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Effect of Sampling Method on Strength of Stabilized Silty Sands with Colloidal Nano Silica

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Abstract Treatment of liquefiable deposits is one of the most important topics in geotechnical earthquake engineering. In this study, the stabilization of liquefiable silty sands with colloidal nano-silica under two different conditions was investigated and the effect of disturbance on the strength of stabilized samples was discussed. First, four cylindrical samples (as undisturbed samples) consisted of sand with variation in silt content from 0 to 30% prepared by sedimentation method in colloidal nano-silica at concentrations of 4.5 wt% and after a curing time of 6 weeks the strength of stabilized samples were investigated by means of unconfined compressive tests. Then, four box models were used to simulate the stabilization of the same soil specimens with permeation of colloidal nano-silica in soil formations using 5 low-head injection and 2 extraction wells. After delivery of colloidal nano-silica was completed the models were cured for 6 weeks. Then the treated soils were excavated and a few samples (as disturbed samples) were extracted for unconfined compressive testing. According to the results colloidal nano-silica can be successfully delivered in silty sand formations and improve the strength characteristics. The strength of disturbed samples was approximately 63-85% of the strength of undisturbed samples. This study also examined the potential for applying scanning electron microscope (SEM) analysis to investigate soil stabilization with colloidal nano-silica.

Keywords Soil stabilization, Physical model, Silty sand, SEM analysis, Un-confined compressive test, Colloidal nano-silica

1. Introduction

Liquefaction is a phenomenon marked by a rapid and dramatic loss of soil strength, which can occur in loose, saturated liquefiable soil deposits subjected to earthquake motion and result in large deformation and settlements, floating of buried structures, or loss of foundation support. Passive site stabilization is a new technology proposed for non-disruptive mitigation of liquefaction risk at developed sites. It is based on the concept of slowly injecting colloidal nano-silica (colloidal silica) at the edge of a site and deliver stabilizer to the target location using either natural or augmented groundwater flow (see Fig. 1). Colloidal silica is an aqueous suspension (a sol) of silica (SiO_2) nanoparticles (7-100 nm) that can be made to gel by changing the ionic strength and pH of the dispersion. In diluted solutions, colloidal silica has a low initial viscosity of about 1.5×10^{-3} Pa.s (1.5 cP; water = 1 cp). After gelation of colloidal silica, a firm, resonating gel forms. The density, controllable gel time, and low viscosity make colloidal silica attractive as a potential grouting material for passive site stabilization [1, 2]. Colloidal silica also has excellent durability characteristics [3, 4], it is chemically and biologically inert, and it is non-toxic [4, 5]. Colloidal silica was proposed as a replacement for the most commonly used chemical grout, sodium silicate [6]. Persoff *et al*. [7] reported colloidal silica stabilizer is expected to be permanent in typical soil conditions. Towhata & Kabahima [8] found that the behavior of loose sand treated with colloidal silica is similar to the behavior of denser untreated sands. Gallagher & Mitchell [9], Liao *et al*. [10], and Diaz-Rodriguez *et al*. [11] reported that colloidal silica significantly increases the cyclic strength of sands. Physical modeling and centrifuge testing have been done to investigate the ability of diluted colloidal silica (5wt %) to mitigate the liquefaction potential of loose sands [12-16]. Few field-scales testing of colloidal silica for environmental remediation has been done in small, limited scales [17-19]. Numerical modeling has also been designed to simulate colloidal silica injection in sand using iTOUGH2, MODFLOW, and UTCHEM numerical simulation. A few number of these numerical models accurately represented the physical experiments [12, 20-21]. Although a few studies have investigated passive site stabilization method for treating of sands, but it is a new technique and requires more research. In this study, the stabilization of liquefiable silty sands with colloidal silica with a minimum concentration of 4.5 wt % was investigated

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under two different conditions (un-disturbance and disturbance), the short term strength of treated samples was determined and the effect of disturbance was evaluated. For this, a few cylindrical samples (as undisturbed samples) consisted of sand with variation in silt content from 0 to 30% prepared by sedimentation method in colloidal silica and the strength of stabilized samples were investigated by means of unconfined compressive (UC) tests. Moreover, a box model was constructed to investigate the ability of the colloidal silica solution to permeate the same fine-grained silty sand specimens under small gradients imposed by injection and extraction wells. After delivery was completed, the treated samples were extracted (as disturbed samples) for UC testing. This research also examined the ability of applying SEM analysis to investigate soil stabilization with colloidal silica.

