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An experimental investigation on the effects of the silicate grouts on the cyclic behavior of the lightly cemented sands

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ABSTRACT

Accurately designed soil improvement projects need sufficient pre-construction knowledge about the behavior of treated soils. Besides, comprehensive investigations applied to study the monotonic behavior of treated sands using silicate grout, a vacancy of information about their cyclic behavior remains. In this paper, silicate grout with a mixture of nano-silicate sodium and calcium chloride is used to improve the cyclic resistance of loose sands against liquefaction. Sand material was extracted from the Enghelab station of metro line 3 of Tabriz city, where the water table is adjacent to the ground surface and the underlying soil has a high liquefaction potential. As Tabriz is located in one of the most seismically active regions of Iran, extending knowledge about the behavior of improved soils against upcoming earthquakes is mandatory for pre-crisis management projects. In this paper, using fully automatic direct simple shear apparatuses, the cyclic behavior of untreated and treated sand samples is studied, and it is demonstrated that the lightly cemented treated samples show 40%-60% more resistance against liquefaction. Compared to the pure sand samples, the treated samples show a rate-dependent behavior, especially for smaller consolidation stresses. In addition, it is revealed that the treated samples mostly show adhesion strength against the applied cyclic loads compared to particle-to-particle friction.

Keywords: *Silicate grout, Liquefaction, Lightly cemented sand, Nano-silicate sodium, Simple shear.*

1. Introduction

By developing demands for new constructions, especially infrastructures, the application of soil improvement techniques is extending these days. One of the most applied methods for the treatment of soil behavior is the use of chemical grouts. Since the application of chemical grouts has been extended in recent decades, investigations into their efficiency have attracted lots of interest. Monitoring the post-casting properties of such improvement techniques can be done with destructive methods where surrounding soil should be excavated and samples extracted from treated media [1]. Such monitoring methods lead to an increase in project costs and can result in damage to treated media; therefore, pre-construction investigations are necessary for treated soils. Different chemical grouts can be used for the treatment of soils; however, investigations to find more environmentally friendly approaches are ongoing. Sodium silicate and calcium chloride are commonly used for soil stabilization due to their ability to improve the strength and durability of soil. When sodium silicate is applied to soil, it reacts with the free calcium ions present in the soil to form a stable calcium silicate hydrate gel. This gel fills the voids between soil particles, bonding them together and increasing the soil's strength and stability. Dissolved polyvalent cations, such as Ca^{2+}, Al^{3+}, and Mg^{2+} react with silicate to produce silicate gel through the metal ion reaction. One example is the reaction between sodium silicate and calcium chloride, which can produce hydrated calcium silicate. Calcium chloride works by attracting water molecules to the soil particles, creating a stronger bond between them. This helps to improve the soil's compaction and stability, making it more resistant to erosion and other forms of degradation. When sodium silicate and calcium chloride are used together for soil stabilization, they can complement each other's effects and provide a more comprehensive solution for improving soil strength and stability. Sodium silicate reacts with free calcium ions in the soil to form calcium silicate hydrate gel, while calcium chloride helps to improve compaction and increase moisture retention in the soil. Overall, the application of sodium silicate and calcium chloride in soil stabilization can significantly improve the mechanical properties of soil, making it more suitable for construction and other engineering projects. These chemical reactions help to create a more stable and durable soil structure, reducing the risk of erosion and other forms of degradation.

The previously conducted studies provide a comprehensive overview of the research on the behavior of cemented soils and the effects of sodium silicate treatment on soil improvement projects. The field tests shed light on the behavior of cemented soils in real-world conditions, providing valuable insights into the performance of these soils.

Laboratory studies, as discussed [2,3] delve into the effects of sodium silicate treatment on various factors, such as sand distribution size, dilution of solutions, and drying temperature. These studies contribute to the understanding of how sodium silicate treatment affects soil improvement and consolidation, providing essential data for future research and projects. Kasehchi et al. [4] investigated the use of geopolymer-stabilized samples made from ceramic waste powder and

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sodium hydroxide solution to improve the mechanical properties of inshore sand soils. It has been shown that experimental factors, such as CWP content, NaOH concentration, curing time, and temperature were tested, resulting in significantly increased unconfined compressive strength and failure strain compared to natural soil stabilized with ordinary Portland cement. The addition of CWP alone had no effect, but when combined with NaOH, significant improvements were seen. The study concludes that geo-polymeric soil stabilization is a cost-effective and environmentally friendly method.

