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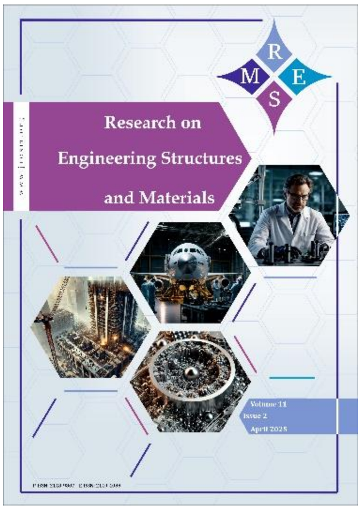

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Research Article

Mitigation liquefaction of sandy soil supporting shallow foundation using sodium silicate liquid injection

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Abstract

Sandy soil liquefaction poses a significant risk to shallow foundation structures. Shallow foundations subject to significant settlement, lateral displacement, and overturning are susceptible to earthquake-induced soil liquefaction. This study investigates the effectiveness of sodium silicate fluid injection as a soil improvement technique to mitigate the potential for liquefaction in loose sandy soils under the 2017 Halabjah earthquake. The research focuses on enhancing the strength, stiffness, and permeability of soils through chemical stabilization. The test program included evaluating the potential of sodium silicate fluid injection technology in addressing foundation liquefaction induced by seismic loadings using a shake table device. Sodium silicate solution was injected into saturated sand samples at 1:1 and 1:2 water-by-weight ratios in the stress bulb region, and the resulting changes in physical and mechanical properties were analyzed. The results indicate a significant improvement in soil strength and a significant reduction in liquefaction due to the formation of a silica gel matrix that bonds the soil particles. Tests conducted on shallow foundation specimens showed an increase in load-bearing capacity, a 57% reduction in settlement, and a 30% reduction in lateral displacement when the polymer was injected at a concentration of 1:2. When the water-sodium silicate ratio was reduced to 1:1, the improvement was further enhanced, with settlement and lateral displacement reduced by 76% and 60%, respectively, under seismic loads. Furthermore, excess pore pressure (Ru) was reduced by 25 and 33% in sand-treated soils at concentrations of 1:2 and 1:1, respectively. The proposed method offers an economical solution for liquefaction mitigation, making it suitable for urban areas and regeneration applications.

1. Introduction

Liquefaction is a critical geotechnical phenomenon that occurs in saturated, loose sandy soils when subjected to seismic loading or other dynamic forces, leading to a temporary loss of strength and stiffness. This consequences in significant deformations, ground failure, and damage to structures supported by shallow foundations. Past earthquakes, such as those in Kobe (1995) and Christchurch (2011), have highlighted the destructive impact of liquefaction on infrastructure, emphasizing the need for effective ground improvement techniques [1]. Particularly susceptible to tilting and settling brought on by liquefaction are structures with shallow foundations, which can compromise their stability and functionality. Studies that liquefaction leads to shear strength reduction, causing ground failure, structural settlement, and tilting of shallow foundations. Recent case studies, such as the Christchurch Earthquake (2011), demonstrated that infrastructure damage was directly for improving soils linked to liquefaction in untreated soil deposits. Traditional methods, including dynamic compaction, drainage systems, and stone columns, have

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shown varying levels of success, while can be costly, time-consuming, and disruptive, especially in densely populated urban areas. Hence, there is a need for alternative solutions that offer cost-efficiency, rapid implementation, and minimal environmental impact [2]. FRP composites also offer durability and low maintenance costs, making them a practical and sustainable option for deep foundations. Furthermore, these composites offer a new approach to improving seismic performance by injecting a polyurethane polymer mortar. Using of polymer micropiles significantly reduces soil and pipeline settlement by 15% to 50% [3]. Using geogrids to reinforce soil is another method that improves soil performance. The effects of square footings on sandy soils, both with and without geogrids, were studied in the 2017 Halabja earthquake. Reinforcement improves soil behavior by reducing foundation settlement and displacement. Furthermore, reinforcement reduces acceleration amplification. Moreover, it reduces the liquefaction ratio (Ru) by reducing the pore pressure that forms in saturated sandy soil [4,5].