2. Experimental Procedure

2.1. Materials

For this testing program, four different liquefiable soil specimens were prepared. The soil specimens consisted of sand with variations in silt (fine-grained soil) content from 0 to 30%. The characteristics of the soil specimens are shown in Table 1.

The sand and silt used to prepare the specimens were Firoozkooh No.161 sand and None-Plastic Firoozkooh silt, respectively. Their gradation curves are shown in Fig. 2. Chemical analysis of Firoozkooh sand and silt are also shown in Table 2.

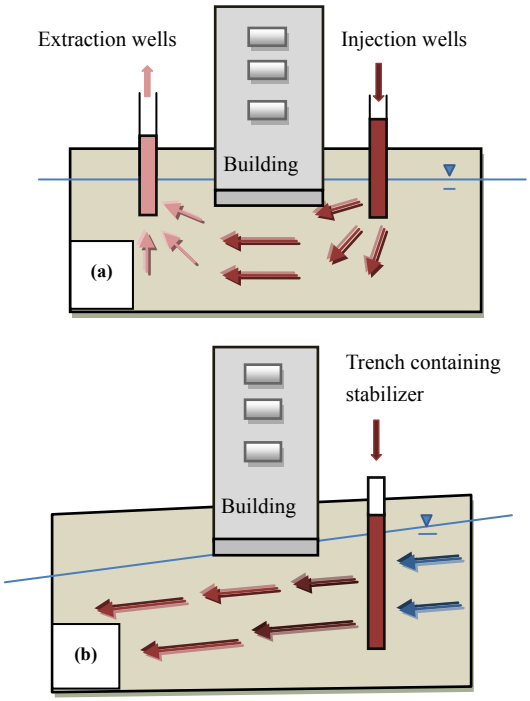

Figure 1. Concept of passive site stabilization; (a) Induced; (b) Natural groundwater flow

Table 1. Characteristics of soil specimens in this study

Specimen	Sand content (%)	Silt content (%)
N0	100	0
N10	90	10
N20	80	20
N30	70	30

To prepare the stabilizer material, SIGMA-ALDRICH Ludox®SM-30 wt% (suspension in water) was diluted to 4.5 wt%. Table 3 shows the characteristics of Ludox®SM-30 wt% according to SIGMA-ALDRICH product information.

Table 2. Chemical analysis of Firoozkooh No.161 sand and silt

Mineral	Content
SiO_2	96-98.8%
Fe_2O_3	0.2-0.7%
Al_2O_3	0.5-1.65%
Cao	0.2-0.5%
Na_2O	0.03-0.08%
K_2O	0.03-0.10%

Table 3. Characteristics of Ludox® SM-30 wt% colloidal silica

Index property	Content
Silica concentration	30 wt%
Average particle size	8 nm
Specific area	320-400 m^2/g
pH	9.7-10.3
Density at 25°	1.22 g/ml
Viscosity	5.5 cP

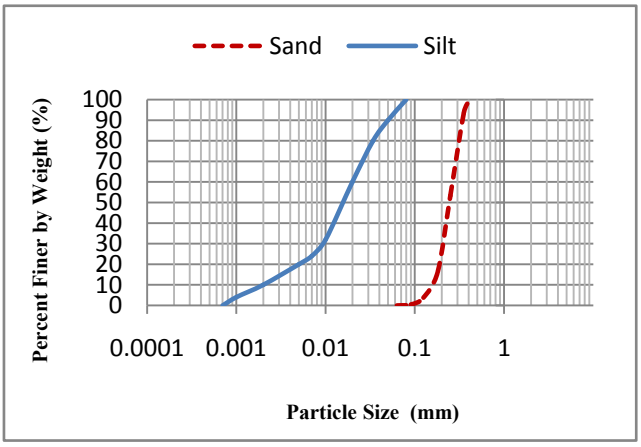

Figure 2. Grain size distribution for Firoozkooh No.161 sand and Firoozkooh silt

For gel time control of the diluted solution, scientific sodium chloride (NaCl) and 6N hydrochloric acid (HCl) were used to adjust the ionic strength and pH, respectively. The ionic strength and pH was adjusted as viscosity remained approximately 1.5 cP during colloidal silica

delivery in each box model test. The properties of diluted colloidal silica solution used in this research are shown in Table 4.

