Research Paper

Evaluation of uniform delivery of colloidal nano-Silica stabilizer to liquefiable silty sands

*Gh. Moradi [1]; Sh. Seyedi *, [2]*

[1]*Associate Professor, Faculty of Civil Engineering, University of Tabriz, Tabriz, Iran*
[2]*Ph.D. Candidate, Faculty of Civil Engineering, University of Tabriz, Tabriz, Iran*

ABSTRACT: Liquefaction is one of the most important and complex topics in geotechnical earthquake engineering. In recent years, passive site stabilization method has been proposed for non-disruptive mitigation of liquefaction risk at developed sites susceptible to liquefaction using colloidal nano-silica stabilizer. In this research, 4 box models were used to investigate the ability to uniformly deliver colloidal nano-silica stabilizer to liquefiable loose mixes of sand with variations in silt content from 0 to 30% using 5 low-head injection and 2 extraction wells. After delivery was completed the models were cured for 30 days. Then the treated soil was excavated and a few samples were extracted for dynamic loading testing. According to the results, colloidal silica can be delivered uniformly in silty sand formations. With the same conditions, the amount of fine grained soil (silt content) strongly affected delivery time. The passive stabilization method can be appropriate for deposits with up to 20% fine graded silt, a concentration of 5 wt% colloidal silica is expected to be able to effectively mitigate the liquefaction risk of these deposits. The strains during seismic cyclic loading will probably be less than 3% and little permanent strain should result.

Keywords: *Colloidal nano-silica; Earthquake; Liquefaction; Physical model; Stabilization; Silty sand.*

INTRODUCTION

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 at the edge of a site and deliver stabilizer to the target location using either natural or augmented groundwater flow. Colloidal nano-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 has excellent durability

characteristics [3, 4], it is chemically and biologically inert, and it is non-toxic [4, 5].

Use of colloidal silica for treating sands has been investigated by several researchers [6-11]. Yonekura & Kaga [6] proposed colloidal silica as a replacement for the most commonly used chemical grout, sodium silicate. 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 4.5 wt% colloidal silica is similar to the behavior of denser untreated sands. Gallagher& Mitchell [9] and Diaz-Rodriguez *et al.* [11] reported that a small amount of 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 to mitigate the liquefaction potential of loose sands [12-16]. Moreover, field-scale testing of colloidal silica for environmental remediation has been done in small, limited areas [17-19]. Numerical modeling has also been designed to simulate colloidal silica injection in sand

✉ *Corresponding Author: Shiva Seyedi
   Email: sh_seyyedi@tabrizu.ac.ir
   Tel.: (+98) 4133349371
   Fax: (+98) 4133392388

using iTOUGH$_2$, MODFLOW, and UTCHEM numerical simulation. The numerical model accurately represented the physical experiments [12, 20-21].

Although a few studies have investigated passive site stabilization method for treating sands, none have concentrated on the treatment of other liquefiable deposits, such as silty sands. Silty sand is a sandy soil with fine grained silt content. It has low hydraulic conductivity compared to pure sand. In this research, a box model was constructed to investigate the ability of the colloidal silica solution to permeate different mixes of sand with variations in silt content from 0 to 30% in a uniform manner under small gradients imposed by injection and extraction wells. During delivery, the concentration profiles across the model were monitored. After delivery was completed, the treated samples were extracted for cyclic loading testing.

EXPERIMENTAL
Materials

For this testing program, four different liquefiable soil samples were prepared and tested separately in a physical box model. The samples consisted of sand with variations in silt (fine-grained soil) content from 0 to 30%. The sand and silt used to prepare the samples were Firoozkooh No.161 sand and None-Plastic Firoozkooh silt respectively. Their gradation curves are shown in Fig. 1. Chemical analysis of Firoozkooh No.161 sand is also shown in Table 1.

