., 2005; Gallagher and Mitchell, 2002; Persoff et al., 1997) that a colloidal silica treatment increases strength, reduces hydraulic conductivity and enhances liquefaction resistance of a soil. The use of colloidal silica for soil treatment in tunnel and dam construction and site stabilization projects has grown recently, thanks to the ease of application, non-toxicity and mechanical as well as chemical stability.

In the present study, a sand sample treated by a newly developed colloidal silica in the laboratory, is tested using a torsional shearing apparatus in order to investigate the cyclic behavior of the sand. Results of the test are compared with the experimental results on untreated and treated samples taken from the field.

2. Laboratory testing materials and methods

2.1. Yatsushiro sand

The soil to be used for the experimental study was taken from a site in Yatsushiro city (Kumamoto) at depth of 2-4 m, where the average SPT value, N is 5. Its grains consist of 86.6% sand and 13.4% silt. The average grain size, D_{50} is 0.271 mm and soil density, ρ_s is 2.69 g/cm^3. It is classified as S-F (sand) by Japanese Geotechnical Society.

2.2. Colloidal silica

The grout used for treating the sand is a colloidal silica solution, named QS-GS, of 6 wt % silica concentration, newly manufactured by Fuji Chemical Co. It is a mixture of three types of silica, namely 'QS Colloid', 'QS Binder' and 'QS Setter-GS'. Table 1 shows details about the properties of the grouts.

Table 1. Properties of QS-GS grout components

Silica type	Specific gravity	pH	Homogel time (hr)	Sand-gel time (min)
QS Colloid	1.038	10.13	72	27
QS Binder	1.060	11.50		
QS Setter-GS	1.052	< 1.0		

2.3. Specimen preparation

The procedure of preparing the specimens in the laboratory is as follows:

i. Dry sand is pluviated into an acrylic cylinder of 10 cm inner diameter to achieve a relative density of 50% approximately;
ii. A confining pressure of 50 kPa is applied onto the sand mass by means of a piston;
iii. Carbon dioxide (CO_2) gas is allowed to enter the sand mass from bottom and displace the pore air in the sand;
iv. After CO_2 treatment is completed, the mass is saturated with de-aired water;
v. After that, silica grout is injected at 20 kPa pressure into the mass from bottom until a total volume of 1.8 liters is used. During the injection, the top of the sand mass is drained so that surplus grout can be collected;
vi. After a curing period of 28 days or more, the specimen is extruded from the cylinder and cut into cylindrical pieces of 12 cm height approximately;
vii. The cylindrical pieces are trimmed to make hollow specimens of 6 cm inner diameter, 10 cm outer diameter, and 10 cm height.

2.4. Testing apparatus

The testing apparatus features two electric servos, which can generate axial load and torque load separately and simultaneously to cause a torsional shear. The piston of each servo can be driven forward and backward by means of controlled air pressure. As a result, precise cyclic loading conditions can be created.

2.5. Testing procedures

Before a specimen is saturated, pore air inside the specimen is removed by following a so-called 'double vacuum' procedure, in which vacuum is simultaneously applied to the specimen and the triaxial cell while maintaining an effective confining pressure of 20 kPa. The vacuum pressures are increased step by step, until the pressure applied to the specimen is -90 kPa, and the cell pressure is -70 kPa. This condition is maintained for 1 hour. After that, de-aired water is allowed to enter the specimen from a tank, which is hung 1.4 m above the triaxial cell, for 1 hour. Pore water pressure coefficient, B, is checked in the end of the saturation process. The specimen is considered saturated if B value equals 0.95 or greater. The specimen is consolidated isotropically under a 50 kPa confining pressure. After consolidation is completed, shearing commences under various conditions (Table 2).

Table 2. Testing conditions for silica treated sand

Case	S-3	S-6	S-9
K_0	1.0	1.0	1.0
Eff. confining stress (kPa)	50	50	50
Cyclic stress ratio	0.48	0.39	0.30
Loading frequency (Hz)	0.1	0.1	0.1
Initial void ratio	0.79	0.75	0.78
Initial moisture content (%)	29.3	28.6	29.7

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3. Test results

Results of the test on S-6 specimen are typical results for all cases and thus are shown here for discussions, in terms of shear stress - shear strain relation (Figure 1a) and the effective stress path (Figure 1b).

It can be seen that the shear strain develops quickly in the first few cycles. The double amplitude (DA) shear strain after the second cycle was as large as 2.5%. After that, the development of shear strain tends to slow down. The test was terminated after 34 cycles when the strain reached 10%.