Table 4. Properties of diluted colloidal silica solution used in this study

Silica concentration	4.5 wt%
NaCl	0.1 normality
pH	6-6.7
Gel time	24-48 hour
Viscosity	< 1.5 cP

2.2. Methods

2.2.1. Preparing and Measuring of Undisturbed Samples Strength

The undisturbed samples for unconfined compressive (UC) test consisted of four soil specimens (N0, N10, N20 and N30; see Table 1) and prepared in their loose condition by sedimentation in colloidal silica, at concentrations of 4.5 wt%. The sedimentation method procedure ensured that the voids were filled with grout. The samples were cylindrical and their dimensions measured 5 cm in diameter and 10 cm in height. The relative density of samples was approximately 20%. The gel time of colloidal silica solution was adjusted to 24 hours according to Table 4 and the samples were cured for a periods of 6 weeks.

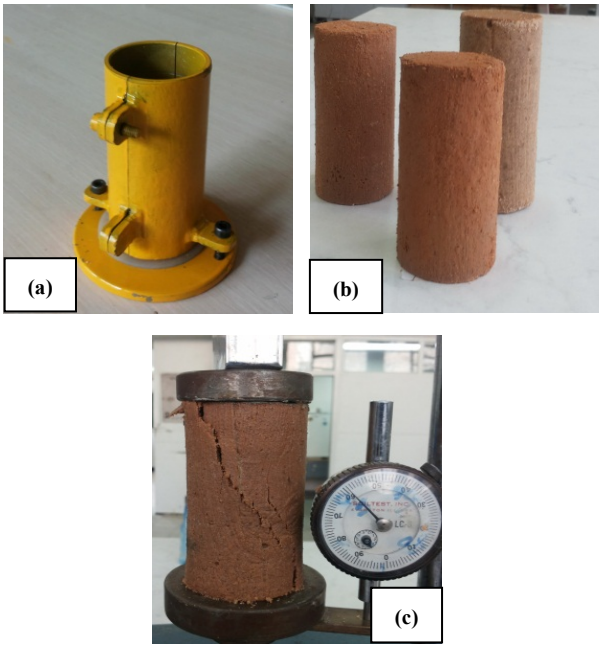

Figure 3. Preparing of samples and running of UC test; (a) Iron mold; (b) Undisturbed cylindrical samples; (c) Ultimate failure after loading in a UC test

For each sample, the appropriate amounts of sand, silt and diluted colloid were measured. Then the required amount of diluted colloid was placed in Iron molds. The molds had an iron plate in the bottom fixed to molds with two bolts. The molds were split longitudinally to facilitate sample removal (see Fig. 3(a)). The molds and bottom plate were sealed against leakage using grease after which sand and silt were poured through a funnel into the diluted colloidal silica, from a height of 5 cm above sample surface. The samples were removed from molds after gelation, sealed with nylon sheet and placed in a constant room temperature (22^{o}C) to cure. Prior to testing, the top and bottom of each sample was sleeked with a straight edge (see Fig. 3 (b)) and the dimensions of samples were measured and recorded.

The unconfined compressive strength tests were run in general accordance with ASTM D2166 standard test method. Fig. 3 (c) shows the ultimate failure of a sample after UC test.

2.2.2. Box Modeling for Passive Stabilization

For physical modeling of passive stabilization, a box model was used in this study. The box model had three compartments, a central chamber for soil placement and two outer reservoirs for water placement and groundwater control. The box was constructed of 10 mm thick Plexiglas with dimensions of 125 x 30 cm and a height of 30 cm. The flow length through the soil sample was 60 cm and each water reservoir was 20 cm long. Screen with a No. 300 mesh size was used between the water and soil compartments. A filter layer of coarse gravel with a thickness of 10 cm was designed to be placed between the screens and the liquefiable soil specimen to prevent soil loss from the central chamber into the water reservoirs. The model setup is shown in Fig. 4. The left and right sides of the soil chamber are the upstream and downstream chambers, respectively.