To prepare the stabilizer material, SIGMA-ALDRICH Ludox®SM-30 wt% (suspension in water) was diluted to 5 wt%. Table 2 shows the characteristics of Ludox®SM-30 wt% according to SIGMA-ALDRICH product information.
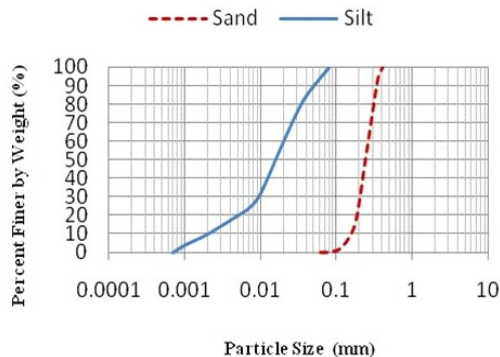

Fig. 1: Grain size distribution for Firoozkooh No.161 sand and Firoozkooh silt.

Table 1: Chemical analysis of Firoozkooh No.161 sand.

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 2: 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

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.

Methods

The box model used for the tests 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 60cm 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 sample to prevent soil loss from the central chamber into the reservoir.

The schematic pattern of the model setup is shown in Fig. 2. The left and right sides of the soil chamber are the upstream and downstream chambers, respectively. Sampling ports in the soil chamber are small taps, and their input sections are covered with filter paper. These

taps are used to extract fluid samples across the soil profile to measure changes in the pore fluid chemistry as the colloidal silica is transferred into the soil medium.

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.
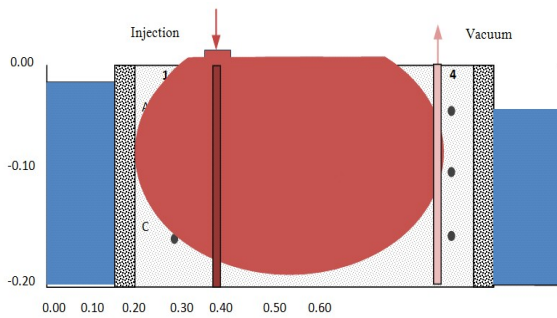

Fig. 2: Schematic pattern of model setup.

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 different liquefiable soil samples. The samples consisted of sand with variations in silt (fine-grained soil) content from 0 to 30%. The characteristics of the samples are shown in Table 3. To ensure of the accuracy of the results, two box model tests were repeated.

For each test, the soil chamber was filled by pouring the soil sample to a height of 20 cmunderloose 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 (5 wt%, 0.1 normality of NaCl) 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 sampling taps at different times. 20 mL specimens of the primary diluted colloidal silica solution (5 wt%) and each extracted pore fluid sample was weighted and placed in an oven at 80^{oc} 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.

Table 3: Characteristics of soil samples in box model testing.

Sample	Sand content (%)	Silt content (%)	Hydraulic conductivity (cm/s)
SM0	100	0	4.74×10^{-2}
SM10	90	10	1.21×10^{-2}
SM20	80	20	3.33×10^{-3}
SM30	70	30	6.81×10^{-4}

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

Index property	Content
Silica concentration	5 wt%
NaCl	0.1 Normality
pH	6-6.7
Gel time	24-48 hour
Viscosity	1.5 cP

After delivery of an adequate amount of colloidal silica in each model, the model was cured for 30 days and then excavated into a few block samples. The block samples were carved into smaller samples for cyclic triaxial testing. The cyclic tests were run in general accordance with ASTM D5311 standard method for load controlled cyclic triaxial strength of soil. Due to low hydraulic conductivity of the stabilized samples, the pore pressure response during cyclic loading could not be measured. Therefore, the axial strain during cyclic loading was used to quantify the results of the stabilized soil samples. Backpressure saturation was not done because it could disturb or destroyed colloidal silica bonds. The confining stress used for all cyclic testing was 100 kPa.