Wang et al. [5] assessed the selection and optimization of slurry ratios for the construction of subway tunnels in poorly graded medium sand strata. An acidic grouting material was developed using sodium silicate and phosphoric acid with properties, such as gel time and viscosity studied. Orthogonal testing was used to determine the optimal ratio of sodium silicate to phosphoric acid for the sand stratum. X-ray diffraction and scanning electron microscopy were utilized to analyze the sand consolidation process. The results showed that the compressive strength of the grouted sand was influenced by factors, such as water content, Baume degree, pH value, and curing time of the slurry. The final selected slurry for reinforcement was prepared using 30°Bé sodium silicate with 14% phosphoric acid at a volume ratio of 0.5. This slurry had a gel time of 51.48 minutes, a funnel viscosity of 16.43 seconds, and a pH of 3.47. The increased strength of the grouted sand was attributed to the increased amount of silica gel generated, which increased with longer curing times. Xu et al. [6] explored the curing efficiency and strength characteristics of water glass in engineering grouting solidification and ecological environment restoration. The study involved designing 10 curing paths within 100 °C and testing mechanical and acoustic characteristics of water glass-cured sandy soils. The relationship between strength, wave velocity, and curing age was established, and a characteristic parameter was proposed based on acoustic emission values. Scanning electron microscopy was used to reveal the solidification evolution process. The results showed that high temperatures significantly enhanced strength with the gel layer being more affected at high temperatures compared to room temperature. The longer the room temperature curing time, the weaker the high-temperature effect. The conversion rate of the gel under high-temperature conditions determined the strength of the specimen, while the rate of strength deterioration was influenced by the hardening effect of undehydrated gel and the excessive dehydration effect of the rigid gel. Falamaki et al. [7] investigated the impact of injecting sodium silicate into a sand formation containing fine grains using an electrokinetic cell. The results showed that adding 5% and 10% Na-silicate solutions significantly increased soil strength, particularly near the cathode electrode. The highest strength improvement was observed when Na-Si was injected with bicarbonate as a catholyte. In contrast, efficiency decreased when Na-Si was injected with phosphoric acid. Higher silicate concentrations resulted in reduced penetration length in both acid and bicarbonate catholytes, and reduced electro-osmotic flow was noted when silicate was added to the anode chamber. Numerical modelling [8] offers a different perspective by simulating the consolidation behavior of treated silica sand using sodium silicate solution. This modelling approach allows researchers to predict and analyze the behavior of the treated soil under different conditions, providing valuable predictive insights. Silicate grouts play a crucial role in soil stabilization [9] by creating bonds between soil particles that limit deformation and improve soil strength. The study by Lucas et al. [9] further explores the consolidation behavior of treated silica sand with sodium silicate solution, shedding light on the various factors influencing soil improvement. Some studies [10, 11] focused on the use of bio-based sodium silicate solution and alkaline sodium silicate, respectively, for stabilizing sandy soils. These studies demonstrate the effectiveness of different types of sodium silicate solutions in improving soil properties and stability. The research by Gonzalez and Vipulanandan in reference [12] stands out for combining Nano-sodium silicate solution with an organic reactant to enhance the mechanical properties of sands. The study showcases significant improvements in unconfined compression and creep tests, indicating the potential of this approach for enhancing soil stabilization and consolidation. Several studies have investigated the impact of silicate grout on the strength of sands. For instance, research has shown that silicate grout does not alter the internal friction angle of sand [13,14], but grouting with silicate solution can enhance the strength of sand by introducing cohesion to the mass [15,16]. Ata and Vipulanandan [17] explored the effects of silicate grout on the cohesive and adhesive strength of sands and developed a model to forecast their mechanical behavior. They also found that the failure of grouted sands under unidirectional compression occurs at significantly smaller strains compared to untreated samples [17]. Furthermore, it was discovered that increased curing time decreases failure strains, suggesting that failure in cemented sands is primarily influenced by the cohesive and adhesive strengths of the grout. Avci et al. [18] explored the effects of sodium silicate grout on the strength and permeability of sand samples, utilizing unconfined compression tests to assess the strength of the treated sands. In order to strengthen the scholarly foundation of this article, it is recommended to include more comprehensive explanations and clearly state the primary objective of the study.

The previous research on the effects of silicate grout on sand strength has primarily focused on unconfined compression and direct shear tests [19]. However, to truly understand the behavior of treated soils, more advanced testing methods, such as triaxial tests are needed. For example, Hassanlourad et al. [20] conducted triaxial tests to investigate the impact of the physical properties of grains on the mechanical behavior of grouted sands. In addition to examining the physical properties of grains, it is important to consider the effects of confining pressure, induced bonds, and grouting on the yield of cemented samples. This can be achieved through monotonic tests, as demonstrated by Hassanlourad et al. [20]. Grouting projects are often used to improve the strength of loose sands against liquefaction, with many such projects being undertaken globally each year. However, the post-construction monitoring of these projects can be expensive and destructive. Therefore, it is crucial to conduct lab-scale evaluations of the seismic behavior of cemented sands before construction. While much of the existing research has focused on the monotonic behavior of treated sand, direct simple shear tests offer a more advanced method to investigate the mechanical behavior of lightly cemented sands [19]. By exploring different strain and stress paths, these tests can provide valuable insights into the effectiveness of grouting in improving sand strength. In summary, while previous studies have primarily utilized direct shear or uniaxial compression tests, the use of a simple shear device in this study offers several advantages, as follows [21, 24]:

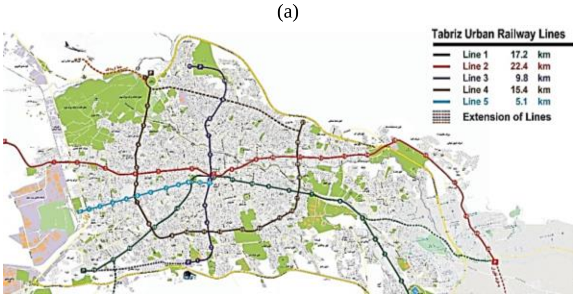
- First and foremost, the simple shear device allows for a more realistic simulation of the in-situ conditions seen in actual engineering applications, as it better replicates the complex stress states and loading conditions experienced by soil deposits. This makes the results of this study more applicable and relevant to real-world scenarios.
- Additionally, the simple shear device allows for easier and more precise control of the applied stress and strain levels, leading to more accurate and consistent test results. This ultimately enhances the reliability and validity of the findings presented in this paper.
- The use of the simple shear device in this study represents a significant advancement in the field of geotechnical engineering research, offering a more comprehensive understanding of the behavior of fine sand when subjected to silicate sodium grout treatment.

The city of Tabriz is located in the northwestern part of Iran and is constructed in a very seismically active region. Nowadays, with the development of metro lines in Tabriz city to the western part of the city, where underlying soil is mostly composed of granular soils and the water table is near the ground surface, soil improvement techniques are needed to ensure the safety of facilities against upcoming earthquakes. In this paper, the cyclic behavior of lightly cemented sands under different scenarios is investigated. To this aim, a liquefiable site located in the northwestern part of Iran, in metro line 3 of Tabriz city, is selected to extract sand material. Untreated and treated behavior of the distributed sand samples under monotonic and cyclic loads is investigated using direct simple shear tests, and the efficiency of the light cementation of the samples to increase the factor of safety against liquefaction using silicate sodium grout is discussed. It should be mentioned that most of the previously applied studies focused on the monotonic behavior of stabilized soils by silicate grout, while this paper covers both the monotonic and cyclic behavior of stabilized sands using silicate sodium grout. The paper is organized as follows: details of the test program, description of the used materials, and employed testing devices are explained in the next section. The achieved results are presented in Section 3, and the last section is dedicated to the discussions and conclusions.