Adding chemical materials such as polymers is one of the non-traditional methods that has been used to improve sandy soils [6]. Polymethacrylate (PMA) polymer was used in a chemical process to increase the swelling of expansive clayey soil. The maximum dry density rises when PMA is added, while the swelling potential falls as PMA content rises. The inclusion of PMA resulted in an increase in both the CBR value and the overall coefficient of expansion (UCS). The findings show that the issues with expanding soil are considerably resolved by polymers [7]. Also, Chemical grouting has been widely studied as a method to improve soil strength and reduce permeability, such as sodium silicate, has been used as an effective solution to modify soil properties by forming gels that bind particles and fill voids [8]. demonstrated that sodium silicate forms a gel-like matrix through chemical reactions, improving soil stiffness and liquefaction resistance. Studies emphasized the role of gel time, viscosity, and injection patterns in ensuring uniform soil stabilization. These works highlighted that sodium silicate, being environmentally friendly and non-toxic, is particularly suitable for urban areas where excavation and heavy machinery use are impractical [9].

Recent studies have demonstrated the effectiveness of sodium silicate injection in mitigating liquefaction hazards near existing structures without requiring excavation. These findings suggest that the technique is particularly advantageous for urban areas where retrofitting is necessary [10]. Sodium silicate liquid injection has emerged as a promising technique for mitigating liquefaction risk by improving soil properties through chemical stabilization. When injected into loose sands, sodium silicate reacts to form a gel-like matrix, reducing permeability, increasing shear strength, and binding soil particles together. Despite its potential, limited studies have comprehensively evaluated its performance under shallow foundations or assessed its behavior under dynamic loading conditions [11]. This study investigates the effectiveness of sodium silicate fluid injection at 1:1 and 1:2 concentrations as a soil improvement technique for reducing the potential for liquefaction in soft sandy soils affected by the 2017 Halabja earthquake. The research focuses on enhancing soil strength, stiffness, and permeability through chemical stabilization.

2. Experimental Test Model

A local manufactured 1g vibration table apparatus is used in this investigation. It is composed of several electrical systems, sensors, and hardware parts. As illustrated in (Fig. 1), the mechanical component of the vibration table system consists of the frame, block, linear guide rod, ball screw with nuts, couplings, and table. The vibration table is driven by the control and operating systems, which create horizontal motion to simulate actual ground vibration. Program control, servo motor, and servo motor control box are present. One kind of servo motor is the LCMT-7. LICHUAN: Xinlichuan Electric Company, Shenzhen, Ltd. The horizontal displacement of the vibration table is accomplished using a servo motor. LICHUAN, a servo motor maker, controls the servo motor. A servo motor receives the signal from the program control via the control box.

LabVIEW 2018 software was used to feed the earthquake data into the system, which was kept in an Excel file. It displays the elements of the shaking table system's control and operation system (Fig. 2). The DAQ hardware will be used to acquire the signals, which will then be sent to a computer. Nation Instruments used the created NI PCI-6259 M series as the DAQ hardware in this study. In order to program the signals provided by the DAQ hardware (PCI-NI6259 card), DAQ software uses the LabVIEW computer application. The DIAdem 2020 application is used to process the saved data.

Fig. 1. The shaking table system's mechanical components

Fig. 2. The components of the shaking table system that control and operate

In this investigation, accelerometers, pore pressure sensors, and displacement sensors were employed. The square foundation's vertical settlement and horizontal displacement are measured using four displacement sensors, including three WFS-1000-P15-11R5 rope displacement sensors. The shaking table is calibrated using a transducer for linear variation displacement (LVDT), which is the fourth sensor. The sand acceleration was measured using four ADXL335 accelerometers: two were positioned in the container at two distinct depths of 10 and 30 cm, in order to calibrate the acceleration, the third was placed on the shaking table, and the fourth was set up on the foundation with the acceleration sensor in a small box that was sealed for waterproofing. The water pressure and liquefaction potential were measured using Transducers of pore pressure (PPTs). Two PPT transducers of the DMKY type were employed, and they were positioned 10 and 30 cm below the soil's surface. Since signal processing involves operations like signal amplification and attenuation, it was utilized to precisely acquire the sensor signal. Pore pressure transducers (PPTs) and two amplifiers were employed in this investigation. The sensors and amplifiers utilized are depicted in (Fig. 3).