RESULTS AND DISCUSSION
Colloidal silica delivery results

The advancement of colored colloidal silica in box models testing was determined with visual monitoring and measurement of extracted pore fluid sample concentrations. A photograph of the box model test for colloidal silica progression in the soil sample of SM10 is shown in Fig. 3. During the periods of 4, 9, 27, and 45 hours, 18 liters (approximately 1.2 pore volumes) of colloidal silica solution (5wt%) was delivered to the soil samples of SM0, SM10, SM20, and SM30 in box model testing respectively. Because of variance in hydraulic conductivity of the soil samples, under identical conditions, a considerable difference in delivery time of colloidal silica occurred. The increase in delivery time of the colloidal silica in silty sand samples as a function of the silt content (fine graded soil) can be described by a time-silt content curve (see Fig. 4). The curve suggests the use of an exponential function of the form

$$t = a_1 \exp(a_2 m) \tag{1}$$

Which t and m are time of one liter of colloidal silica delivery in silty sand formation and silt content respectively, and, a_1 and a_2 are fitting parameters. The hydraulic conductivity of samples also followed an exponential function with silt content, so an exponential relation could be expected between delivery time of colloidal silica and silt content in model testing.

According to these results, colloidal silica can be delivered uniformly in silty sand formations. Under identical conditions, however, the amount of fine grained soil (silt content) strongly affected delivery

time. Because of the long delivery time of colloidal silica in silty sands with 30% silt, in practice,the passive stabilization method would be appropriate for deposits with up to 20% fine grained silt.
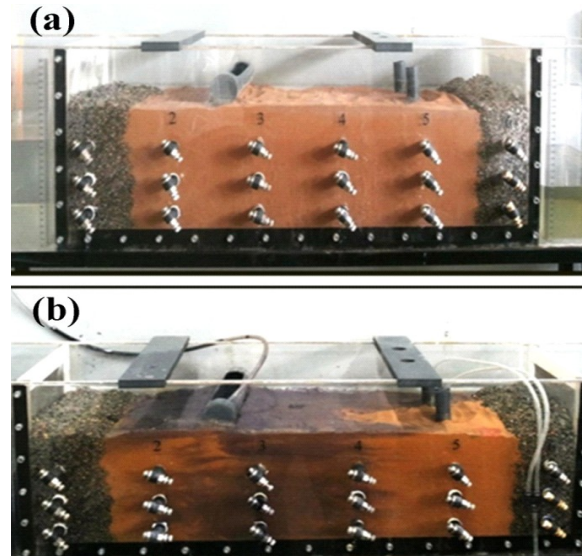

Fig. 3: Box model experiment for colloidal silica delivery study; (a) before injection; (b) during injection, flow is from left to right.
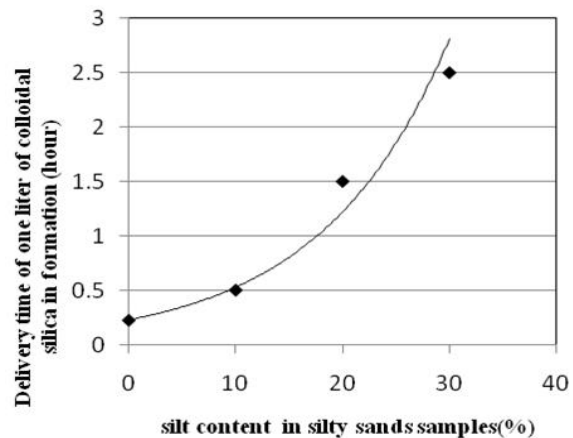

Fig. 4: Effect of silt content on the delivery time of one liter of colloidal silica in silty sand formation at box models.

Cyclic test results

The success of the colloidal silica treatment in box models testing was also evaluated by comparing the cyclic deformation resistance of treated and untreated soil samples. The deformation resistance of the stabilized samples of each model test was measured in

terms of DA axial strain, which is the largest difference in strain that develops during an entire cycle of compression and extension. If the stabilized samples accumulate less strain during cyclic loading than untreated samples at a given CSR, then the stabilization would be considered successful. The CSR is defined as the ratio of the maximum cyclic shear stress to the initial effective confining stress.

Cyclic triaxial testing was performed on a total of 8 samples measuring 5 cm in diameter and 10 cm in height. Of these, 4 were untreated samples with characteristics presented in Table 3, and Table 4 were treated samples

extracted from 4 box models after colloidal silica delivery. The samples were tested at a CSR of 0.2. Cyclic deviator stress during cyclic testing is shown in Fig. 5.