2. Testing device, material, and Procedure

The western regions of the city of Tabriz in the northwestern part of Iran, which mainly consists of granular soils, have less strength against liquefaction. Fig. 1 shows the location of the city of Tabriz. The northwestern part of Iran is a seismically active region and experiences earthquakes annually. Based on the applied seismic hazard analysis, an earthquake with a magnitude larger than 7 is expected in the upcoming decade.

(a)



(b)

Fig. 1. (a) Location of the Tabriz city, and (b) metro lines of the Tabriz city.

Western regions of the city have been used as residential and industrial areas. Therefore, considering problematic underlying soil and the development of life facilities (especially metro lines) in these areas, soil improvement projects have been employed in these sites at an ascending rate. As described in Section 1, the application of silicate grouts is one of the most trending soil improvement techniques these days. However, the efficiency of such improvement techniques in increasing strength against liquefaction (under cyclic loads) needs further investigation. To this aim, some samples of the sandy soil were extracted from the sites adjacent to the Enghelab station of metro line 3 of Tabriz city. The grain size distribution of the particles (after separating grains with diameters larger than 4.75 mm and smaller than 0.0475 mm) is shown in Fig. 2. The main physical properties of the sand are presented in Table 1.

The efficiency of silicate grout to increase strength against liquefaction is evaluated using direct simple shear (DSS) tests in this paper. A stack-ring type full-automated DSS device, which is shown in Fig. 3, is employed in the tests. The device can implement monotonic and cyclic tests; however, the maximum frequency of input motion is restricted to 1 Hz. In this research, the sample's diameter is selected as equal to 7 cm, and the height of the samples is selected as equal to 2 cm.

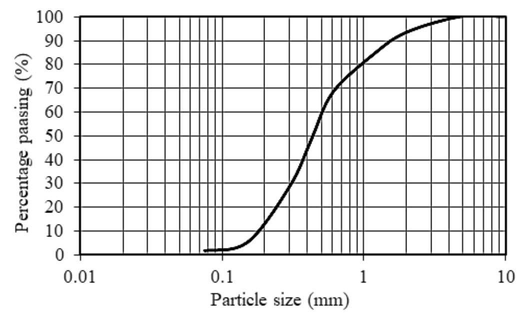


Fig. 2. Grain size distribution of the employed sand.

The test program consists of 40 tests where details of each test are provided in Table 1. The selection of the loading parameters was done to make evaluation of the results possible. Different values of the initial vertical effective stresses chosen in this study can help compare the effects of the different depths of samples on their behavior. In addition, different cyclic stress values were used to investigate the cyclic behavior of samples under various magnitudes of earthquakes. The applied CSRs were increased from 1% to 15% to ensure the occurrence of liquefaction under the existing stress state. Therefore, resistance against liquefaction can be compared for treated and untreated samples. In addition, the selection of the loading frequencies was made by considering the limitations of the used direct simple shear apparatus. The used apparatus can apply frequencies of 0 to 1 Hz. While this range cannot cover cyclic loads with larger frequencies, it seems to be sufficient for the evaluation of the cyclic behavior of rate-independent materials, such as sands. As can be found in Table 1, both monotonic and cyclic tests are conducted to investigate the efficiency of the treatment method. Monotonic tests are applied in constant volume (CV) and constant pressure (CP) situations with strain rates equal to 0.5mm/min and 0.05 mm/min, respectively. In a simple shear test of sand, constant volume and constant pressure tests are two different methods used to measure the shear strength of the soil. In the constant volume test, the soil sample is confined in a rigid container with a fixed volume, so that the volume of the sample remains constant during shearing. This test is often used to simulate undrained conditions, where the excess pore water pressure cannot dissipate freely and the soil cannot consolidate under the applied stress.

Table 1. The main physical properties of the sand material.

Gs	Mean diameter (d_{50})	Maximum void ratio (e_{max})	Maximum void ratio (e_{min})
2.66	0.43	0.86	0.49

(a)

(b)

Fig. 3. (a) The used direct simple shear apparatus, (b) an untreated sample for testing on the mold, and (c) a treated sample.

Table 2. Details of the applied tests.

Name	Sv* (kpa)	Type	Dr (%)	CSR (%)	F (Hz)	Improvement
No 1	100	CV**	50	-	-	Untreated
No 2	200	CV	50	-	-	Untreated
No 3	300	CV	50	-	-	Untreated
No 4	100	CP***	50	-	-	Untreated
No 5	200	CP	50	-	-	Untreated
No 6	300	CP	50	-	-	Untreated
No 7	300	Cyclic	50	1	0.1	Untreated
No 8	300	Cyclic	50	2	0.1	Untreated
No 9	300	Cyclic	50	5	0.1	Untreated
No 10	300	Cyclic	50	10	0.1	Untreated
No 11	100	Cyclic	50	10	0.1	Untreated
No 12	100	Cyclic	50	15	0.1	Untreated
No 13	200	Cyclic	50	10	0.1	Untreated
No 14	50	Cyclic	50	15	0.1	Untreated
No 15	100	Cyclic	50	10	0.1	Treated
No 16	100	Cyclic	50	15	0.1	Treated
No17	200	Cyclic	50	10	0.1	Treated
No 18	200	Cyclic	50	15	0.1	Treated
No 19	300	Cyclic	50	10	0.1	Treated
No 20	300	Cyclic	50	15	0.1	Treated
No 21	50	Cyclic	50	10	0.1	Treated
No 22	50	Cyclic	50	15	0.1	Treated
No 25	300	Cyclic	30	5	0.1	Treated
No 26	300	Cyclic	30	10	0.1	Treated
No 27	50	Cyclic	30	10	0.1	Treated
No 28	100	Cyclic	30	10	0.1	Treated
No 29	200	Cyclic	30	10	0.1	Treated
No 30	300	Cyclic	30	10	0.1	Treated
No 31	100	CV*	30	-	-	Untreated
No 32	200	CV	30	-	-	Untreated
No 33	300	CV	30	-_	-_	Untreated
No 34	300	Cyclic	50	10	0.5	Treated
No 35	50	Cyclic	50	10	0.5	Treated
No 36	200	Cyclic	50	15	0.5	Treated
No 37	100	Cyclic	50	10	0.5	Treated
No 40	50	Cyclic	30	15	0.1	Treated
No 41	100	Cyclic	30	15	0.1	Treated
No 42	200	Cyclic	30	15	0.1	Treated
No 43	300	Cyclic	30	15	0.1	Treated