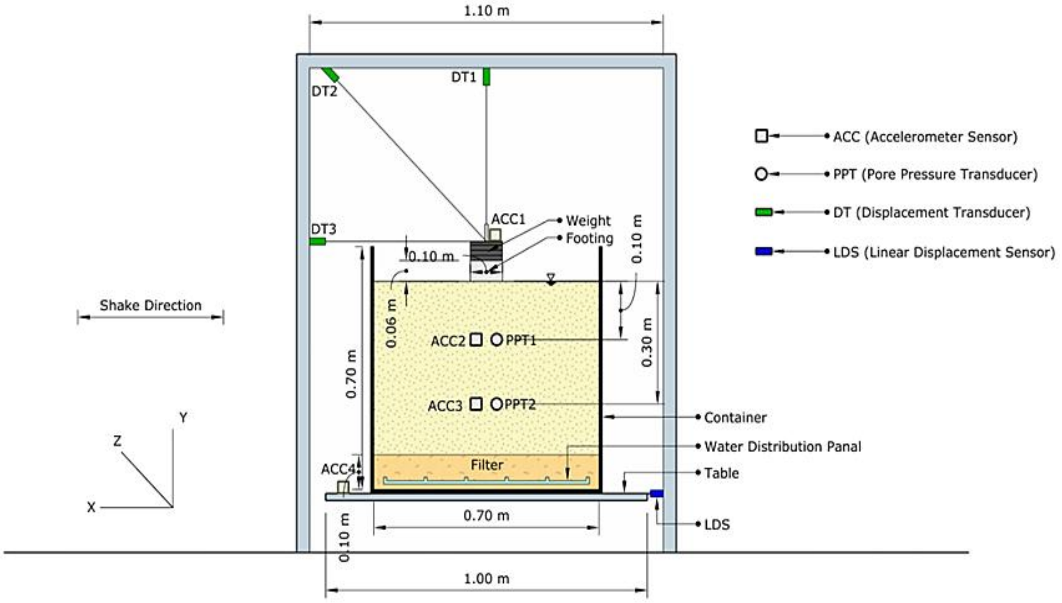


Fig. 3. Test model layout

The test model consisted of a shallow foundation with an additional load of 5.5 kPa. This model was made of a solid aluminum block of 2.2 kg with an area of 0.1×0.1 mm and a height of 0.06 mm. The lower face of the block was covered with glass paper to simulate the friction angle of concrete with saturated loose sand of 22 degrees. The type "AA240" was found to be suitable. The container utilized in the study has the following measurements: 0.7×0.7×0.7 m. Four U-shaped plates that are bolted to the shaking table hold it in place and stop it from slipping. It is made up of four steel plates, each measuring 4 cm. There was a water distribution panel within the steel container. The panel that distributed water was constructed from a pipe that is perforated 0.75 inches, united in a square shape, wrapped with fabric, and pipe-connected that was passed through the height of the container. This pipe is attached to a tube that is fastened to the tank that stores water in order to create a steady head, which mimics groundwater. After that, a filter layer of 10 cm composed of 2.36 mm and 4.75 mm aggregate was applied. The water distribution system, steel container, and frame utilized in this study are shown in (Fig. 4). The 2017 Halabjah earthquake, which lasted 180 seconds and had an acceleration of 0.16 g at peak ground, was selected as the historical earthquake used in this research based on Seismology and the Iraqi Meteorological Organization [12] (see Fig. 5).