Five injection and two extraction wells were constructed from 20-mm PVC pipe. The injection wells had four 5-mm injection ports arranged in one vertical column at depths of 3.5, 6, 8.5, and 11 cm below the soil surface. The ports were covered with a No. 16 mesh and a layer of propylene granules with a width of 6 mm. This layer prevents soil loss into the injection wells, while facilitating the flow process of colloidal silica from the injection ports into the soil sample. The injection wells intervals were 5 cm and the ports were in the downstream direction. These wells were located 15 cm from the filter layer (coarse gravel) and had a distribution bay to maintain a constant supply of colloidal silica to the wells. Two extraction wells were used to withdraw fluid from the soil formation at a rate of 10 mL/min with a small suction apparatus. The extraction wells had seven 5-mm-diameter ports covered with a No. 300 mesh. The ports were uniformly distributed along the length of the well, starting at a depth of 2.5 cm below the soil surface. The wells were located adjacent to the downstream filter layer edge of the model at equally spaced intervals. The extraction ports were in the upstream direction. The model was tested for four liquefiable soil specimens (N0, N10, N20 and N30; see Table 1).

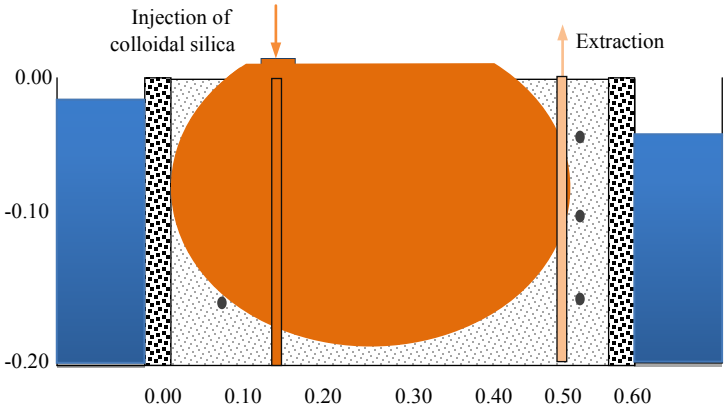

Figure 4. Box model setup in this study

For each test, the soil chamber was filled by pouring the soil specimen to a height of 20 cm under loose soil conditions (at a relative density of approximately 20%). After soil placement, the upstream reservoir was filled with water to saturate the soil. After saturation, an overall gradient of 0.03 was established using the constant-head flow in each reservoir chamber. After the overall gradient was established, the colloidal silica solution was introduced to the soil using injection wells as the stabilizer material. The pH was adjusted as viscosity remained approximately 1.5 cP during colloidal silica delivery in each box model test (see Table 4). During colloidal silica delivery, a constant head of 21 cm from the bottom of the soil chamber was maintained in the injection wells. This head resulted in colloidal silica movement in both upstream and downstream directions. For visual monitoring of the advancement of colloidal silica, the colloidal silica solution was colored with colored material. Pore fluid samples were extracted from the box model at different times. Each extracted pore fluid sample was weighted and placed in an oven at 80ºC for 24 hours. After desiccation, the weights of the specimens were measured again, and the desiccated silica concentration was calculated. The relative concentration of desiccated silica in each extracted pore fluid sample was used as a tracer of colloidal silica present in the soil matrix. After delivery of an adequate amount of colloidal silica in each model, the model was cured for 6 weeks and then excavated into a few block samples. The block samples were carved into smaller samples (as disturbed samples) for UC strength testing. Similar to the undisturbed samples, the disturbed samples were cylindrical and their dimensions measured 5 cm in diameter and 10 cm in height. The UC tests were also run in general accordance with ASTM D2166 standard method.

2.2.3. SEM Analysis

For SEM analysis, a few specimens of the samples stabilized with colloidal silica were dried in an oven at a constant temperature of 80°C for 24 hours and prepared in powder form. Then a few specimens of both treated and untreated soils were scanned with SEM and the micrographs were evaluated to identify differences in the microstructure of their particles.

3. Results and Discussion

3.1. UC Strength of Undisturbed Samples

UC strength testing was selected to investigate the short term and static strength of stabilized samples, so the results could be compared with past studies on the efficiency of colloidal silica. Moreover, UC tests are often done on chemically stabilized sands and have the advantage of being fast and easy. Essentially, loose sands and silts have no unconfined compression strength but after treatment with colloidal silica, they have showed considerable compressive strength. The results of this section are according to the findings of Persoff *et al*. [7], and Gallagher & Mitchel [9].