* Vertical stress, ** Constant volume, *** Constant pressure

On the other hand, in the constant pressure test, the excess pore water pressure is always equal to zero. This test is often used to simulate drained conditions, where the excess pore water pressure can dissipate freely and the soil will fully consolidate under the applied stress. Regarding the conventional triaxial tests, the constant volume test can be compared to a consolidated undrained triaxial test, where the soil is not allowed to fully consolidate and excess pore water pressures are retained. The constant pressure test, on the other hand, can be compared to a consolidated drained triaxial test, where the soil is allowed to fully consolidate and excess pore water pressures are dissipated.

Overall, the choice between constant volume and constant pressure tests in simple shear tests of sand depends on the desired conditions (drained or undrained) and the level of accuracy needed in measuring the shear strength of the soil. Each method provides valuable insights into the behavior of the soil under shearing, helping engineers to better understand and predict the soil's response in real-world applications. Effects of the initial relative density (Dr=30% and 50%), frequency of input motion (f=0.1 Hz and 0.5 Hz), the magnitude of the cyclic stress ratio (CSR), and consolidation stress (Sv=100, 200, and 300kpa) were evaluated. All cyclic tests were conducted with force-controlled shear loading (CSR tests), where both untreated and treated samples were employed to understand the effects of treatment on the behavior of the selected sandy soil.

To prepare silicate grout, nano-silicate sodium with calcium chloride (as the reagent) was used. The percentage of each material is presented in Table 3. Fig. 4 shows the used sand, nano-silicate sodium, and calcium chloride.

Table 3. The percentage of the used material in silicate grout.

Name	Water	Nano-silicate sodium	Calcium chloride
Percentage in grout (%)	70	10	20

(a) (b) (c)

Fig. 4. (a) The used sand, (b) Nano-silicate sodium, and (c) Calcium chloride.

The percentage of each material for silicate grout was selected by a trial-and-error procedure to prepare lightly cemented sand samples. The results of the applied trial-and- error procedure were measured by comparing the unconfined compression strength of the treated samples. Through the trial-and-error process, it was observed that different mix ratios of the nano-silicate sodium and calcium chloride resulted in varying levels of unconfined compression strength in the samples. Some mixes produced higher strengths, while others yielded lower strengths. It can be seen in Fig. 5a that Ca concentration can lead to an increase in the unconfined compression strength until a threshold value, and then more increments will result in a reduction in the unconfined compression strength. In addition, Fig. 5a shows that the highest unconfined compression strength can be achieved by 67% nano-silicate sodium and 33% calcium chloride (for 100% of chemical agents). It should be mentioned that the water ratio of the grout was kept equal to 70% to ensure the workability of the grout and its mixing with soil. As the main aim of the research is the evaluation of the behavior of the lightly cemented sands, the mixture that resulted in almost 100 kPa was selected as the appropriate mix ratio for the study. It should be mentioned that the evaluation of the behavior of highly cemented samples is considered by the authors to be presented in the future.

This paper is focused on the lightly cemented samples because of two main reasons. First, the heavily cemented samples will shear on the DSS device without maintaining a simple shear mode of failure (they will shear most likely to direct shear mode where parallel plates will not be parallel during the test). The second reason relates to the research's aim, which is about reducing liquefaction potential, not increase properties, such as bearing capacity. After the injection of the grout into samples, the samples were allowed to dry at lab temperature (25 ºc) for one week, and then completely dried in the oven at a temperature equal to 80 ºc. The unconfined compression strength of samples which are prepared based on the described method reaches an average value of 0.9 kg/cm2 (90kpa). Fig. 5b shows the result of an unconfined compression test on a treated sample.

3. Results

In this section, the behavior of the untreated and treated sand samples is presented. First, the behavior of untreated sand is discussed, and the effects of the applied treatments are evaluated.

3.1. The behavior of untreated sand

Monotonic tests were applied to determine the sand sample's basic mechanical properties. To this aim, constant volume monotonic shear tests for samples with initial relative densities equal to 50% were conducted and the achieved results are depicted in Fig. 6. As it can be seen in Fig. 6a, all samples showed a phase transformation during shear load where the contraction behavior transformed into the dilative behavior.

Further constant volume tests for samples with initial relative densities of 30% were applied and the results of shear stress-shear strain behavior are presented in Fig. 7. Compared to the samples with Dr=50%, the peak shear stress of samples with Dr=30% decreased; however, the same steady-state stress ratio was achieved for all tests. Based on the applied monotonic tests, the steady-state stress ratio was equal to 0.6, which corresponds to a steady-state friction angle of 31 degrees. Similar to the samples with Dr=50%, the samples with Dr=30% show behavior with a phase transformation during the tests, while the softening behavior of samples is more evident in samples with lower relative densities.

Different cyclic loads with varying values of CSR (1%, 2%, 5%, and 10%) are applied to samples with Dr=50% that initially consolidated up to Sv=300kpa. The frequency of the cyclic input load was selected equal to 0.1 Hz, and cyclic loads consist of 15 cycles. As shown in Fig. 8, the sample with CSR=10% is completely liquefied, while lower CSR values lead to a non-liquefy behavior. Significant softening occurred in the liquefied sample (with CSR=10%), as depicted in Fig. 8d.

