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ORIGINAL ARTICLE

Experimental study of applying colloidal nano Silica in improving sand-silt mixtures

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Abstract

Passive method is a new procedure in stabilizing loose soils. This methodology is a type of interlocking soil particles structures. In order to optimum improve in this method, it is necessary to achieve proper penetration length and increase the shear strength of parameters. Researchers have shown an increased resistance to liquefaction and decreased permeability due to colloidal Nano silica injection in soil. In this research, sandy soil was mixed with silt in 5%, 10%, and 15% percent. Then, specimens in dry and saturated conditions were placed under the influence of Nano silica colloid. For determining geotechnical properties of improved specimens, direct shear test was performed in three situations (dry, saturated, and injected). Moreover, for studying drainage condition after stabilizing specimens, constant head, permeability test was carried out. The results showed that geotechnical properties in the injected state increased compared to the non-injected state. Generally, this increase in cohesion and integral friction respectively on average in specimen's equal 2%, 1.18% and in saturate state equal 1.21%, 1.13%. Besides, with the injection of Nano silica colloid, the amount of vertical settlement in the samples on average 22% decreased. Furthermore, the amount of permeability of the stabilized materials showed on average 58% went down.

Keywords: *Colloidal Nano Silica; Injection; Sand; Shear Strength; Silt; Viscosity.*

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INTRODUCTION

Problematic soils are one of the important subject in construction projects can cause technical and engineering difficulties. Problems are including cracking in building, non-homogenous settlements in foundation and capillarity due to water table at low depths can create swelling in soil layers under foundation. Also, Liquefaction phenomenon due to earthquake is another type of problem can happen in loose saturate sandy and sandy silt soil layers. Selection of soil improvement method is depending on different factors as type of soil, percent of fines content (silt and clay), area and depth of improving, strength and compressibility, soil settlement criteria, access to technical skills, type of equipment, material and cost. Stabilization methods related to decreasing liquefaction potential in loose and saturate sandy and sandy silt soil layers include deep dynamic compaction of ground, vibro-compaction, stone columns, compaction grouting and jet grouting with very fines cement. Although, dynamic and vibratory methods for soil improving but is not suitable in urban areas. Methods related to jet grouting could be suitable for improving of granular soils, but preparing mechanical equipment and appropriate mixtures for grouting have high cost (FHWA-2017) (Table 1) [1].

Nowadays, nanoparticles have been use for soil stabilizing instead of applying traditional material. This material have fundamental impact on physical, chemical and engineering properties

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of soils for two reasons: firstly, increasing specific surface area, secondly, dominance of quantum effects. While, a size particle is fine, more percent of atomic and molecules are observed on surface. Therefore, surface properties (i.e. physical, chemical electrical and reactivity) will be important for sustainability process. Whereas, mass properties have becomes unimportant. In this research, for stabilizing and improvement of sandy and sandy silt soils colloidal Nano silica was used. For grouting colloidal Nano silica in soil passive method is applied. This procedure of soil stabilizing is suitable for urban area and sites have susceptible structures deformation due to vibrations. Also, this improvement method have some advantages such as possibility of soil improvement and performance modification in situ, saving time, reduce cost and unknown risks. Passive stabilization is a new way to improve developed areas with low space. This process begins through the injection wells in the upstream area of the desired area and leads to the extraction wells below the groundwater flow. Fig.

Table 1. Comparative unit cost by ground modification technology, November 2016 [1].

Category	Technology	Unit cost ($)
Vertical drains and accelerated consolidation	PVDs; with and without fill preloading	0.5-4 / 1ft
Lightweight Fills	Compressive strength fill; geofoam; foamed concrete	75-150/yd^3
Lightweight Fills	Granular fills; Wood fiber; Blast furnace slag; Fly ash; Boiler slag; Expanded shale; Clay and slate; Tire shreds	3-15/yd^3
Deep compaction	Deep dynamic compaction	10-30/yd^2
Deep compaction	Vibro-compaction	5-9/1ft
Aggregate columns	Stone columns and rammed aggregates piers	15-60/1ft
Column supported embankments	Column supported embankment	9/ft^2+cost of column
Column supported embankments	Columns: Non-compressible	30-80/1ft
Column supported embankments	Columns: compressible	20-100/1ft
Soil mixing	Deep mixing (dry)	60-125/1ft
Soil mixing	Mass mixing	15-75/yd^3
Grouting technologies	Chemical grouting	20/ft+0.65/qt
Grouting technologies	Compaction grouting	75-750/yd^3
Grouting technologies	Bulk void filling	50-150/ yd^3
Grouting technologies	Slabjaking	6.5-9.5/ft^2
Grouting technologies	Jet grouting	250-750/ yd^3
Grouting technologies	Rock fissure grouting	25-80/ft^2
Pavement support technologies	Mechanical stabilization	1-5/ yd^2
Pavement support technologies	Chemical stabilization	2-5/ yd^2
Pavement support technologies	Moisture control	3-12/1ft
Reinforced soil	Reinforced embankment	2-12/ yd^2
Reinforced soil	MSE walls	30-65/ft^2
Reinforced soil	Reinforced soil slopes	3-25/ft^2
Reinforced soil	Soil nail	20-50/1ft

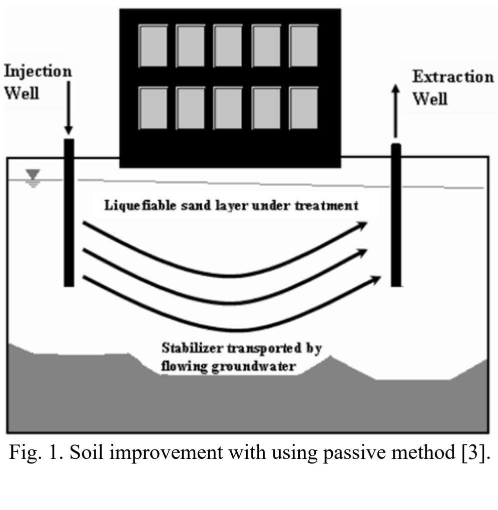


Fig. 1. Soil improvement with using passive method [3].

1 shows a model of this method in which a low viscosity material is slowly injected into susceptible liquefied soils. Earlier studies have been based on the non-passive stabilization feasibility and the identification of the appropriate stabilizing material, how to stabilize the correct position at the desired time, and the evaluation of the time and cost of this process [2, 3]. Through the use of different methods, injections could be improved in terms of strength and permeability (Table 2).

Nanotechnology in geotechnical engineering could be studied under two headings: first, soil particle structure studies on a nanometer scale. Second, this is better understanding of nature of the soil through recognizing the efficiency with different Nano structures. Soil manipulation at the atomic or molecular scale is usually facilitated by the addition of Nano materials as an external factor [5]. Dilute colloidal silica is a suitable stabilizer for improving loose sandy soils [2, 3]. It is a colloid suspended matter, the continuous phase of which is water and its dispersed particles of silica Nano particles and could be gelled by adjusting PH and ionic strength. One of the most important factors in hydraulic or electro synthetic injection is injection process [6]. As a harmless substance for the environment, Nano silica colloid has different uses in research and engineering projects. Gel is a process in which a silica colloidal solution forms a gel-shaped solid-state chain and then forms a three-dimensional and uniform grid. This process continues until it is completed. Increasing the ionic strength causes a break in the dual layer around the particles and increases the chance of particle collisions. Increasing the ionic strength causes a break in the dual layer around the particles and increases the chance of particle collisions. The presence of cations in underground water and exchangeable cations in soil could affect the gelation time. The shortest gelation time occurs in the range of 5< PH<7, and beyond this range, this time could be greatly increased [6]. After dilution and pre-gelation, there is an initial range of available viscosity, followed by a sudden increase in viscosity and subsequent gelatinization. The shape of this curve is generally different from gelation times [6]. Fig. 2 demonstrates changes in gel modulus for a diluted solution with 5% w and

Table 2. Soil improvement methods for liquefaction mitigation [4].