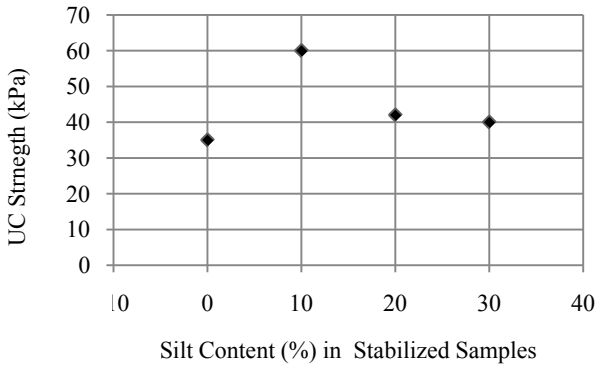

Figure 5. Unconfined Compressive (UC) strength of undisturbed samples stabilized with 4.5wt% colloidal silica at 6 weeks curing time

The results of UC strength tests for undisturbed samples (see section 2.2.1) are summarized in Fig. 5. As shown, after a period of 6 weeks, the UC strength of samples N0, N10, N20, and N30 stabilized with colloidal silica (4.5 wt%) was 35, 60, 42 and 40 kPa, respectively. It is also shown, an increase in UC strength was achieved when the silt content was made up to 10%; however, a further increase in the amount of silt resulted in decreased strength. It seems by

increasing silt to a threshold content of 10%, the voids between sand aggregates became filled with silt particles. This led to increased strength (at 10% silt content) but with increase in the silt content, the particles of silt made loose bridges between sand aggregates and this caused decreasing UC strength.

3.2. The Box Models Results

The delivery of colored colloidal silica in box models testing was determined with visual monitoring and measurement of extracted pore fluid sample concentrations. According to these results, colloidal silica can be delivered uniformly in silty sand formations. During the periods of 4, 9, 27, and 45 hours, 18 liters (approximately 1.2 pore volumes) of colloidal silica solution (4.5 wt%) was delivered to the soil specimens N0, N10, N20, and N30 (see Table 1) respectively. As shown, under identical conditions, the hydraulic conductivity of the soil specimens had a considerable effect on delivery time of colloidal silica. A photograph of the box model test for advancement of colloidal silica in the soil formation (N10) is shown in Figure 6.

The strength of samples stabilized with colloidal silica in box models (as disturbed samples) was evaluated by UC testing. The range of UC strength of extracted samples from each box model is summarized in Table 5. The results of this section are according to the findings of Gallagher & Finstere [12]. The average baseline strength of four soil specimens of N0, N10, N20, and N30 after treatment in box models was approximately 30, 45, 29, and 20 kPa, respectively. These values were assumed as the UC strength of disturbed samples in this study.

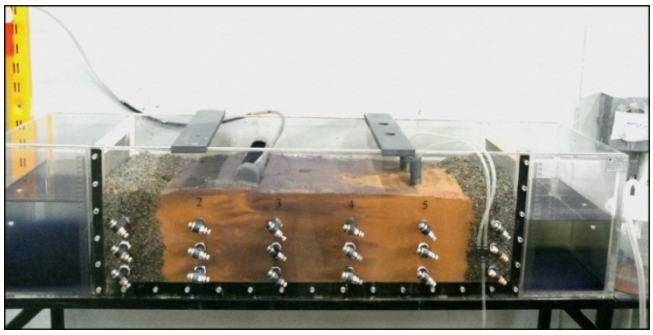

Figure 6. Physical model experiment for colloidal silica delivery in this research, flow is from left to right

By comparing the results of UC testing for disturbed and undisturbed samples (see Fig. 7), it is shown the strength of disturbed samples with the soil type of N0, N10, N20 and N30 were 85, 75, 69 and 63% of undisturbed samples strength, with the same curing time, respectively. The low hydraulic conductivity of silty sands (N10, N20, and N30) caused less permeation of colloidal silica in soil voids at box models and more difference in strength of disturbed and undisturbed samples. However, the considerable UC strength of disturbed samples, with only 6 weeks curing period, indicated the success of passive stabilization method in treatment of silty sand with fine grained soil (silt).