Distinctly different deformation properties were observed between treated and untreated samples. Untreated samples liquefied under dynamic loading. However, once liquefaction was triggered, large strains occurred rapidly and the samples collapsed. The pure sand sample (SMO) withstood a total of 7 cycles before it collapsed (see Fig. 6).The silty sand samples with
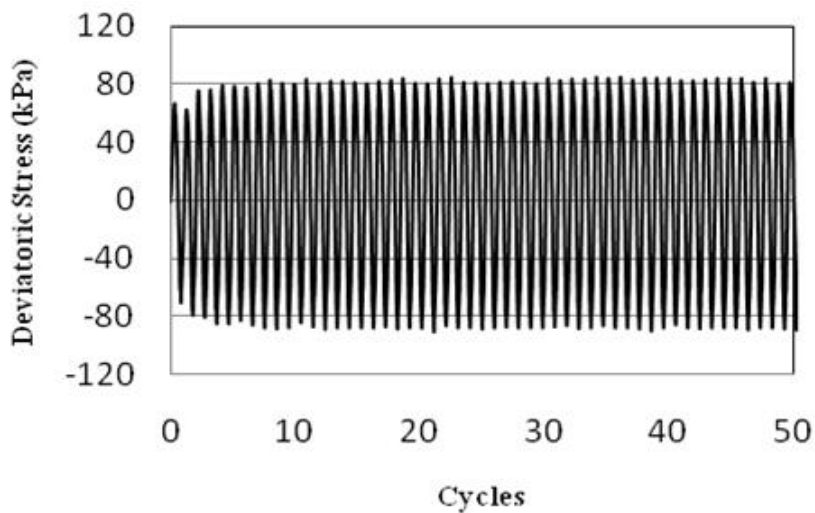

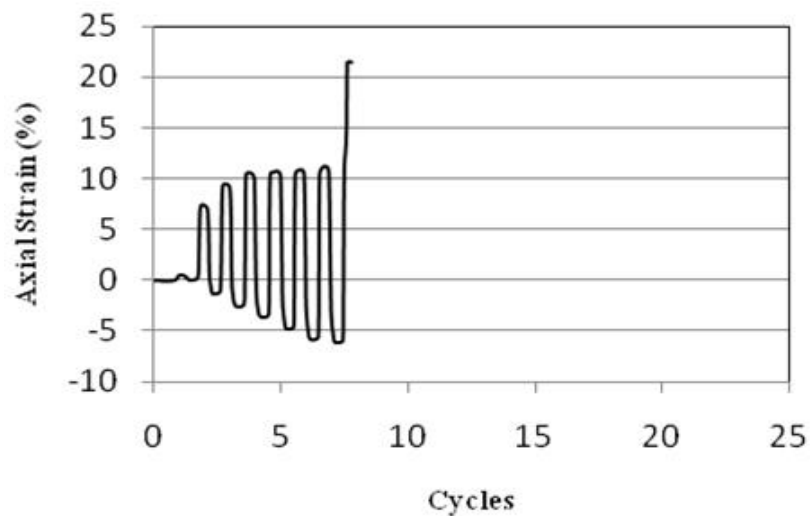Fig. 5: Cyclic deviatoric stress during cyclic testings in this study, CSR=0.2.

Fig. 6: Cyclic stress-strain behavior of untreated sand, Dr= 20%, CSR=0.2.

10%, 20%, and 30% silt (SM10, SM20, and SM30) collapsed immediately at the first cycle of loading.

In contrast, the axial deformation for samples at the same relative density and CSR, but treated with 5 wt% colloidal silica in box models, was much less. The first 100 cycles of tests on the 4 treated samples are shown in Figs. 7-10. The treated silty sand samples with 0%, 10%, 20%, and 30% silt (TSM0, TSM10, TSM20, and TSM30) reached approximately1.5%, 1.2%, 2.3% and, 2.5 % DA strain in 100 cycles. (see Table 5). The treated

samples never collapsed and all returned to their original height after cyclic loading. For comparison, a magnitude 7.5 earthquake would be expected to generate 15 significant uniform stress cycles [22]. The results of this study are according to the findings of Gallagher & Mitchel [5].