	Technique	Sand	Sandy silt	Silt	Accessibility
Densification	Dynamic Compaction	yes	feasible	feasible	No
	Vibro-Densification	yes	feasible	feasible	No
Densification/ Drainage/ Reinforcement	Vibro-stone column	yes	feasible	feasible	No
Solidification	Permeation grout	Yes (Fines ≤ 5%)	uncertain	No	yes
	Compaction grout	yes	yes	Marginal	yes
	Soil mixing	yes	yes	yes	No
	Jet grout	yes	yes	yes	yes
	Electro-kinetic injection	uncertain	yes	yes	yes
	Passive grouting	yes	Depend on hydraulic conductivity	Depend on hydraulic conductivity	yes

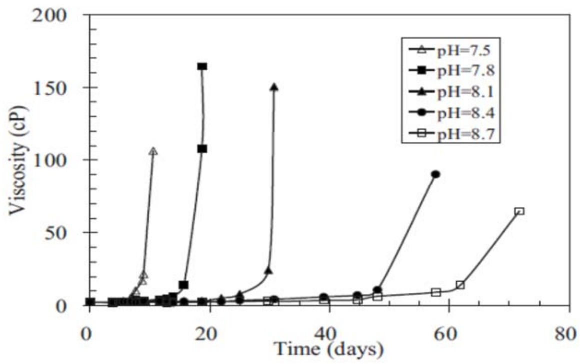


Fig. 2. Variations of viscosity versus time in several PH values for 5% colloidal Nano silica solution [6].

with ion strength of 0.1 for different PH values. The duration of viscosity remains variable, but the overall shape follows a similar process.

The time between mixing and rapid increase of viscosity could range from seconds to several months. During this time, the colloidal Nano silica solution acts as an evolving non-Newtonian fluid. When the viscosity reaches a value above 1000 cP, it behaves like a non-Newtonian fluid [7]. Persoff et al. presented a table to explain the gelatin states of gelation 1 to 11. Mode 1 is a time when the viscosity of the solution remains unchanged. In the latter case, the viscosity increases slowly. The solution then continues to increase viscosity in different conditions. In the state of 10, the material is rigid [8]. To determine the length of the penetration and the time of motion, it is defined from the onset of mixing to entering the second state, which occurs in the approximate value of the 4 cP viscosity, and the time of gelation is the time at which state 10 is obtained [6]. A model for calculating viscosity is presented in terms of time, in which the viscosity of silicon, which penetrates into length l at time t, is calculated from the logarithmic equation [6]:

$$\mu(l) = \mu_{(l)} = a_1 + a_2 exp(a_3) \qquad (1)$$

In the above equation, a_1, a_2 and a_3 are obtained from the fitting of the data obtained from the viscosity measurements. During the process of gelling, there are two opposing forces. There is the gravitational force between the particles that causes the gel to form and the shear forces that break the forming structure. Thus, in grout, it causes a breakdown of the molecular network. In this case, the viscosity is less than the amount of colloid solution in the stationary state at the same time as the mixing process.

Use of colloidal Nano silica for treating sand has been investigated by several researchers. Such as Yonekura and Miwa have used silica nanoparticles to increase the compressive strength of the sand. They showed that by adding 30% to the weight of Nano silica after 1000 days, soil resistance increased by 3.5 times [9]. Using nano-SiO2 in loose sand, Noll et al. could reduce the permeability and absorption of metals from the solution [9]. Persoff et al. found that in sandy soils, increasing the percentage of Nano silica raises the soil compression strength with a maximum increase of 400 KPa. Similarly, the permeation coefficient decreases with the addition of silica nanoparticles [10]. Gallagher and Mitchell have studied the effects of Nano-silica grout on the liquefaction potential and cyclic behavior of saturated loose sand. The results indicated that Nano silica significantly increased the resistance of loose sandy soil to changes in cyclic loading [3]. Gallagher and Lin argued for the reduction of soil liquefaction potential**.** Nano silica enhances soil cohesion and provides sufficient resistance to liquefaction. The results of uniaxial compressive strength test showed that the addition of 5% Nano silica to the weight of the soil is suitable for reducing liquefaction risk [8]. In order to reduce the settlement of soil layers, Hamderi et al. applied Nano silica as an additive in wells including sandy soils and created a liquefaction by explosion. After the explosion, almost 40% improvement in the amount of land was reported in the modified areas [11]. Through performing uniaxial compressive strength, triaxial and consolidation tests on a mixture of Nano silica and soils, Butron et al. found that the behavior of this soil is in the early stages elastic and then becomes elastoplastic. During the time when the soil mixed with Nano silica is exposed to vibration caused by the explosion, it could be less dangerous [12]. Taha studied the effect of nanotubes from pellet aggregates on soil geotechnical properties. Atterberg limit and uniaxial compressive strength tests were performed on kaolinite soil after the addition of Nano clay. The soil plasticity index including nano-clay decreased in comparison to the ones without Nano clay [13]. Abolhasani studied the effects of Nano silica and cement on bentonite. The findings showed that just Nano silica impacts bearing capacity in the short time. However, with applying cement and Nano silica in bentonite, simultaneous strength went up significantly [14]. Moradi et al. evaluated the effect of nanoclay silica on the improvement of silty sandy soils under dynamic loading in 2014 and 2017. They observed that silica Nano colloid could be used to increase the resistance to sand liquefaction by up to 30% [15, 22]. According to field studies conducted by Moridis et al. in 1996 [16] successfully used 30% (by weight) colloidal Nano silica to create subsurface barrier in unsaturated, heterogeneous deposits of silts, sands, and gravels. Due to its small Nano-sized particles, field test have shown that silica solution penetrate apertures smaller than 50μm. Based on this characteristics, a more recent application of colloidal silica was used as a way to seal narrow fractures in tunnels where hydraulic tests revealed a sealing efficiency of about 70% (Funehag and Fransson, 2005)[17]. Also, studies conducted by Bahadur et al. in 2007 [18], Funehag in 2012 [19] showed that colloidal Nano silica grouting could use for tunnel lining. Bahmani et al. in 2014 evaluated stabilization of residual soil using SiO_2 Nano particles and cement [20]. They found that with adding 0.4% Nano silica to cement compressive strength of residual soil improved up to 80%.Papatzani in 2016 evaluated effect of Nano silica and montmorillonite Nano clay particles on cement hydration and micro structure [21]. He observed that Nano silica solids in blended cement pastes should be limited to 0.5%. Whereas, Nano clay solids to almost 1% binder. Haeri et al. in 2017 researched on stabilization of collapsible soil with using Colloidal Nano Silica [23]. Their research results showed improvement of Gorgan city collapsible soil with adding 0.1% Colloidal Nano Silica was completed. Eswaramoorthi et al. in 2017 studied influence of Nano Silica and lime particles on the clayey soil behavior [24]. They observed that simultaneous applying 5% Nano Silica and 10% lime could be used to increase uniaxial strength of clayey soil. Hari Krishna et al. in 2017 assessed effects of Nano Silica and Meta kaolin on properties of recycled coarse aggregates concrete [25]. Results showed that with mixing 50% recycled coarse aggregates, 15% meta kaolin and 2% nano silica strength of concrete considerable went up. Furthermore, regarding the applications of colloidal Nano Silica in other branches of science, one can cite Kordani and Sadough Vanini [26], Abd Ellatief and Maitra [27], and Tayebee et al. [28]. The main purpose of this study is to investigate the effect of Nano silica colloid application on the improvement of bearing capacity of silty sand soils. Therefore, fines content is considered equal to 5, 10, and 15%. Furthermore, in the present study, the penetration length of Nano silica in silty sand soil by passive method, determination of appropriate gelation modulus for injection, and the rheological properties of Nano silica solution are discussed.

EXPERIMENTAL

Soils tested

The sand used in the study was Firoozkooh Sand (No.161), a commercially available material from Firoozkooh Mine in the North-East of Tehran. It is uniformly graded sand (SP) with a mean grain size of 0.25 mm, which is grain sub angular to sub rounded in shape**.** The non-plastic silt used in the testing program was derived from the fine-grained portion of the Firoozkooh silty sand. Fig. 3 (a, b) shows scan electronic microscope pictures of the material. Grain size distributions of the soils used in this study were evaluated according to ASTM D421 [29] and ASTM D422 [30] and proposed in Fig. 4. Clean sand with three mixtures of sand-silt was used in this study. The mixtures were obtained by mixing 5, 10 and 15 of silt with sand, respectively.