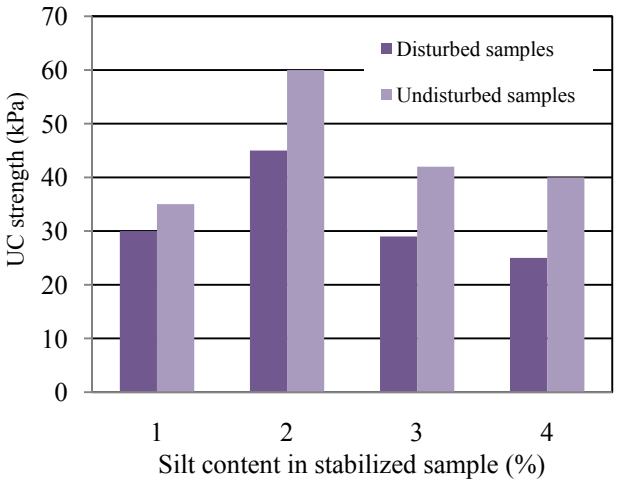

Figure 7. Comparison of Unconfined Compressive (UC) strength of disturbed and undisturbed silty sand samples stabilized with colloidal silica (4.5 wt%) after 6 weeks curing

3.3. SEM Micrographs

The grains within each treated and untreated sample were evaluated for the presence of a few surface textures, as described by Helland *et al.* [22]. Fig. 8 shows the grains of Firoozkooh sand and silt. As shown the grains of Firoozkooh sand were angular and, of low relief with mechanical textures associated with breakage including conchoidal fractures, straight and arcuate steps and fractured plates. In Fig. 9 the grains of Firoozkooh sand and silt stabilized with 4.5 wt% colloidal silica are shown. The treated grains were angular, of high relief with abundant mechanical texture associated with adherence of colloidal silica including straight and arcuate steps, imbricated blocks, fractured plates, meandering ridges and irregular depressions. These features of the treated sands surface textures caused increase in strength and stiffness. In fact, the aggregates of intact stabilized samples were stuck together with colloidal silica gel but after drying in the oven, the particles were separated for clearer scanning. The undertaken grain surface texture analysis indicated a clear difference between treated and untreated samples and the potential of this technique in investigating of soil stabilization with colloidal nano silica.

Table 5. Unconfined compressive (UC) strength of samples stabilized with colloidal silica (4.5 wt%) in box models after 6 weeks curing

Soil type in box model	Range of UC strength in extracted samples (kPa)	Average UC strength of extracted (disturbed) samples (kPa)
N0	18-35	30
N10	22-47	45
N20	18-32	29
N30	14-28	25

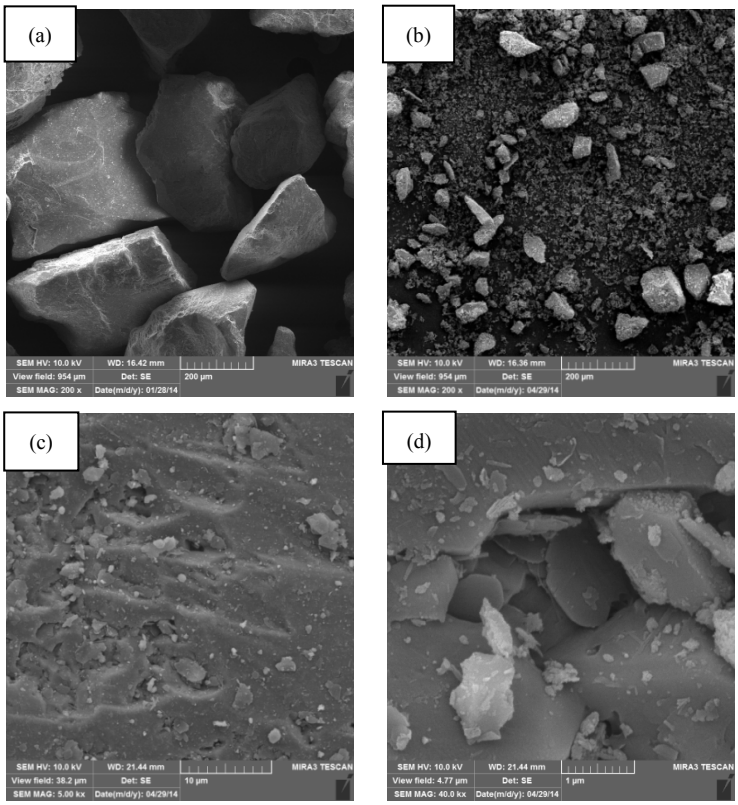

Figure 8. Micrographs of untreated soil grains; (a) Firoozkooh sand grains, MAG: 200×; (b) silt (fine grained) grains, MAG: 200×; (c) sand and silt grains mixing, MAG: 5 k×; (d) sand and silt grains mixing, MAG: 40 k×