Fig. 4. The footing, water distribution system, frame, and steel box

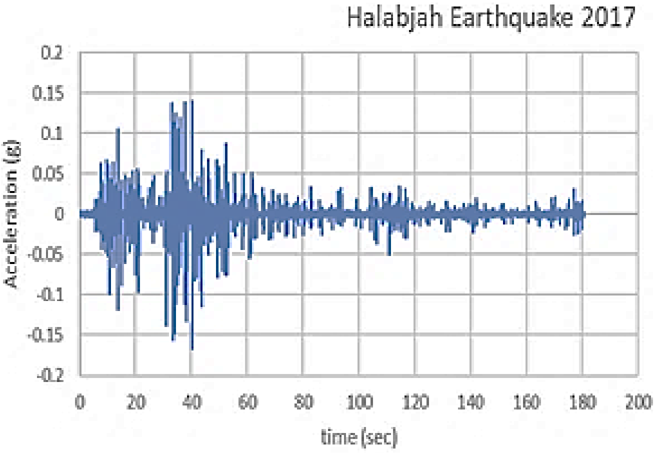


Fig. 5. The 2017 Halabjah acceleration history

3. Materials

3.1. Sandy Soil

The "Al-Akhdar" sand (Karbala) was the soil used in the model experiments. After being crushed and left to air dry, the sand was sieved using a No. 10 (2 mm) sieve. Table 1 lists the physical and chemical properties of the soil. Poorly graded is the classification given to the soil. ASTM D 4253 [13] and D 4254 [14] standards procedures were followed to calculate the maximum and lowest dry unit weight, respectively. A 30% relative density of loose sand was used to prepare the sand soil. Since the container's capacity and maximum and lowest unit weights are known, it is possible to calculate the amount of sand required to fill the steel container. The container was filled with layers of sand that were 10 cm deep. Following the creation of the soil profile and during the filling process, the foundation was positioned in the soil's surface center, and the dead weight was loaded onto it. The accelerometer was then fixed to the dead weight, and three displacement transducers were attached to the dead weight's center using a screw nut.

Table 1. The sand soil's index characteristics

Soil index	Specific gravity	D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	Maximum dry unit weight (kN/m^3)	Minimum dry unit weight (kN/m^3)	Relative density (%)	Dry unit weight (kN/m^3)	Water content (%)
Value	2.65	0.24	0.39	0.79	18.077	14.456	30%	15.38	23

3.2. Sodium Silicate

Sodium silicate injection is a widely used chemical grouting technique employed in civil engineering, construction, and geotechnical applications to enhance soil stability and waterproofing. Water glass is a frequent name for sodium silicate, is a water-soluble compound of sodium oxide (Na_2O) and silicon dioxide (SiO_2). When injected into soils or porous materials, it reacts with certain chemicals or carbon dioxide in the environment to form an insoluble gel or precipitate, which strengthens and seals the treated area [15]. This method is particularly advantageous in controlling water seepage in underground structures, sealing cracks in concrete, and improving the load-bearing capacity of weak soils. Its versatility and ease of application make sodium silicate injection a preferred choice for projects such as tunneling, foundation stabilization, and groundwater control. A class of compounds known as sodium silicates has a variety of different chemical and physical characteristics. In the industrial sector, they are employed as cleaning agents, rust inhibitors, cements, adhesives, bleaching agents, deflocculants, detergents, protective coatings, and catalytic bases.

According to their intended purpose, silicates are created at different water levels, particle sizes, and alkali (Na_2O) to silica (SiO_2) ratios. The comparatively plentiful raw ingredients of silica, sodium salts, and water are typically used to make them. Sodium silicates are easily accessible and can be purchased in a variety of packages for commercial application because manufacturers have widely dispersed outlets for their products [16,17]. Numerous researches have documented sodium silicate's efficacy as a soil-stabilizing additive since 1945. The silicate was employed both alone and in conjunction with other compounds at different times. Sherwood came to the conclusion that sodium silicate alone is only appropriate for stabilizing sandy soils in climates that are moderate [18].

Table 2. Chemical composition of sodium silicate [19]

Composition (%)	Silica (SiO_2)	Sodium Oxide (Na_2O)	$Na_2O:SiO_2$	Total solids	Water content	Viscosity	pH
Value	34.78	16.22	1:3.75, 2:1	51.00	49.00	0.4 to 600,000 Cp, fp	3 to 9

4. Sodium Silicate Injection

In the sodium silicate test, 6 thin-walled steel tubes of 12 mm diameter were inserted into the soil with relative ease using a small wrench. All of the tubes were angled 10 degrees toward the center of the foundation, with a distance of 3.3 cm between tubes, as seen in Fig 7. The tubes were inserted to three different depths of 5, 10 and 15 cm into the model and on both sides towards the X-axis because this is the axis on which the seismic load is applied. These depths were chosen to result in a bottom-up injection near the base of the liquefiable layer, allowing the sodium silica to diffuse throughout the stress bulb layer. According to references [20-22], the stress bulb zone size in relation to depth is 1.5 B away from the model's base and 1.5 B below it (where B is the base's breadth).