The specific gravity (Gs) values of mixtures were determined according to ASTM D854 [31] and proposed in Table 3. The minimum void ratio (e_{min}) was determined based on the vibratory table test according to ASTM D4253 [32] (Fig. 5). Also, the maximum void ratio (e_{max}) of the materials was evaluated according to ASTM D4254 [33]. The values are presented in Fig. 6. The studied soil specimens were prepared with a relative density of 40% so that the conditions were loose and therefore ready to be injected.

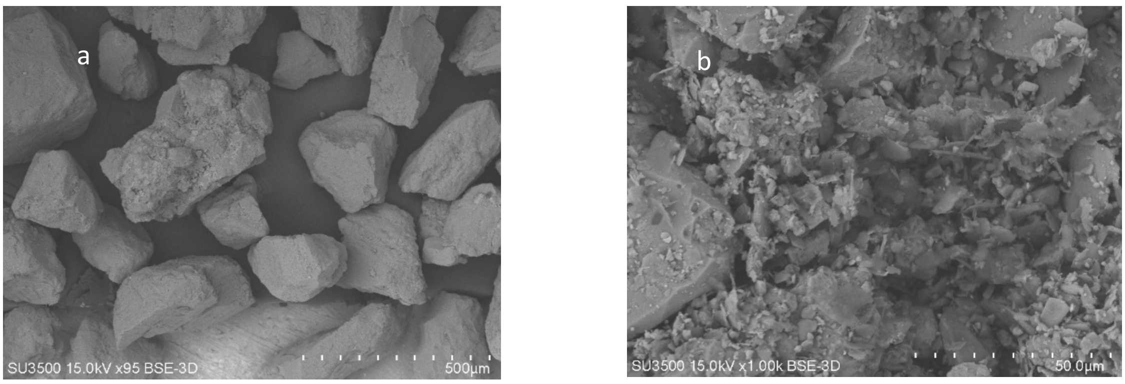


Fig. 3 (a, b). SEM pictures of materials in this study, a-sand, b-silt.

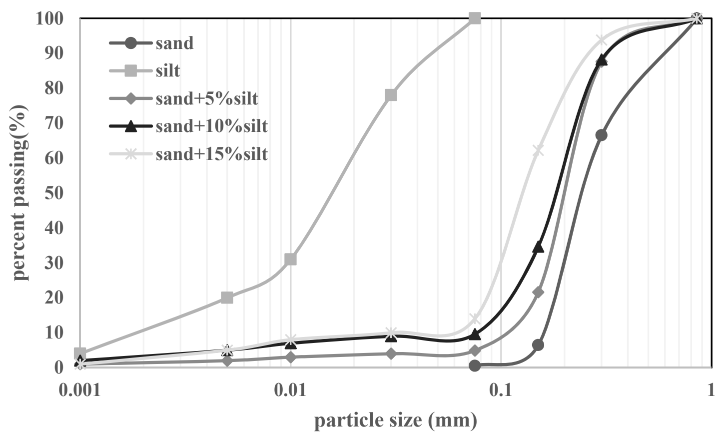


Fig. 4. Grain size distribution curves of materials in this study.

Table 3. Specific gravity (Gs) of values of materials.

Sand	Sand+15%silt	Sand+10%silt	Sand+5%silt
2.62	2.59	2.64	2.61

Colloidal Nano silica and specimen preparing

Colloidal Nano silica is used from commercially available materials supplied by MSA Company [34]. Properties of colloidal Nano silica (30%) can be seen in Table 4. The average size of colloidal Nano silica particles is 10 nm with PH greater than 7. For preparation of colloidal Nano silica solution (5%) for grouting to soil with ionic strength of 0.2 and a PH of 6.1, distilled water, concentrated hydrochloric acid (HCL) and sodium chloride (Nacl) added to concentrated solution.

Injection

Considering the percentage of relative density and the specific gravity evaluated for different mixtures, the required dry weight material was obtained for every 10 cm of the tube length for injection. Then, in a Plexiglas tube with a length of 1 meter and a diameter of 4 cm, every 10 cm of the material was poured over to form a uniform specimen in terms of structure. Afterwards, the water inlet and outlet ports, which have pneumatic holders, were connected at two ends of the tube and connected to the reservoir hinges at a height of two meters. The prepared solution was injected into the soil column in the tube with the specified characteristics of two meters high. The investigation of injection conditions was performed in sand and silt mixture with 5%, 10%, and 15% in two conditions. In the saturated state, water was first injected into the soil column in tube and replaced with a water reservoir after the flow of the water into the inlet and outlet of the Nano silica colloid was uniform. In the dry state, the reservoir was filled with colloidal Nano silica solution from the beginning and then injected. In the saturation mode, the amount of injected water as well as the flow rate at injection time could be obtained. But, in dry condition, in both cases, the amount of penetration

Fig. 5. Vibratory table apparatus in this study.

length could be measured by adding a colored material to the initial solution. A view of the injection device is fully illustrated in Fig. 7.

Saturate condition

At this stage, three injections were carried out in the studied materials in which a total of 9 injection tests were performed after making the desired solution and preparing the corresponding soil specimen. The average results of the discharge (rate of flow), penetration length and viscosity at speeds of 30 and 60 rpm are presented in Figs. 8 and 9. It is noteworthy that the relative density of the studied specimens is 40%, and the measured values for the length of one meter solution penetration are available in the specimen. Based on Fig. 8 (a, b), it could be seen that with an increase in the percentage of fines content material in sandy soils, the time required to move and penetrate the solution also rises. In addition, it could be seen that with increasing the percentage of fines content discharge, the solution output from the samples slows down due to the spillage of the pores by fine particles. As a verification of the results, the soluble viscosity values of the studied samples could be seen in Fig. 9 (a, b). The smaller the percentage of fine content, the faster the fixation at a high viscosity. Conversely, when the amount of fine grained soil reaches 15%, due to a growth in viscosity, the duration of fixation

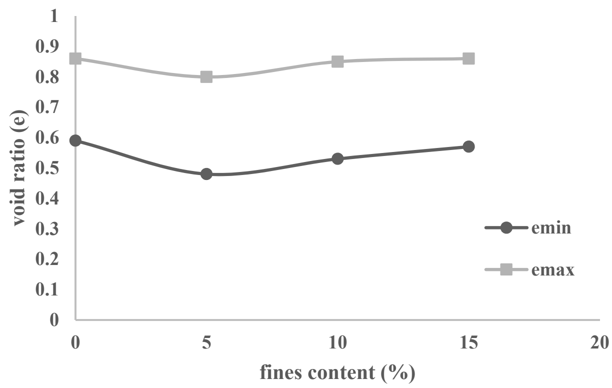
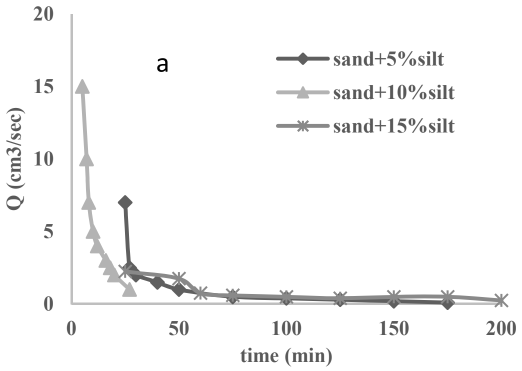


Fig. 6. Variations of maximum and minimum void ratios of materials.

Table 4. Colloidal Nano silica properties in this study [34].

SiO_2 content (%)	30±0.5
PH value	9.5 to 10
Mean particle diameter (nm)	9.30 to 10.5
Surface area (m^2/g)	250 to 280
Specific gravity at 25°c (gr/cm^3)	1.2 to 1.218
Viscosity at (on Ford B cup) 27°c (in seconds)	12.5 to 13

Fig. 7. Injection pipe with L=1m and D=4cm in this study.