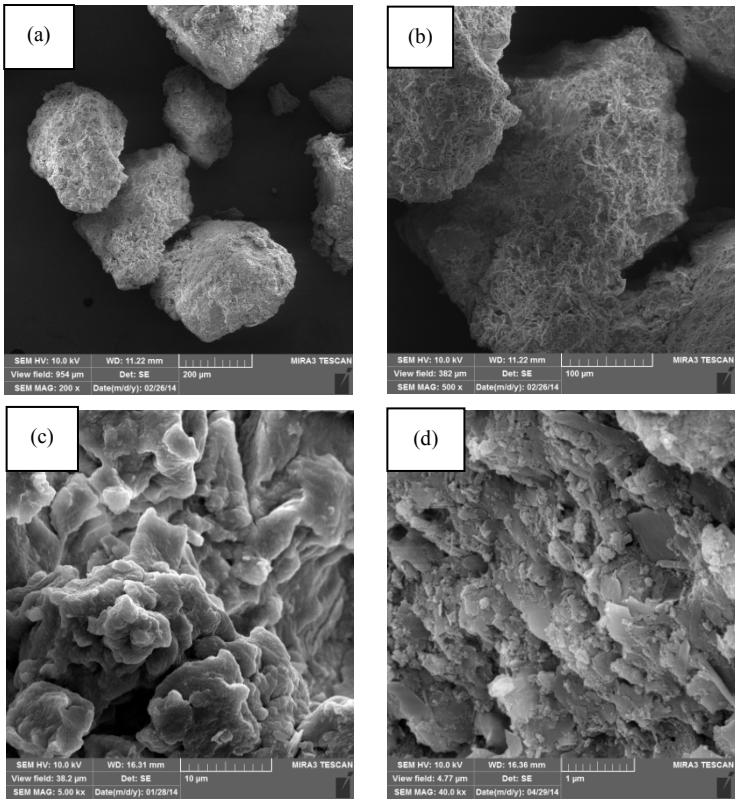

Figure 9. Micrographs of soil grains treated with colloidal silica (4.5 wt%); (a) MAG: 200×; (b) MAG: 500×; (c) MAG: 5.00 k×; (d) MAG: 40 k×

4. Conclusions

Physical modeling and unconfined compressive tests were done to investigate the short term strength of silty sand samples stabilized with colloidal nano-silica under different conditions. According to the results colloidal nano-silica with a minimum concentration of 4.5 wt% can be successfully delivered in silty sand formations, improve the strength characteristics and mitigate the liquefaction risk of saturated loos deposits during earthquake. The method of sampling and disturbance affect the strength of stabilized soils so that the unconfined compressive strength of disturbed samples is approximately 65-85% of undisturbed cylindrical samples strength. The results of this study also show the differences between untreated and treated soil grains texture in SEM analysis and the ability of using this technique in practice as a tracer of colloidal silica present in the stabilized soil matrix.

REFERENCES

[1] Gallagher, P.M. Passive site remediation for mitigation of liquefaction risk. *Ph.D Dissertation, Virginia Polytech. Inst. and State Uni.*, Blacksburg, (2000).

[2] Gallagher, P.M. & Koch, A. J. Model testing of passive site stabilization: A new technique. *Proc. 3rd Int.l Conf. on Grouting and Ground Treatment, New Orleans,* 2 (2003) 1478-1490.

[3] Yonekura, R. & Miwa, M. Fundamental properties of Sodium Silicate based grout. *Proc. 11th Southeast Asia Geotech. Conf.*, Singapore, (1993) 439-444.

[4] Whang, JM. Chemical Based Barrier Materials. *In Assessment of Barrier Containment Technologies for Environmental Remediation Applications* (Rumer RR, Mitchel Jk, Editors). Section 9, Springfield, VA: National Technical Information Service, (1995).