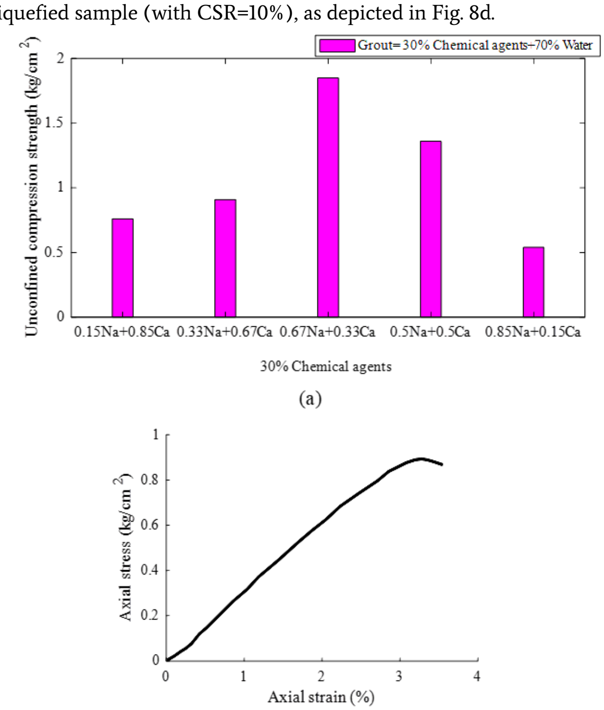


Fig. 5. (a) Achieved unconfined compression strength of the samples with different amounts of chemical mixtures, and (b) The results of the unconfined compression test on treated sand with the selected mixture.

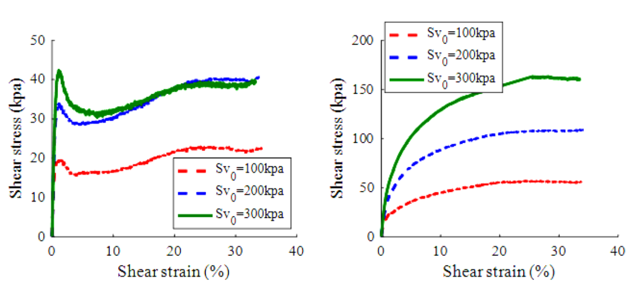


Fig. 6. The results of the tests for untreated samples with Dr=50%, (a) constant volume shear stress-shear strain curves, and (b) constant pressure shear stress-shear strain curves.

The stress paths of the samples with Dr=50% and Sv=300kpa are shown in Fig. 9. As can be observed in Fig. 8, lower values of CSRs do not lead to significant strength reduction while a considerable loss of strength can be detected in Fig. 9 for the sample under cyclic loading with CSR=10%.

To evaluate the effects of consolidation stress on the cyclic response of samples, normalized stress paths of the samples with Dr=50% at three different Sv were presented in Fig. 10a. In addition to the stress paths, normalized cyclic shear stress-shear strain curves for these tests are presented in Fig. 10b. Normalization is applied by dividing shear stresses and effective stresses by the consolidation stress. This figure shows the results of tests with CSR=10%, where the frequency of input motions and the number of cycles were kept the same as the previously described cyclic tests (f=0.1 Hz and Num_{cycle}=15). As shown in Fig. 10, two samples with Sv=200 and 300kpa were completely liquefied, while the sample with Sv=100kpa only experienced softening without liquefaction. This result indicates that the sample with Sv=100kpa (and Dr=50%) is in a denser situation compared to the other two samples.

Since the samples with relative densities equal to 50 under consolidation stresses equal to 100kpa (or smaller values) exhibited a non-liquefiable behavior in tests with CSR=10%, these samples were tested again with a CSR of 15%. The achieved results are shown in Fig. 11. As this figure shows, in cyclic tests with CSR=15% (F=0.1 Hz, Dr=50%, and Num_{cycle}=15) both samples are completely liquefied.

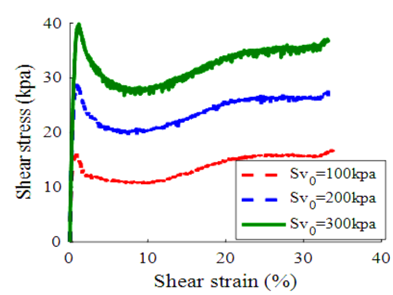


Fig. 7. The results of the tests for untreated samples with Dr=30% (constant volume shear stress-shear strain behavior).

3.2. The behavior of treated samples

To evaluate the silicate grout's efficiency on the sand material's behavior, treated samples were tested with different values of relative densities, cyclic stress ratios (CSRs), and consolidation stresses. Fig. 12a shows normalized cyclic stress paths of samples with initial relative densities of 50% under consolidation stresses equal to 300kpa. As shown in Fig. 12a, the samples lost some strength and exhibited softening behavior; however, they did not experience complete liquefaction. To compare with the untreated sample, it should be mentioned that, as Fig. 11 shows, the sample with Sv=100kpa and Dr=50% lost its total shear strength in the test with CSR=15%, while the treated sample maintained almost 40% of its shear strength. Fig. 12b and Fig. 12c show the normalized cyclic stress paths of samples with Dr=50% under consolidation stresses of 200 and 100 kpa, respectively. As these figures show, for both tested CSRs (CSR=10% and CSR=15%), a non-liquefied behavior was recorded. Comparing these results with untreated samples revealed that the application of silicate grout significantly increased the shear strength of sands (40% for samples with CSR=15% and 60% for samples with CSR 10%).

For samples with smaller values of initial relative densities (Dr=30%) where the soil is in a looser state (in the stress-void ratio space), cyclic tests were applied as well. It is shown in Fig. 13 that although the treated soils had looser states, they did not experience liquefaction. Fig. 13 shows normalized cyclic stress paths of the applied tests on samples under four different consolidation stresses and under CSR=10%. The frequency of input motion for these tests was equal to 0.1 Hz.

The effects of the frequency of the input motion are also investigated and the achieved results for cyclic stress paths are depicted in Fig. 14. As this figure shows, the frequency of the input motion had no significant effects on the samples with higher consolidation stresses. However, lower frequencies for lower consolidation stresses lead to greater shear strength reduction in the treated samples. Therefore, it can be noted that despite pure sand samples where the frequency of input motion is not significant to the samples' strength, frequency can affect the treated samples, especially at lower consolidation stresses.