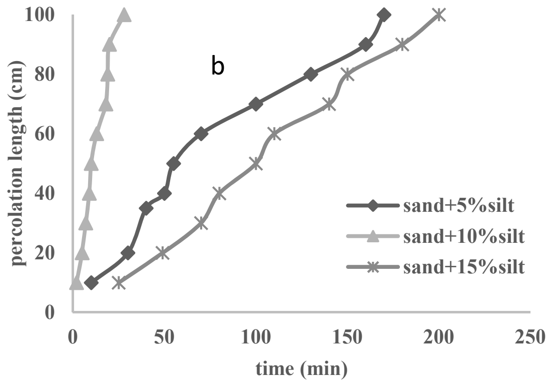
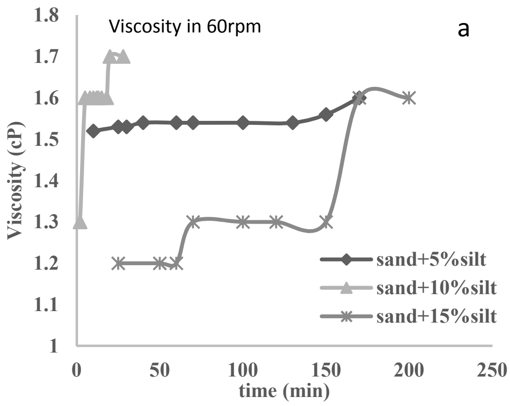


Fig. 8 (a, b). Injection in saturate condition: a-fines content effects on outflow solution versus time, b- effects of fines content on percolation length versus time.



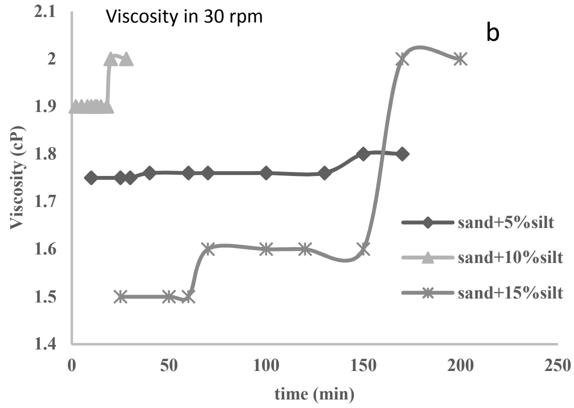


Fig. 9 (a, b). Effects of fines content on solution viscosity variations versus time: a- Viscosity in 60 rpm, b- Viscosity in 30 rpm.

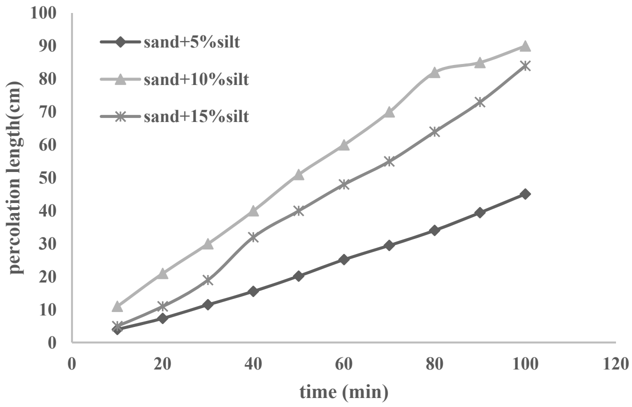


Fig. 10. Variation of penetration length versus time.

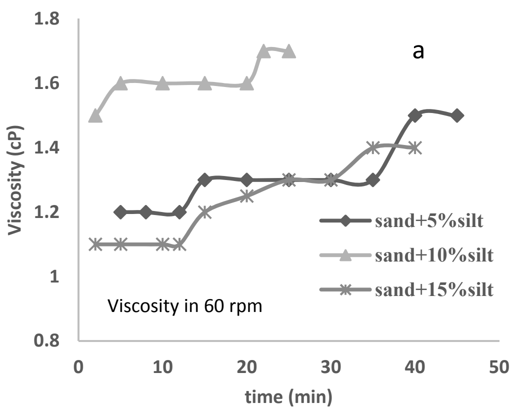
increases, thereby resulting in reduced hydraulic conductivity in the sample. In the case of sand samples containing 10% silt, flow variation rate is not very noticeable. Finally, it could be stated that in low viscosity and 40% relative density, as long as the viscosity is less than 2 cP, the injection rate in the 15% silt is also possible and responds to one meter penetration length. However, as the viscosity rises, the hydraulic conductivity decreases and as a result, the passive state of the discharge is lost, and the soil becomes dense. Accordingly, penetration stops.

Dry condition

In dry state specimens before injection, water has not entered in the porous medium. Therefore, flow rate cannot be checked. It is only available by assessing the penetration time of the injection method. Changes in penetration length and its corresponding viscosity in two different speeds for the studied specimens are shown in Figs. 10 and 11 (a, b). In all injections in the dry state, due to the appropriate viscosity selection, injection was fully performed. In sandy soils with 5 and 10 %silt, it could be seen that the penetration process is associated with a reduction in penetration rate, as in previous scenarios. This phenomenon could be obtained by reducing the infiltration slope in terms of time. It is relatively close to the time of full injection with the saturated state. In the sand with 15% silt, the viscosity is also suitable for successful injection. A similar behavior in the injections is due to the fact that an increase in viscosity reduces the penetration rate during injection. For this reason, the choice of a solution with proper properties, even in soils with 15% non-plastic fines content helps to stabilize loose soils.

Procedure

As mentioned previous parts, the main purpose of this study was to improve and increase bearing capacity of sand-silt mixtures by using injection colloidal Nano silica. For evaluating the



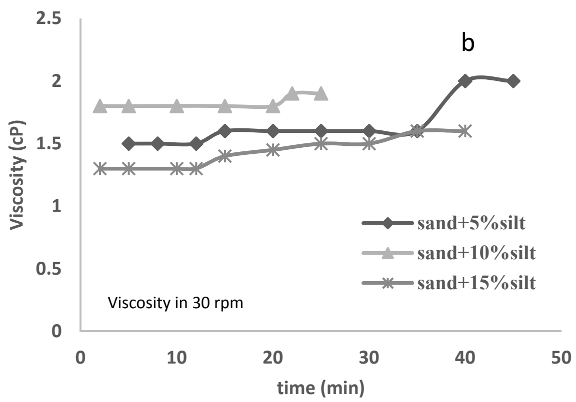


Fig. 11 (a, b). Variations of solution viscosity versus time in dry condition: Viscosity in 60 rpm, b- Viscosity in 30 rpm.

Fig. 12. Specimen preparing with the injection of colloidal Nano silica for direct shear test.

geotechnical properties of the stabilized sand-silt mixtures, a direct shear test was performed according to ASTM D3080-98 [35]. This experiment was performed in three vertical stress 40, 80, and 120 kPa in three states (i.e., dry without injection, saturate, and injected Nano silica colloidal conditions). The dimensions of the square sample were 6 cm. The speed of the strain rate was 0.3 mm/min. In order to prepare the injection conditions in the materials as shown in Fig. 12, new prototype molds were made of polymer and wood materials with pneumatic inputs and outputs. It should be noted that the curing time of the injected samples is 1 month. Fig. 13 illustrates how to perform a direct shear test in saturated and without injection modes.

Furthermore, to determine the permeability of samples stabilized by Nano Silica colloid before and after treatment, the constant load permeability test was performed according to ASTM D2434-68 [36].

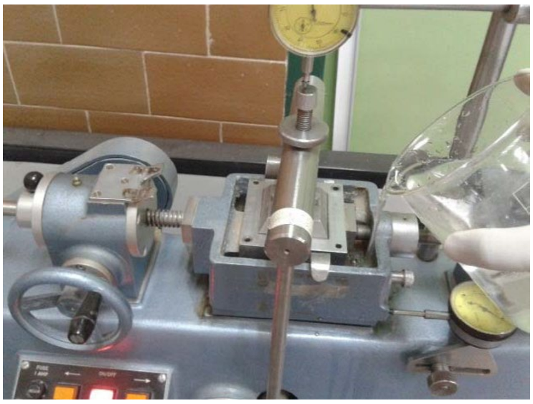


Fig. 13. Performing direct shear test in specimen with saturated condition.