Similarly, Figure 1b shows that the effective stress decreases rapidly in early cycles. After that, the rate of the effective stress loss gradually decreases and that in the last few cycles is very small. When the test was completed, the effective stress was about 8 kPa, thus showed that the specimen was far from liquefaction, despite the large strain.

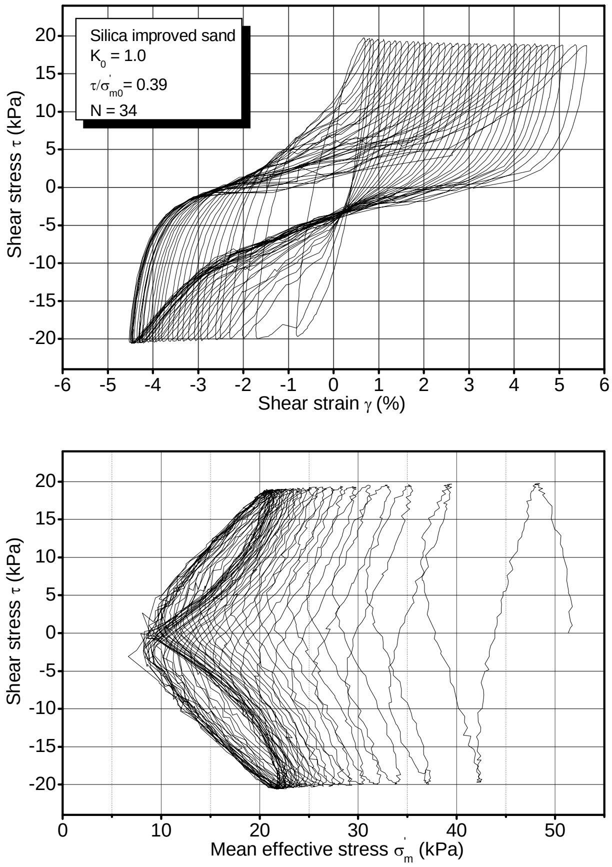

Figure 1: Test results for case S-6

Figure 2 shows the comparison between the sands treated with colloidal silica in the laboratory and in the field in terms of cyclic loading resistance. It can be seen that under the same cyclic stress ratio, the former generally reached a DA shear strain of 7.5% after fewer cycles. For instance, at the cyclic stress ratio of 0.5, a laboratory specimen took only 2 cycles, as compared to about 12 cycles for a field specimen. At the stress ratio of 0.4, a laboratory specimen generated 7.5% DA strain after 12 cycles, as compared to about 35 cycles for a specimen obtained from the field.

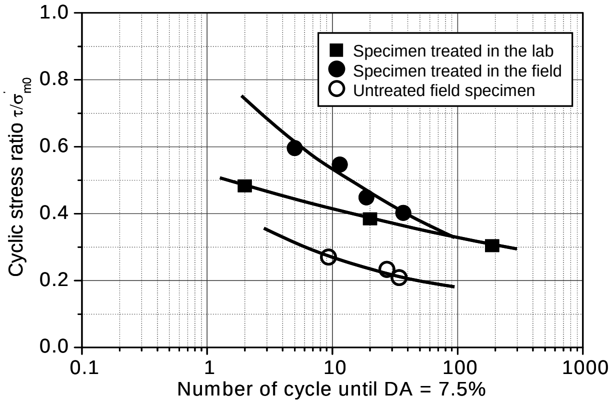

Figure 2:Test results for field and laboratory specimens

However, at lower cyclic tress ratio, the performance of a specimen prepared in laboratory is similar to that of a specimen obtained from the field. For instance, under the cyclic stress ratio of 0.3, both specimens could stand nearly 200 cycles before DA strain reached 7.5%.

Also shown on Figure 2 is the result of tests performed on untreated sand. It is clear that the silica treatment by either laboratory method or field practice increases the cyclic loading resistance of the sand. Untreated specimens tested under low cyclic stress ratios quickly reach large strain after a small number of loading cycles. Under a cyclic stress ratio as small as 0.22, they could stand about 30 cycles and under the cyclic stress ratio of 0.3, they reached 7.5% strain just after 7 cycles, as compared to 200 cycles for treated specimens.

4. Conclusions

Silica improved sand specimens were prepared in the laboratory following a technique that simulates grouting practice in real life. Cyclic torsional shear tests were carried out and results were compared with the results of tests performed on the specimens obtained from the field.

It has been found that the silica treatment greatly increased the cyclic shear strength of the sand. In all cases, the specimens did neither collapse nor liquefy. In general, shear strain in the silica treated sand develops quickly in early stage then slows down while the effective stress decreases at a small rate. At low cyclic stress ratios, the specimens prepared in the laboratory perform similarly to the field specimens. However, under higher ratios, the laboratory specimens appear weaker.

5. References

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