[5] Iler, RK. *The Chemistry of Silica: Solubility, Polymerization Colloid and Surface Properties, and Biochemist Try*. New York: Wiley, (1979).

[6] Yonekura, R. & Kaga, M. Current chemical grout engineering in Japan. In R.H. Borden et al. (Ed.), *Grouting, soil improvement and geosynthetics* (pp. 725-736). New York: ASCE, (1992).

[7] Persoff, P., Apps, J., Moridis, G. & Whang, J. M. Effect of dilution and contaminants on sand grouted with colloidal silica. *J. of Geotech.l and Geoenvironment. Engng*. 125, No. 6 (1999) 461–469.

[8] Towhata, I. & Kabashima, Y. Mitigation of seismically-induced deformation of loose sandy foundation by uniform permeation grouting. *Proc. Earthquake Geotech. Engng Satellite Conf., 15th Int.Conf. of Soil Mech. and Geotech. Enginng*, *Istanbul*, (2001) 313-318.

[9] Gallagher, P.M. & Mitchell, J.K. Influence of colloidal silica grout on liquefaction potential and cyclic undrained behavior of loose sand. *Soil Dynamics and Earthquake Engng*. 22, No. 9-12 (2002) 1017-1026.

[10] Liao, H.J., Huang, C.C., & Chao, B.S. Liquefaction resistance of a colloidal silica grouted sand. In L.F. Johnsen et al. (Ed.), *Grouting and grout and deep mixing* (pp. 1305-1313). Proceeding of the Third International Conference. New Orleans, LA. Reston, VA: ASCE, (2003).

[11] Diaz-Rodriguez, J.A., Antonio-Izarras, V.M., Bandini, P. & Lopez-Molina, J.A. Cyclic strength of natural liquefiable sand stabilized with colloidal silica grout. *Canadian Geotech. J.* 45, No. 10 (2008) 1345-1355.

[12] Gallagher, P.M., & Finstere, S. Physical and numerical model of colloidal silica injection for passive site stabilization. *Vadose Zone J.* 3, No. 3 (2004) 917-925.

[13] Gallagher, P.M., Pamuk, A. & Abdun, T. Stabilization of liquefiable soils using colloidal silica. *J. of Materials in Civil Engng.* 33, No. 1 (2007) 33-40.

[14] Pamuk, A., Gallagher, P.M. & Zimmie, T.F. Remediation of piled foundations against lateral spreading by passive site stabilization technique. *Soil Dynamic and Earthquake Engng*. 27, No. 9 (2007) 864–874.

[15] Gallagher, P.M. & Lin, Y. Colloidal silica transport through liquefiable porous media. *J. of Geotech. and Geoenvironmen. Engng*. 135, No. 11 (2009) 1702–1712.

[16] Hamderi, M. Pilot scale modeling of colloidal silica delivery to liquefiable sand. *Ph.D dissertation, Drexel University. USA,* (2010).

[17] Moridis, G.J., Apps, J., Persoff, P., Myer, L., Muller, S., Yen P & Pruess, K. A field test of a waste containment technology using a new generation of injectable barrier liquids. Spectrum 96, Seattle, WA, (1996).

[18] Noll, M.R., Bartlett, C., Dochat, T.M. In situ permeability reduction and chemical fixation using colloidal silica. Proceedings of the Sixth National Outdoor Action Conference. Las Vegas, NV, (1992) 443-457.

[19] Gallagher, P.M., Conlee, C.T. & Kyle, M. Full scale testing of colloidal silica grouting for mitigation of liquefaction risk. *J. of Geotech. and Geoenvironment. Engng*. 133, No. 2 (2007) 186-196.

[20] Hamderi, M. & Gallagher, P.M. An optimization study on the delivery distance of colloidal silica. *Scientific Reserch and Essays.* 8 (27), (2013) 1314-1323

[21] Hamderi, M., Gallagher, P.M. & Lin, Y. Numerical model for colloidal silica injected column tests. *Vadose Zone J.* 13, No. 2 (2014) 138-143.

[22] Helland, P.E., Huang, P.H. and Diffendal, R.F. "SEM analysis of quartz sand grain surface textures indicates alluvial/colluvial origin of the quaternary "glacial" boulder clays at Huangshan (yellow mountain), east-central China", *Quaternary Research*, 48(2), (1997) 177-186.