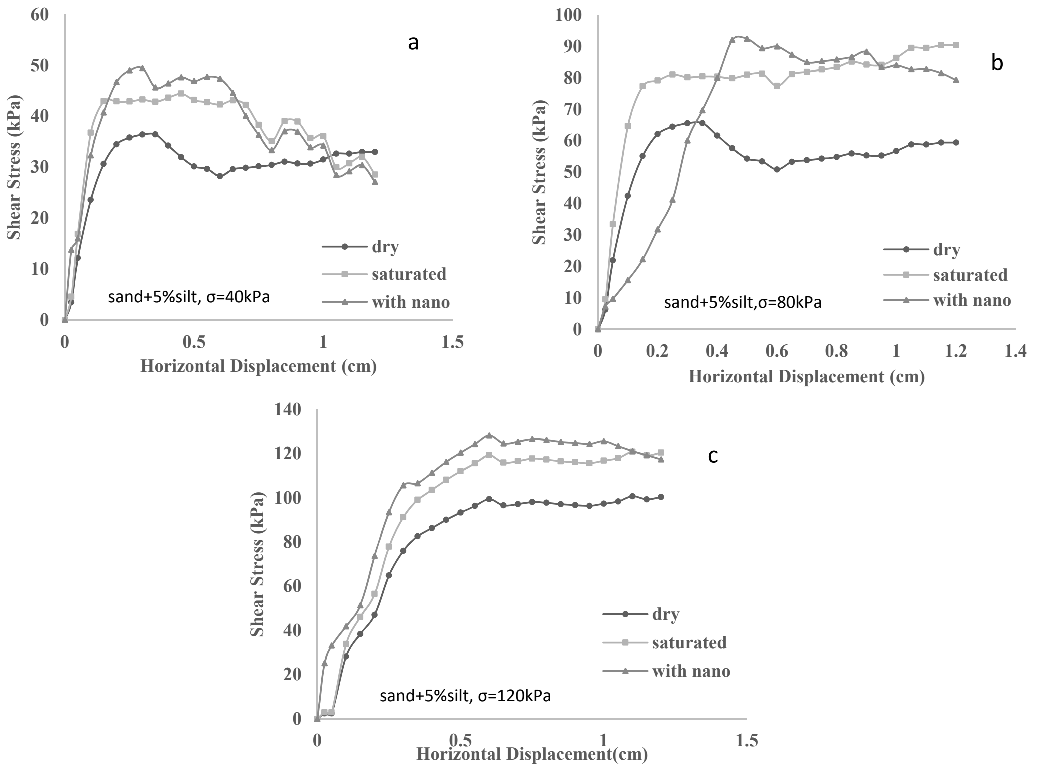


Fig. 14 (a, b, c). Variations of Shear stress versus horizontal displacement in specimens, a- Sand+5%silt (σ_v=40kPa), b-Sand+5%silt (σ_v=80kPa), c-Sand+5%silt (σ_v=120kPa).

RESULTS AND DISCUSSIONS

The results of the direct shear test on the specimens are as follows:

1- An example of shear stress variations versus horizontal displacement on the specimens is shown in Fig. 14 (a, b and c). Based on the obtained results, it could be seen that in all modes, in comparison with the dry specimens, the specimens with Nano silica colloidal injections have the highest shear strength, and then the saturated samples have the highest possible bearing capacity.

2-. Based on the results, it could be seen that the specimens in the dry state generally have the lowest vertical displacement. The saturated samples have the highest vertical settlement. When the Nano silica colloid is stabilized in the samples, it is observed that according to low and medium overburden stress (σ_v) vertical displacements keep occurring. In contrast, in high overburden stress, vertical displacement rate decreased. An example of the vertical displacement changes is given in Fig. 15 (a, b and c).

3- Concerning direct shear test, one of the important results is the evaluation of the vertical strain rate versus shear strain. Based on the findings, it could be seen that in general, saturated samples have the highest strain, while dry samples have the minimum amount for vertical strain. When Nano silica colloid is injected into the samples, it is evident that the vertical strain rate is controlled compared to the saturation state, but is not optimum. An example of the results is provided in Fig. 16 (a, b, c).

4- The effect of Nano silica colloid on geotechnical properties parameters of the specimens was studied, and its results are shown in Fig. 17 (a, b). Based on the findings, it could be seen that when the mixtures specimens were tested dryly, with an increase in the fines content in the sand the amount of cohesion increased and the angle of internal friction decreased. Also, we found that that in saturation state the cohesion and the angle of the internal friction in the specimens increased in general compared to the dry state. But with raising fines content in the sand the degree of internal friction angle decreased. Although, cohesion went up. Finally, by injecting Nano silica colloid into sand-silt mixtures, we observed that the highest cohesion values and internal friction angle were created in comparison

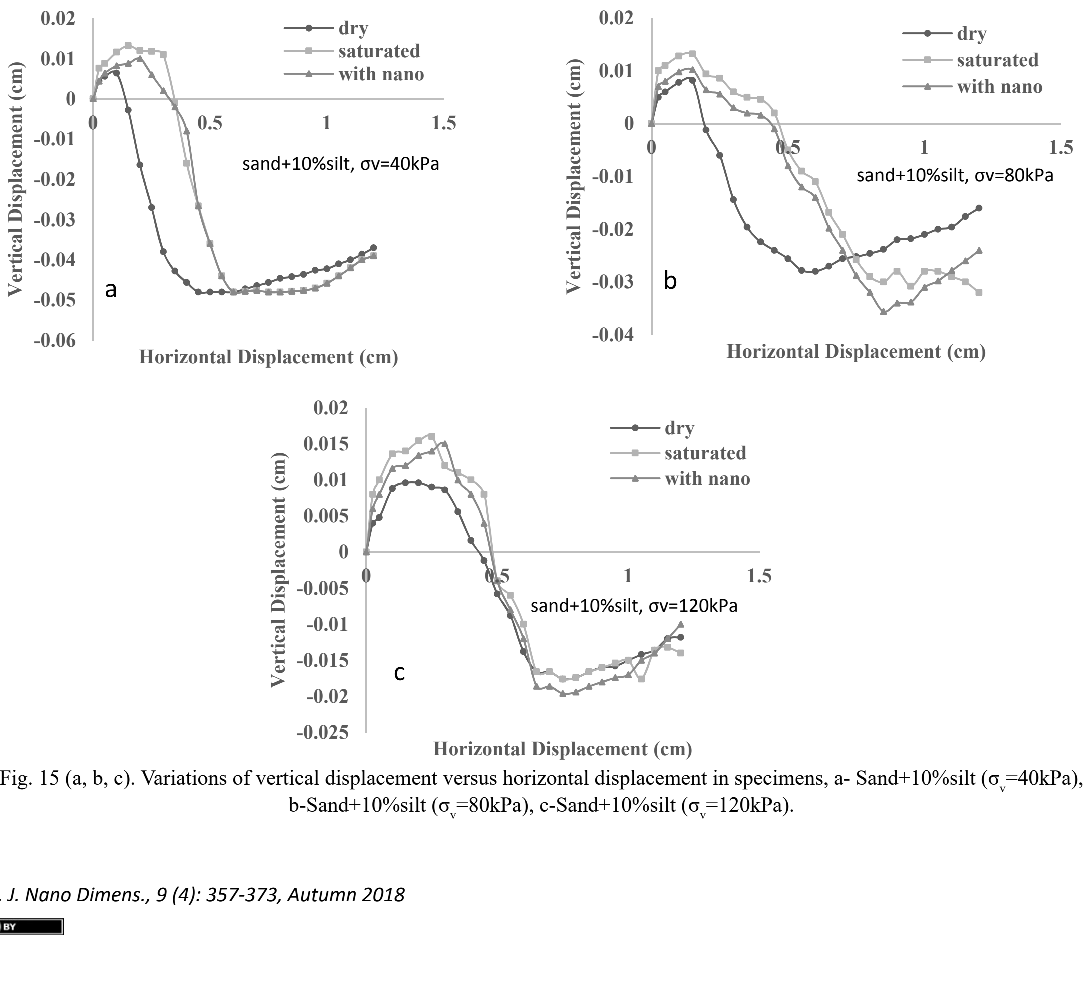


Fig. 15 (a, b, c). Variations of vertical displacement versus horizontal displacement in specimens, a- Sand+10%silt (σ_v=40kPa), b-Sand+10%silt (σ_v=80kPa), c-Sand+10%silt (σ_v=120kPa).