Based on these results, a concentration of 5wt% colloidal silica is expected to be able to effectively mitigate the liquefaction risk of saturated silty sand deposits during an earthquake.
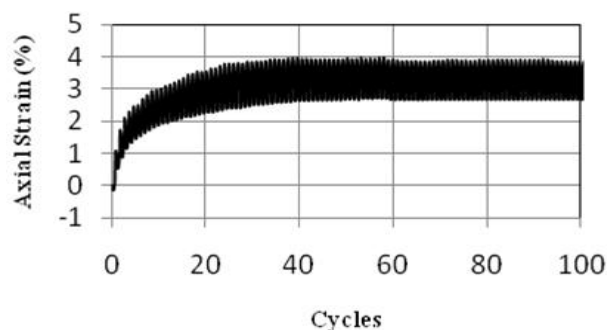

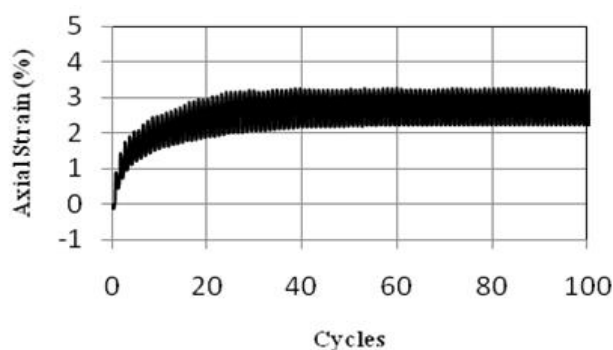Fig. 7: Axial deformation during cyclic loading for treated sand (TSM0), CSR=0.2.

Fig. 8: Axial deformation during cyclic loading for treated sand with 10% silt (TSM10), CSR=0.2.
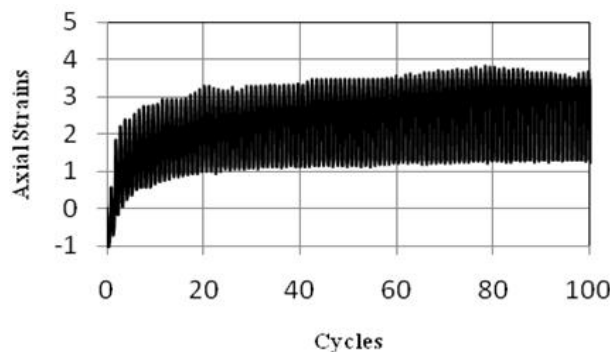

Fig. 9: Axial deformation during cyclic loading for treated sand with 20% silt (TSM20), CSR=0.2.
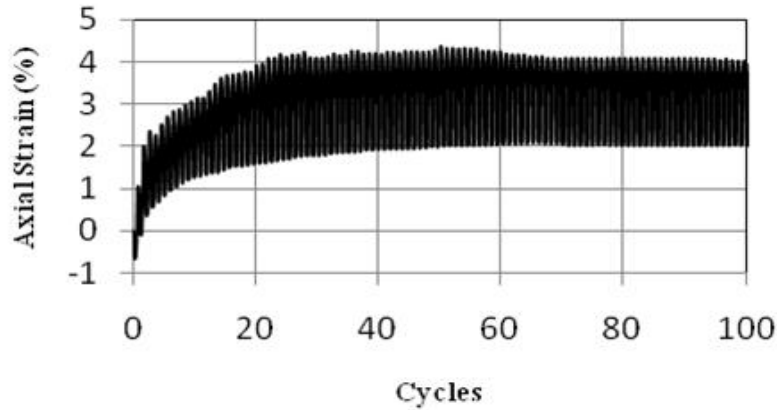
Fig. 10: Axial deformation during cyclic loading for treated sand with 30% silt (TSM30), CSR=0.2.

Table 5: Cyclic testing results (CSR=0.2).