The size of the stress bulb region was measured in the current study at 200 and 150 mm from the base in relation to depth and a double component grouting machine PU was used in this process where sodium silicate solution was injected into the tubes into saturated sand samples with 1% by weight of soil at two concentrations of 1:1 and 1:2 to water by weight (sodium silicate to water ratio (S/W)). All of the sensors used in this study—displacement, accelerometer, and pore pressure sensors were then employed after the model had solidified for a full day, see (Fig 6 and Fig 7).

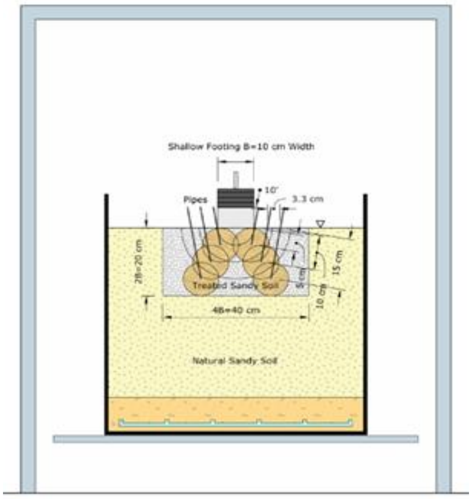


Fig. 6. Test model layout injection

Fig. 7. The pipes injection and the PU machine.

5. Results and Discussion

5.1 Vertical Settlement

Figure 8 shows the settlement of the foundation built on saturated sandy soil treated with sodium silicate injected at two concentrations 1:1 and 1:2 (S/W). It is evident that the settlement rose between 20 and 60 seconds, when the acceleration peaked, and then was nearly constant for the remainder of the test. Observation [23] is comparable to this. Figure 8 illustrates how higher foundation settlement results from saturated sandy soil because the soil's shear strength deteriorates where the settlement rate of the soil reached 14.15 mm. The injection of sodium silica at a ratio of 1:2 reduced the settlement by 57%. Whereas the vertical settlement rate (VSR) (the proportion of the divide between the vertical settlement without treatment and the vertical settlement using sodium silica injection to the vertical settlement without treatment) while when the water ratio was reduced and the sodium silica concentration was 1:1 the settlement rate became 76% due to the formation of a silica gel matrix that binds the soil particles.

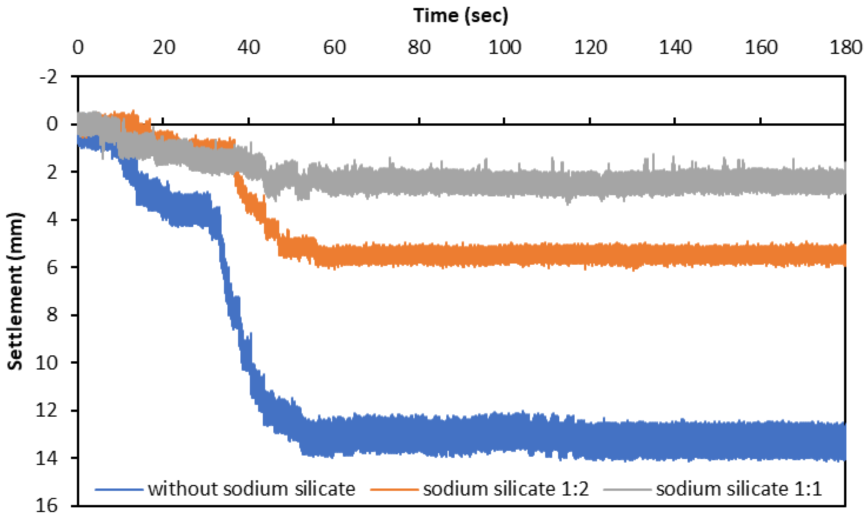


Fig. 8. During the Halabja earthquake, a square foundation settlement on sandy soil that had been wet and injected