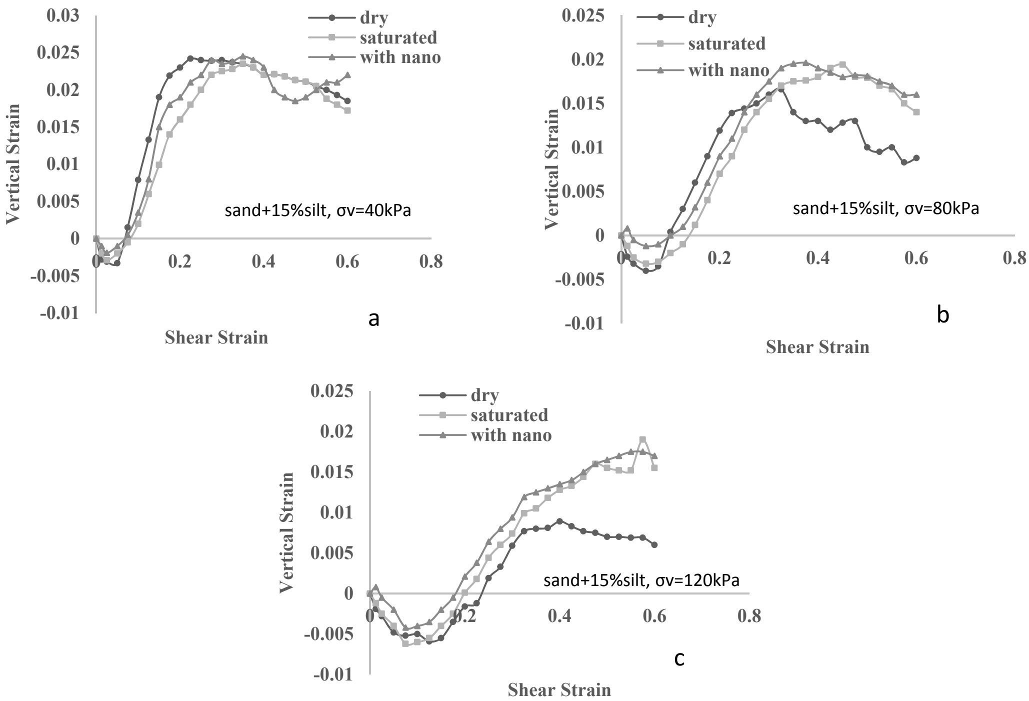


Fig. 16 (a, b, c). Variations of Vertical strain versus horizontal strain in specimens, a- Sand+15%silt (σ_v=40kPa), b-Sand+15%silt (σ_v=80kPa), c-Sand+15%silt (σ_v=120kPa).

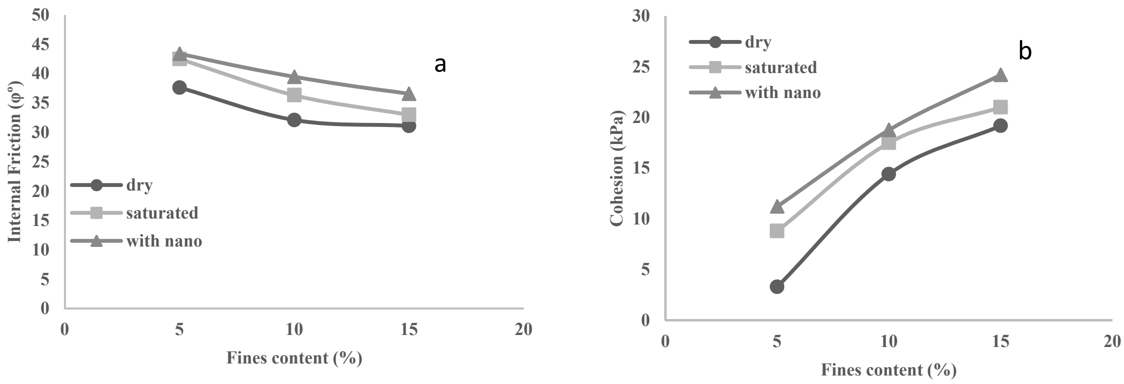


Fig. 17 (a, b). Effects of colloidal Nano silica on shear strength parameters, a- Internal friction, b- Cohesion.

to the previous ones. Nevertheless, similar to previous studies with increasing the amount of fine contents the value of cohesion went up and the angle of internal friction decreased.

5- The effect of Nano silica colloid on shear strength at the failure of the specimens was evaluated, the results of which are shown in Fig. 18 (a, b and c). Based on the findings, it could be concluded that in general, the shear strength increase with a rise in the percentage of fines content at the moment of failure. Furthermore, when the Nano silica colloids are injected into sand-silt mixture, it could be seen that in all fine content rates the shear strength at failure is in its highest compared to the other ones.

6- The effect of Nano silica colloid on the maximum vertical strain rate of the sand-silt mixtures was compared, the results of which are shown in Fig. 19 (a, b and c). Based on the obtained results, the maximum vertical strain rate could be increased in tandem with increasing vertical stresses. Also, the highest strain rate occurred

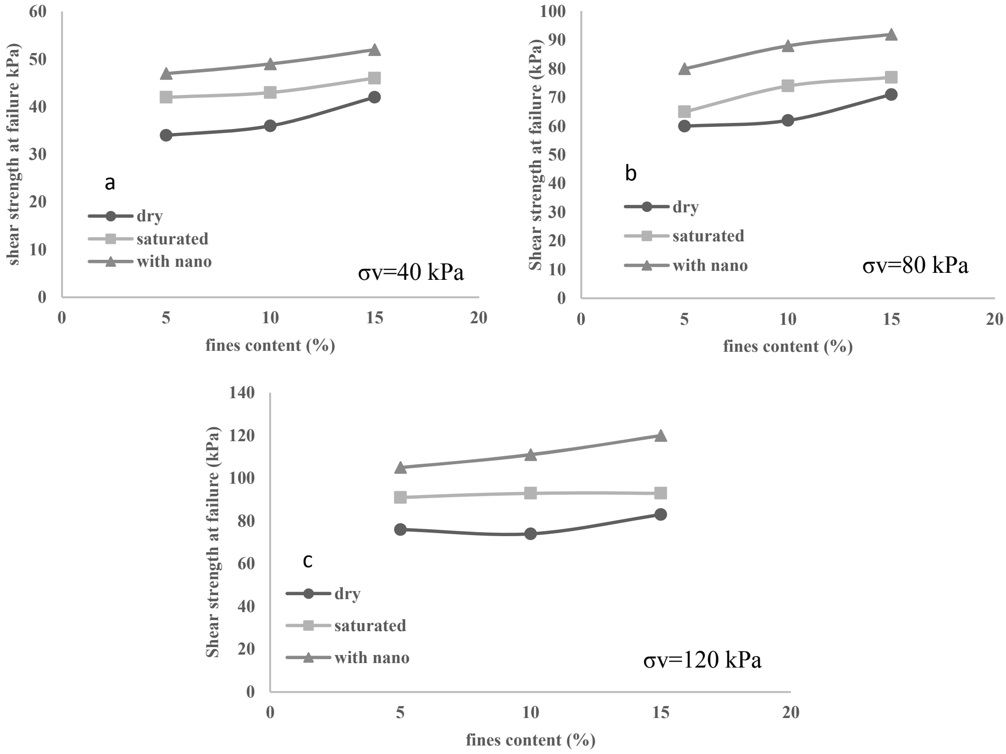


Fig. 18 (a, b, c). Effects of colloidal Nano silica on shear strength at failure in specimens, a-σ_v=40kPa, b- σ_v=80kPa, c- σ_v=120kPa.