Sample	Silt content (%)	Colloidal silica (wt%)	Condition	Number of cycles	DA strain (%)
SM0	0	-	Untreated	7	Collapsed
SM10	10	-	Untreated	1	Collapsed
SM20	20	-	Untreated	1	Collapsed
SM30	30	-	Untreated	1	Collapsed
TSM0	0	5	Treated in box model	100	1.5
TSM10	10	5	Treated in box model	100	1.2
TSM20	20	5	Treated in box model	100	2.3
TSM30	30	5	Treated in box model	100	2.5

CONCLUSION

Laboratory experiments were performed to examine the feasibility of nano colloidal silica stabilizer to permeate sand with different content of silt content in a low-gradient groundwater flow field.According to the results, there is an exponential relation between delivery time of stabilizer in formation and fine grained soil (silt). For passive site stabilization, a 5 wt% concentration of colloidal silica is expected to be able to uniformly deliver in silty sand deposits and adequately mitigate the liquefaction risk. The strains during cyclic loading would probably less than 3% and little permanent strain should result. Because of the long delivery time of colloidal silica in silty sand with 30% silt, in practice,the passive stabilization method would be appropriate for deposits with up to 20% fine grained silt.

REFERENCES

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

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

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

[4] Whang, J. M., (1995), 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.

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

[6] Yonekura R., Kaga M., (1992), Current chemical grout engineering in Japan. In R.H. Borden (Ed.), *Grouting, soil*

improvement and geosynthetics. (725-736). New York: ASCE.

[7] Persoff P., Apps J., Moridis G., Whang J. M., (1999), Effect of dilution and contaminants on sand grouted with colloidal silica. *J. Geotech. Geoenvironment. Engng*. 125: 461–469.

[8] Towhata I., Kabashima Y., (2001), 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*. 313-318.

[9] Gallagher P. M., Mitchell J. K., (2002), Influence of colloidal silica grout on liquefaction potential and cyclic undrained behavior of loose sand. *Soil Dynamics and Earthq. Engng*. 22: 1017-1026.

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

[11] Diaz-Rodriguez J. A., Antonio-Izarras V. M., Bandini P., Lopez-Molina J. A., (2008), Cyclic strength of natural liquefiable sand stabilized with colloidal silica grout. *Canadian Geotech. J*. 45: 1345-1355.

[12] Gallagher P. M., Finstere S., (2004), Physical and numerical model of colloidal silica injection for passive site stabilization. *Vadose Zone J*. 3: 917-925.

[13] Gallagher P. M., Pamuk A., Abdun T., (2007), Stabilization of liquefiable soils using colloidal silica. *J. Mater. Civil Eng*. 33: 33-40.

[14] Pamuk A., Gallagher P. M., Zimmie T. F., (2007), Remediation of piled foundations against lateral spreading by passive site stabilization technique. *Soil Dynamic and Earthq. Eng*. 27: 864–874.

[15] Gallagher P. M., Lin Y., (2009). Colloidal silica transport through liquefiable porous media. *J. Geotech. Geoenvironmen. Engng*. 135: 1702–1712.

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

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

[18] Noll M. R., Bartlett C., Dochat T. M., (1992), In situ permeability reduction andchemical fixation using colloidal silica. Proceedings of the Sixth National Outdoor Action Conference (443–57). Las Vegas, NV.

[19] Gallagher P. M., Conlee C. T., Kyle M., (2007). Full scale testing of colloidal silica grouting for mitigation of liquefaction risk. *J. Geotech. Geoenvironment. Engng*. 133: 186-196.

[20] Hamderi M., Gallagher P. M., (2013), An optimization study on the delivery distance of colloidal silica. *Scientif. Res. Essays.* 8: 1314-1323

[21] Hamderi M., Gallagher P. M., Lin Y., (2014), Numerical model for colloidal silica injected column tests. *Vadose Zone. J*. 13: 138-143.

[22] Seed H. B., Idriss I. M., (1982), *Ground motions and soil liquefaction during earthquakes*. Berkeley, CA: Earthquake Engineering Research Institute.