5.2 Horizontal Displacement

Both the x and y directions are used to measure the square foundation's horizontal displacement. (Fig 9a, Fig 9b) display findings from the square foundation's horizontal displacement lying on saturated sand soil and soil that has been injected with sodium silica in the directions of x and y, respectively. The shear force of seismic waves that cause the foundation to oscillate back and forth is what causes displacement of the square foundation laterally, as shown in (Fig 9a). The square foundation resting on saturated earth without injection had a horizontal displacement of 26.24 mm. However, when sodium silicate is added to the soil, the HDR, or horizontal displacement ratio decreases (The ratio of horizontal displacement without treatment to horizontal displacement with injection of sodium silica for the horizontal displacement without treatment) was 30 and 60% for the square foundation that was sitting on sand that had been injected with 1:2 and 1:1 proportion, respectively. The outcomes of a y-directional horizontal displacement shown in Fig. 9b showed that the horizontal displacement of the soil without treatment was the highest with a maximum displacement of 2.69 mm.

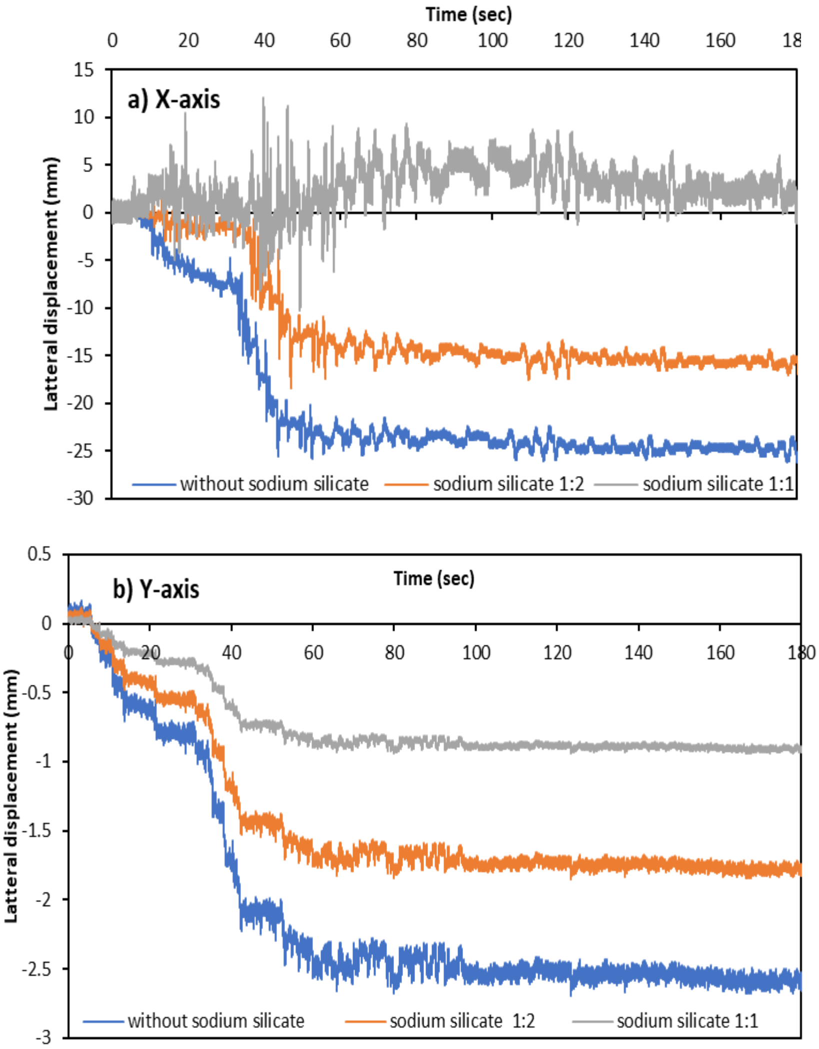


Fig. 9. The Halabja earthquake caused the square foundation to shift horizontally on saturated and injected sandy soil. (a) X-axis and (b) Y-axis

The injection of sodium at a concentration of 1:2 decreased the horizontal displacement using HDR by 31%. While when the water ratio in the sodium silicate concentration was reduced and the concentration became 1:1, the improvement increased as the ratio of horizontal displacement was about 65%. The effectiveness of the injection in improving the sandy soil was proven by creating a silica gel matrix that increases the bonding of soil particles with each other. Additionally, it can be seen that was a noticeable rise in the horizontal displacement between 20 and 60 seconds, when the acceleration intensity increased, and then stayed nearly constant until the test was over.