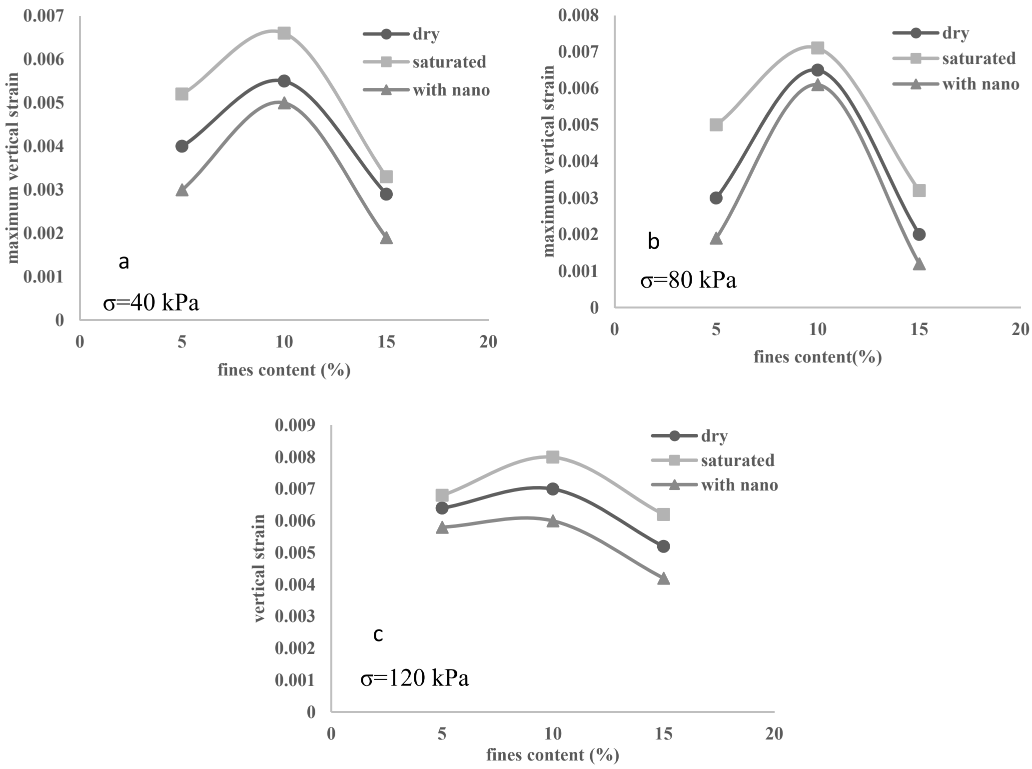


Fig. 19 (a, b, c). Effects of colloidal Nano silica on maximum vertical strain (settlement) in specimens, a-σ_v=40kPa, b- σ_v=80kPa, c- σ_v=120kPa.

when 10% of the silt was added to the sand. Besides, when the percentage of fine contents reached 15, it was observed that the lowest vertical settlement occurred in the specimens. In addition, by comparing the graphs, it could be seen that the vertical strain rate in all samples is high in the saturated state compared with other situations, and when the colloidal Nano silica was injected into the soil samples, the minimum settlement and maximum vertical strain occurred.

7- The results of the constant permeability test on sand-silt mixtures are shown in Fig. 20. Similar to the findings of Noll et al. at 1992 [8], it could be seen that the value of permeability decreased in specimens stabilized with Nano silica colloid. Also, the amount of permeability decreased by increasing the percentage of fine particles.

CONCLUSION

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. Also, results of recent researches such as Dabiri et al. in 2011 [37], Askari et al. in 2011 [38]. Showed that liquefaction phenomenon could be happened in sand-silt mixtures. Therefore, in this research effect of colloidal Nano silica on improving sand-silt was evaluated. In present research, Firoozkooh sandy soil mixed up with silt in 5%, 10% and 15%. Afterwards, based on direct shear test performed through ASTM D3080-98 [35], the geotechnical parameters of the mixtures are studied. Finally, permeability of stabilized sand-silt mixtures was determined with using ASTM D2434-68 [36]. Similarly, the amount of penetration length during Nano silica colloid injection was investigated. In this study, the solution properties included weight, PH, ionic strength, and viscosity measured and evaluated. The overall findings of the present study could be summarized as follows:

1- According to the results of the injection in saturated sand-silt mixtures, a decrease in the flow rate with an increase in time and the corresponding increase in viscosity are clearly evident. The viscosity of the solution was measured at two different speeds and at two shear strain rates. The penetration rate decreased with increases in injection time. This is also proportional to the decrease in flow rate. A set of injections in saturated soils shows that in low viscosity and a relative density of 40%, as long as the viscosity is less than 2 cP, the injection rate is also possible in 15% silt rate and is optimal for 1 meter penetration length. However, as viscosity rises, hydraulic conductivity decreases and as a result, the passive state of the discharge is lost. Thus, the soil becomes compacted, thereby stopping penetration.

2- In specimens of dry materials, there is no possibility of checking the flow and the injection method. Injection behavior is only understood by measuring penetration length. In all injections, it

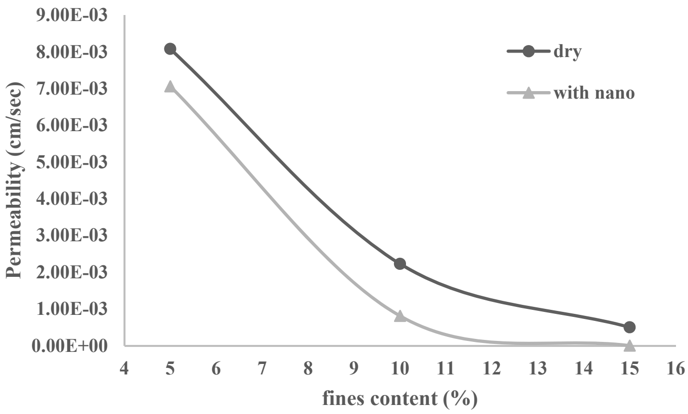


Fig. 20. Effects of colloidal Nano silica on permeability in specimens.

is observed that increasing viscosity reduces the penetration rate during injection. The findings revealed that the choice of a solution with proper properties. Even in sandy soils with 15% silt helps to stabilize loose soils.

3- In terms of geotechnical parameters, it is observed that the cohesion values in the injected state increased compared to the non-injected state. Compared to dry state, these increases in 5%, 10%, and 15% percent silts were found to be 3.4%, 1.34%, and 1.26%, respectively. When compared to the saturation state, these increases were 1.28%, 1.07%, and 1.28%, respectively. Similarly, increasing the angle of friction in the injected state rather than the dry state for 5, 10, and 15% was 1.15%, 1.23%, and 1.17%, respectively. The internal friction angle in the injected state was 1.02%, 1.07%, and 1.29 % relative to the saturation state for 5, 10, and 15%, respectively. In general, according to Moradi et al. [14, 21], it could be seen that the increase in the parameters of the shear strength obtained from the direct shear strength in the injected state is greater than that of the dry state in comparison to the increase in the saturation state, which allows liquefaction.

4- By observing the results of a constant-height permeability test, we found that that the amount of permeability coefficient decreased in post-treatment stabilized specimens, indicating improved permeability properties in the tested soils. These conditions cause the drainage conditions to decrease in sand-silt mixtures and reduce the risk of possible earthquake-induced liquefaction.

5- Passive site stabilization was proposed by Gallagher in 2000 [2] is a new technique whereby colloidal silica stabilizer under low heads and then transported beneath the site with the flowing ground water. It can be advantageous at sites with restricted access that are not well suited to treatment by conventional methods. It should be noted that passive site stabilizing method was proposed for reducing liquefaction risk due to earthquake in saturate loose granular soils. Therefore, variation of ground water level does not effect on performance of this method. Also, colloidal Nano silica mixed up with water, high resistance particle is formed. Then, particles with absorbing water can create cemented structures between aggregates of soils. This condition cause increasing of cohesive, reduction of void ratio and rising up dense in soil.

Table 5. Cost comparisons of colloidal silica and other stabilizing materials [2].

Treatment	Cost per m^3 soil
Colloidal silica (5%)	60$
Colloidal silica (15%)	180$
Microfine cement	100-200$
Sodium Silicate	180$
Acrylmide	500$

6- As mentioned previous parts, Gallagher (2000) [2] established the feasibility of passive site stabilization by identifying colloidal silica as a suitable stabilizer and testing it, determining the liquefaction resistance increase when the stabilizer was used to treat samples, modeling delivery techniques using computer methods, and performing a cost analysis. Passive site stabilization is expected to be competitive with other types of grouting soil modification methods (have costing $60-$100) per cubic meter of treated soil (Table 5). Additionally, colloidal Nano silica is cost competitive with other potential stabilizing materials and procedures (Table 1). With comparison between soil modifications technologies in Table 1 and Table 5 can observe that cost of colloidal Nano silica is so low than other technologies. Also, colloidal Nano silica (30%) used in this research was so concentrated. This condition was effective in gelation time, then, HCL and Nacl added to colloidal Nano silica (30%) to dilute solution. In final, colloidal Nano silica (5%) was prepared and used for stabilizing specimens. In Iran for preparation of solution about cost equal with 60000 Rials needed. Therefore, it can be expressed that stabilizing of sandy and sandy silt soils with loose and medium relative density with using colloidal Nano silica in closed urban area from the point view of time save time and cost. Also, colloidal Nano silica has also been found to be permanent, nontoxic, biologically and chemically inert, and has excellent durability characteristics (Iler, 1979 [39] and Whang, 1995 [40]).