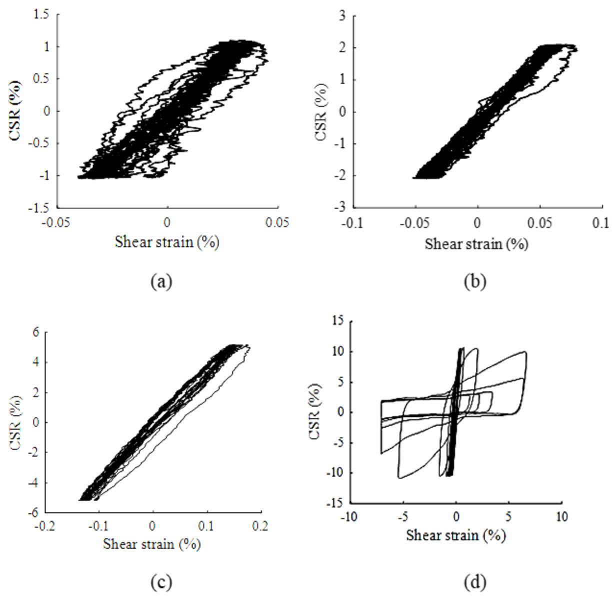


Fig. 8. The shear stress-shear strain behavior of samples with Dr=50% and Sv=300kpa, (a) CSR=1%, (b) CSR=2%, (c) CSR=5%, and (d) CSR=10%.

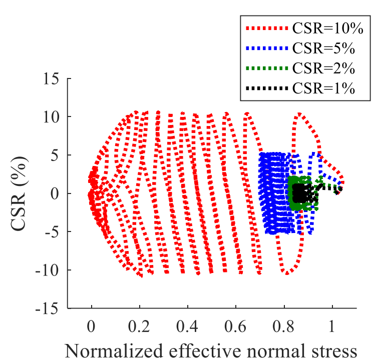


Fig. 9. Stress paths of the samples with Dr=50% and Sv=300kpa under cyclic load with different CSRs.

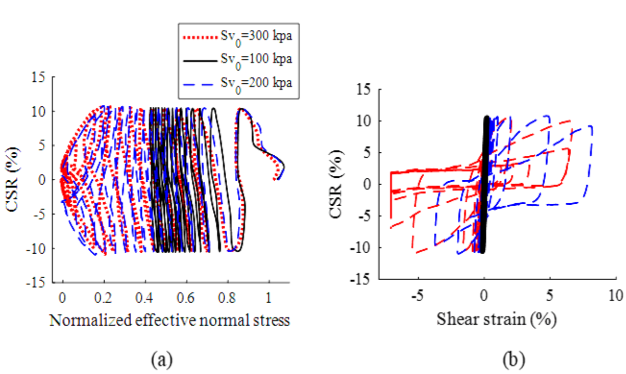


Fig. 10. (a) Normalized cyclic stress paths, and (b) normalized cyclic shear stress-shear strain curves of samples with Dr=50% under three different consolidation stress (f=0.1 Hz).

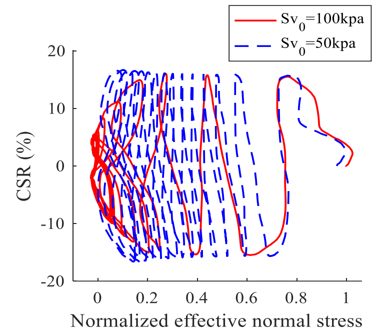


Fig. 11. Normalized cyclic stress paths for samples with Dr=50% and consolidation stresses of 100kpa and 50kpa under tests with a cyclic shear ratio of 15%.

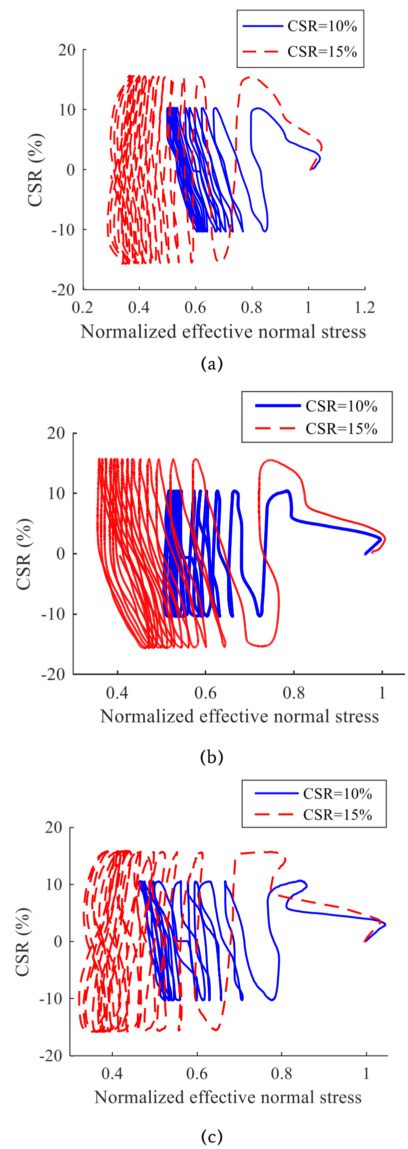


Fig. 12. Normalized cyclic stress paths of samples with Dr=50% under consolidation stress of (a) 300kpa, (b) 200kpa, and (c) 100 kpa.

The theoretical explanation for the significant increase in shear strength observed in the samples treated with silicate sodium grout can be attributed to the cementation effect. When the grout is introduced into the soil matrix, it acts as a binding agent, improving the interlocking of particles and reducing pore water pressure. This, in turn, enhances the overall strength of the soil and prevents failure during cyclic loading.