Therefore, with regard to the above findings it could be noted that with time the amount of injected rate of flow decreases in both dry and saturated states. The reason is that both the hydraulic gradient decreases with increasing penetration length and that the increase in viscosity reduces the hydraulic conductivity and decreases the movement in the soil. Besides, in high levels of viscosity the injection at the height of the load used in the tests causes the specimen to be compressed loose. Alternatively, if passive state is injected, it becomes condensed. This sometimes leads to damage of the way soil particles are deposited and occasionally with the closure of the pores the fines are cut off and do not continue to be injected. Although increasing the percentage of virtual cohesion amount as in the direct shear test is larger, this trend of cohesion is seen in all three test modes, namely dry, saturated, and injected. Increasing the silt also reduces the internal friction angle. This behavior was observed in all three modes. In the injected mode, increasing the percentage of fines content indicates the same behavior as noted in previous conditions. However, with the injection of colloidal Nano silica to sandy soils with 5 to 15 %, which is the target area of this study, soil stabilization increased.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

REFERENCES

[1] FHWA, (2017), Ground modification methods reference manual. *U.S. Depart. Trans. Feder. High. Admin.* Vol. 1 and Vol. 2. Publication No. FHWA- NHI -16-028.

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

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

[4] Thevanayagam S., JIA W., (2003), Electro-osmotic grouting for liquefaction mitigation in silty soils. *Geotech. Spec. Pub.* 2: 1507-1517.

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

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

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

[8] Gallagher P. M., Conlee C. T., Rollins K. M., (2007), Full-scale field testing of colloidal silica grouting for mitigation of liquefaction risk. *J. Geotech. Geoenvironm. Eng.* 133: 186-196.

[9] Noll M. R., Bartlett C., Dochat T. M., (2007), In situ permeability reduction and chemical fixation using colloidal silica. *Proc. 6th National Outdoor Action Conf. Aquifer Restoration*. (443-57), Las Vegas, NV.

[10] Persoff P., Apps J., Moridis G., Whang J. M., (1999), Effect of dilution and contaminants on sand grouted with colloidalsilica. *J. Geotech. Geoenvironmen. Eng.* 125: 461-469.

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

[12] Butron C., Axelsson M., Gustafson G., (2009), Silica sol for rock grouting: Laboratory testing of strength, fracture behaviour and hydraulic conductivity. *Tunnel. Under. Space Techn.* 24: 603-607.

[13] Taha M., (2009), Geotechnical properties of soil-ball milled soil mixtures. *Nanotechnol.Construction*. 3: 377-382.

[14] Abolhassani M., (2011), Study of mechanical properties of bentonite stabilized with Nano silica and Cement. *Ms.c. Thesis*. KNT University, Tehran, Iran.

[15] Moradi Gh., Seyedi Sh., (2014), Evaluation of uniform delivery of colloidal nano silica stablizer to liquefiable sily sand. *Int. J. Nano Dimens.* 6: 501-508.

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

[17] Funehag J., Fransson A., (2005), Sealing narrow fractures with a Newtonian fluid: Model prediction for grouting verified by field study. *Tunnel. Under ground Space Technol.* 21: 492-498.

[18] Bahadur A. K., Holter K. G., Pengelly A., (2007), Cost-effective pre-injection with rapid hardening microcement and colloidal silica water ingress reduction and stabilization of adverse conditions in a headrace tunnel. *Underground Space, The 4th Dimension of Metropolises-Bartak, Hrdina, Romancov and Zlamal (eds)*.

[19] Funehag J., (2012), Guide to grouting with silica sol for sealing in hard rock. *Befo report 118, Rock Engineer. Research Found., Chalmers University of Technology*.

[20] Bahmani S. H., Huat Bujang B. K., Asadi A., Farzadnia N., (2014), Stabilzation of residual strength soil using SiO_2 nano particles and cement. *Const. Build. Mater*. 64: 350-359.

[21] Papatzani S., (2016), Effects of nano silica and montmorillonite nano clay particles on cenment hydration and microstructure. *Matr. Sci. Technol*. 32: 138-153.

[22] Moradi Gh., Seyedi Sh., (2017), Evaluation of effective strength parameters and mirco structural variations of silty sands stabilized with nano colloidal silica. *J. Civil Eng. Environ.* 46: 78-90.

[23] Haeri M., Nikoonejad Kh., Valishzadeh A., (2017), Strength evaluation of collapsible soil specimens stablized by Nano Silica. *Proc. 10th Nation. Conf. Civil Eng.*, *Sharif University,* April, Tehran, Iran., 1-9.

[24] Eswaramoorthi P., Sachin Prabhu P., Senthil Kumar V., Prabu P., Lavanya S., (2017), Influence of nano size silica and lime particles on the behaviour of soil. *Int. J. Civil Eng. Techno.* 8: 353-360.

[25] Hari Krishna P., Azaruddin S., Bala Krishna B., (2017), Effect of nano silica and meta kaolin on properties of recycled coarse aggregates concrete. *Int. Res. J. Eng. Techno*. 4: 831-837.

[26] Kordani N., Sadough Vanini A., (2015), Yarn pulling out test and numerical solution of penetration into woven fabric target impregnated with shear thickening fluid using SiO_2/ Polyethylene Glycol. *Int. J. Nano Dimens.* 6: 409-416.

[27] Abd Ellatief T, Maitra S., (2017), Some studies on the surface modification of sol-gel derived hydrophilic Silica nanoparticles. *Int. J. Nano Dimens.* 8: 97-106.

[28] Tayebee R., Abdizadeh M. F., Amini M. M., Mollania N., Jalili Z., Akbarzadeh H., (2017), $Fe_3O_4@SiO_2-NH_2$ as an

efficient nanomagnetic carrier for controlled loading and release of acyclovir. *Int. J. Nano Dimens.* 8: 365-372.
[29] ASTM D421-85, (1985), Dry preparation of soil samples for particle-size analysis and determination of soil constants. *Annual Book of ASTM Standards*. (reapproved 1998).
[30] ASTM D422-63, (1963), Standard test method for article-size analysis of soils. *Annual Book of ASTM Standards* (reapproved 1998).
[31] ASTM-D 854-02, (2002), Standard test method for specific gravity of soil solids by water pycnometer. *Annual Book of ASTM Standards*.
[32] ASTM D4253-16, (2006), Standard test methods for maximum index density and unit weight of soils using a vibratory table. *Annual Book of ASTM Standards*.
[33] ASTM D4254-16, (2006), Standard test methods for minimum index density and unit weight of soils and calculation of relative density. *Annual Book of ASTM Standards*.
[34] MSA Company, http://msatechnology.com.
[35] ASTM D 3080-98, (1998), Standard test method for direct shear test of soils under consolidated drained condition. *Annual Book of ASTM Standards*.
[36] ASTM D2434-68, (2006), Standard test method for permeability of granular soils (Constant head). *Annual Book of ASTM Standards*.
[37] Dabiri D., Askari F., Shafiee A., Jafari M. K., (2011), Shear wave velocity based liquefaction resistance of sand-silt mixtures: Deterministic versus probabilistic approach. *Iran. J. Sci. Techno. Transactions Civil Eng.* 35: 199-215.
[38] Askari F., Dabiri D., Shafiee A., Jafari M. k., (2010), Effects of non-plastic fines content on cyclic resistance and post liquefaction of sand-silt mixtures based on shear wave velocity. *J. Seis. Earth. Eng.* 12: 13-24.
[39] Iler R. K., (1979), The chemistry of silica: Solubility, polymerization, colloid and surface properties, and biochemistry. *John Wiley & Sons, New York*.
[40] Whang J. M., (1995), Section 9–Chemical-based barrier materials. *Assess. Barr. Contain. Techno. Environ. Remed. App.*, R. R. Rumer and J. K. Mitchell, eds., NTIS, Springfield. VA. 211-247.