The non-liquefied behavior observed in treated samples at various consolidation stresses and relative densities can be explained by the effective reinforcement of the soil structure by the silicate grout. By enhancing particle interlock and reducing pore water pressure, the grout helps to maintain the integrity of the soil, even in looser states. This reinforces the soil against excessive deformations and ensures the retention of strength under cyclic loading conditions. The sensitivity of treated samples to the frequency of input motion, especially at lower consolidation stresses, can be explained by the dynamic response of the soil structure. Lower frequencies may lead to a reduction in shear strength as the soil is less densely consolidated and more susceptible to deformations. This highlights the importance of considering both the physical and chemical properties of the soil when assessing its behavior under varying loading conditions. Overall, the application of silicate sodium grout with calcium chloride has been shown to effectively enhance resistance to liquefaction in sands by modifying the physical and chemical properties of the soil. Further research into the specific mechanisms of cementation induced by the grout will help deepen our understanding of its effectiveness in mitigating liquefaction risks and will inform future engineering practices in soil stabilization. In addition to the cementation effect, the filling of pores in sandy soils by grouting plays a crucial role in reducing the liquefaction potential. By filling the void spaces within the soil matrix with grout, the pores are effectively sealed off, reducing the mobility of water and preventing an increase in pore water pressure during cyclic loading. This helps to stabilize the soil and prevent it from losing strength and collapsing under external forces. The filling of pores with grout also improves the overall density and cohesion of the soil, making it more resistant to deformation and failure under dynamic loading conditions. This reinforcement of the soil structure helps to enhance its shear strength and stability, ultimately reducing the risk of liquefaction occurring. By effectively filling the pores in sandy soils with grout, the potential for an increase in pore water pressure is significantly reduced, thereby lowering the risk of liquefaction. This highlights the importance of considering not only the cementation effect but also the filling of pores in soil stabilization efforts to enhance the overall strength and stability of the soil against liquefaction hazards.

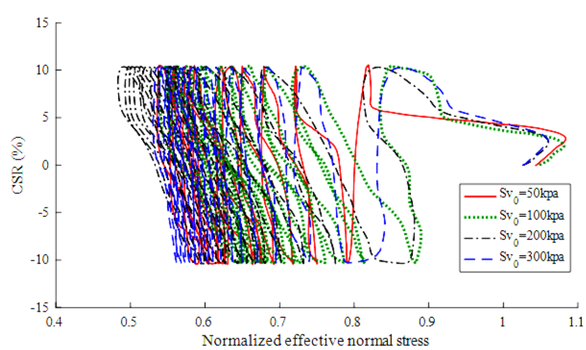


Fig. 13. Normalized cyclic stress paths of samples with Dr=30%, CSR=10%, and F=0.1 Hz.

Further elaborating on the comparison between the two series of tests conducted on untreated sand and the treated sample can be provided by comparing the achieved results. In the untreated sand samples, it was observed that the samples with initial relative densities of 50% exhibited a phase transformation during shear load, transitioning from contraction behavior to dilative behavior. The peak shear stress decreased for samples with initial relative densities of 30%, but a steady-state stress ratio of 0.6 was achieved for all tests. The samples with lower relative densities demonstrated larger softening behavior during the tests, indicating a lower resistance to shearing forces. Under cyclic loading with varying cyclic stress ratios (CSRs) applied to the untreated samples with initial consolidation stresses of 300kpa, it was found that the sample with a CSR of 10% completely liquefied, while samples with lower CSRs exhibited non-liquefiable behavior. The stress paths and normalized shear stress-shear strain curves further indicated a significant loss of strength in the liquefied samples. On the other hand, the treated samples showed improved behavior compared to the untreated samples. The application of the silicate grout significantly increased the shear strength of the sands with the treated samples maintaining a higher percentage of shear strength under cyclic loading. The treated samples with initial relative densities of 50% under consolidation stresses of 200kpa and 100kpa did not experience liquefaction, showcasing the effectiveness of the treatment in enhancing the soil's stability. Moreover, the effects of the frequency of the input motion on the treated samples were also investigated. It was observed that lower frequencies for lower consolidation stresses led to more shear strength reduction in the treated samples, highlighting the sensitivity of the treated samples to the input motion frequency, especially under lower consolidation stresses.

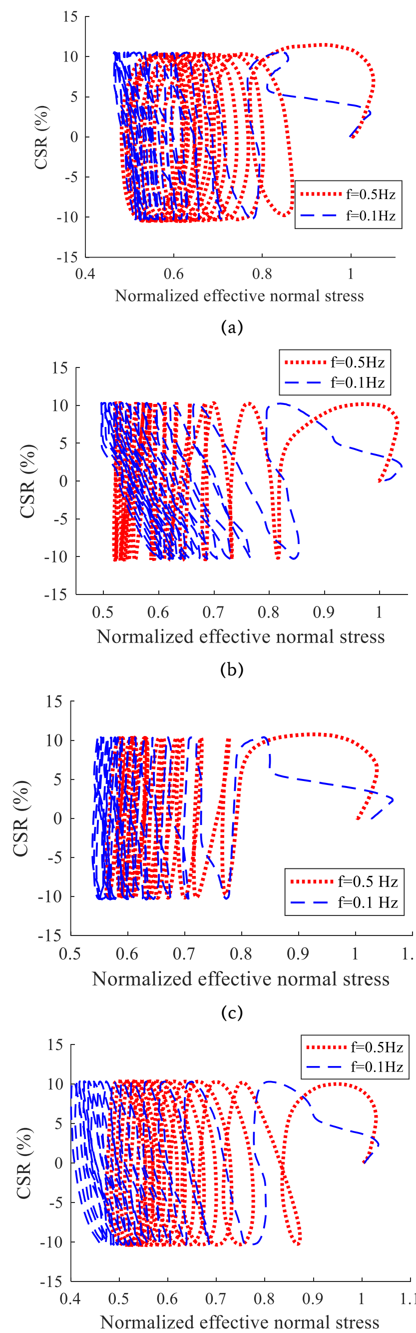


Fig. 14. Normalized cyclic stress paths of samples with initial relative densities of 50% under cyclic shear stress with 15 cycles (a) Sv=300kpa, (b) Sv=200kpa, (c) Sv=100kpa, and (d) Sv=50kpa.

4. Validation of results

Validation of the results is a critical aspect of any experimental study, as it ensures the reliability and accuracy of the findings. In the case of the simple shear and unconfined compression tests conducted on lightly cemented sands using sodium silicate grout, validation of the results was achieved through a rigorous approach that focused on repeatability. To validate the results of the unconfined compression tests, each test was repeated three times. The peak uniaxial compression strength was recorded for each test, and the results were considered valid if the differences between the peak strengths were less than 5%. This criterion ensured that the results were consistent and reproducible, and any outliers or anomalies could be identified and addressed. Similarly, validation of the results for the monotonic simple shear tests was done by repeating each test three times and comparing the peak shear strength values. Once more, a difference of less than 5% was used as the criterion for determining the validity of the results. This approach allowed for the identification of any inconsistencies or errors in the tests, thereby ensuring the accuracy and reliability of the findings. In addition to the unconfined compression and simple shear tests, validation of the results was also carried out for some of the cyclic simple shear tests which were selected randomly. By repeating these tests three times and comparing the results, any variations or inconsistencies could be identified and addressed, ensuring that the results were reliable and accurate. By conducting multiple tests and comparing the results, any errors or inconsistencies could be identified, and the reliability and accuracy of the findings could be ensured. This rigorous approach to validation is essential in experimental studies, as it allows for confidence in the results and ensures that they can be relied upon for future research and applications.

In addition, the results obtained from the direct simple shear tests conducted to assess the effects of nano-silicate sodium grouting on the liquefaction resistance of sands were validated by comparing them with the findings of other researchers. Salvatore et al. [22] indicated that nano silica gel in the interparticle pores in treated soils led to a slower pore pressure build-up compared to untreated soils. This resulted in a contractive tendency in the untreated sand and a dilative tendency in the treated sand. The treated material exhibited a longer time to reach the peak pore pressure ratio but always maintained positive mean effective stress during loading-unloading cycles. These results are consistent with the findings in the current study, which showed that treated samples maintained a significant portion of their shear strength and did not experience complete liquefaction even under high cyclic stress ratios. For example, while the untreated loose sand in the study liquefied under a cyclic shear load with CSR=10%, the treated sand showed 45% higher strength against liquefaction. As shown in Fig. 15, these results have good agreement with the findings of our study.

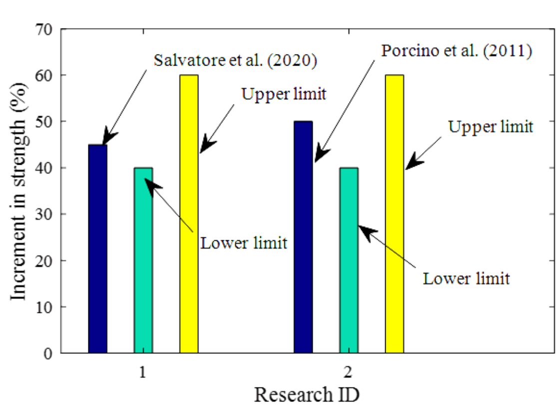


Fig. 15. Comparing the increment of resistance against liquefaction in treated sands with silica grout between the results of the current study and previously applied investigations.

Similarly, Porchino et al. [23] compared the undrained cyclic triaxial response of treated and untreated specimens subjected to the same cyclic stress ratio. The treated samples demonstrated a more stable response with minimal excess pore water pressure development and limited axial strain accumulation compared to untreated samples. For example, it was shown by Porchino et al. [23] that treated samples under 15 cycles demonstrate almost a 50% increment in the liquefaction-induced cyclic stress ratio. This corresponds with the achieved results of this research, where treated samples show a 40% to 60% increment in the cyclic shear strength against liquefaction (Fig. 15). This aligns with the outcomes of the current study, where treated samples exhibited a stiffer and more stable behavior under cyclic loading conditions, with minimal shear strength reduction and strain accumulation. In summary, the findings of the current study are validated and supported by the results reported by Salvatore and Porchino, indicating the effectiveness of nano-silicate sodium grouting in improving the liquefaction resistance of sands and enhancing their stability under cyclic loading conditions.

5. Conclusion

Soil enhancement methodologies, such as the utilization of silicate grout are increasingly employed on problematic construction sites globally to bolster soil stability against liquefaction. While previous research predominantly examined the monotonic response of treated samples, this study investigates the cyclic behavior of treated and untreated sand samples from the Enghelab station site in Tabriz. Silicate grout formulated with nano-silicate sodium and calcium chloride was utilized to produce lightly cemented samples exhibiting a strength of 90kpa. Stress-controlled cyclic simple shear tests were conducted on both treated and untreated samples, revealing the efficacy of the silicate grout in enhancing soil characteristics. The primary findings of this investigation can be summarized as follows:

- Treated samples demonstrate superior resistance to liquefaction at higher consolidation stresses compared to untreated samples.
- The lightly cemented samples treated with the specified silicate grout exhibit 40%-60% greater resistance to shear loads (for CSR=15% and CSR=10%, respectively) than untreated samples.
- Notably, a rate-dependent behavior in the treated samples was observed, in contrast to the rate-independent behavior of pure sands.

It is important to approach the conclusions of this study with caution, considering the inherent limitations that could influence their generalizability and validity. Key limitations of this study encompass the restricted sample size comprising sand samples solely from a specific site in Tabriz, Iran, potentially constraining the transferability of the findings to other soil types and locations. Moreover, the absence of long-term data, as the research solely encompassed stress-controlled cyclic simple shear tests, may not offer a comprehensive insight into the long-term cyclic behavior of treated soils. The absence of a comparative analysis of the efficacy of silicate grout against alternative soil enhancement techniques limits the understanding of its efficiency. Furthermore, the study primarily focused on resistance against liquefaction and rate-dependent behavior, overlooking crucial parameters, such as durability, cost-effectiveness, and environmental ramifications. Notably, potential biases in the research design or data analysis were not acknowledged, prompting concerns regarding the reliability and validity of the study outcomes.

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