Additionally, it shown that when the vibration was applied in the x direction, the x-directional horizontal displacement was noticeably greater compared to that in the direction of y. Sodium silicate injection further increases the bearing capacity and toughness of sandy soil by forming a silica gel matrix between sandy soil particles as well as sodium silicate solution. In addition, sodium silicate fills the voids between soil particles, reducing water flow and alleviating pore pressure build-up during seismic events.

5.3 Porewater Pressure Results

Even if the permeability of the sand is high, the pore pressure increases when loose saturated sand is subjected to shaking caused by earthquakes typically rises significantly in a short amount of time without anticipating fast drainage. This step, known as the liquefaction stage, occurs when the pore pressure is excessively high for the sand to withstand; as a result, The shear strength decreases as the sand particles lose touch with one another. drastically drops to less than the pore pressure. The ratio of the effective strength of the sandy soil to the pore pressure created in the saturated sand is known as the liquefaction ratio (Ru) [24]. Liquification takes place if Ru is greater than 1. The pore water pressure was measured in this investigation using two pore pressure transducers, one of which was positioned at a depth of 30 cm (PWP2) and 10 cm (PWP1), respectively. As shown in Fig. 10, three trials were carried out: one for saturated sandy soil that had not been treated, one for saturated sandy soil that had been injected with a 1:2 concentration, and one for a 1:1 concentration. According to the findings, during the Halabja earthquake, in the untreated saturated sandy soil, the pore water pressure accumulates slowly with increasing acceleration, (ru1) reaches the initial liquefaction (1.167) at the shallow soil depth only after 39 s, while (ru2) at the intermediate depth reaches (0.64) and the pore water pressure generation begins to dissipate at about 80 s and reaches the initial value at about 180 s. While sodium silicate was injected at a concentration of 1:2, the highest excess pore water pressure ratio (Ru) recorded at the two depths was (ru1 = 0.88 and ru2 = 0.59), while when the water ratio was decreased with sodium concentration and became 1:1, the Ru ratio was (0.78 and 0.53 (ru1 and ru2) respectively. Compared to the case of loose saturated sand, a significant deterioration in liquefaction potential occurs as the treated soil exhibits a much lower pore pressure ratio. This decrease in pore pressure highlights the effectiveness of sodium silicate injection in improving soil stability and preventing the increase and leakage of pore water pressure upwards, thus reducing the accumulation of excess pore water pressure. Additionally, it can make soil more resistant to liquefaction and thus reduce and delay the liquefaction ratio, and settle the foundation, as shown in (Fig. 10).

5.4 Acceleration Results

The acceleration distribution for the saturated soil as well as the soil treated with sodium silicate is measured by placing four accelerometers; two accelerometers are placed at two different depths of the typical soil (10 and 30 cm from the soil bed's top) and one is placed on the table, while the other is placed on the foundation. The ACC measurement range is ±3 g and the excitation voltage are ± (1.8-5) V. Accelerometers used in saturated soil are insulated with a layer of polyurethane and covered with a plastic cover, then the cover is filled with silicone, and is also fixed with screws to enable the sensor to stick to the soil.

Accelerometer measurement includes a graph of acceleration readings versus vibration time. Generally speaking, a variety of factors, including density of the soil, structure mass, soil type and condition (moist or dry), can either decrease or increase acceleration. The results of untreated sandy soil showed that the acceleration of Halabja tremors inside the soil column is less than the inlet acceleration at the table level, and that the acceleration at the middle depth of the soil column is almost higher than the acceleration at the bottom, while at the top of the soil column the acceleration becomes relatively higher than the acceleration at the middle depth, and is almost equal to the table inlet acceleration because of the study's low relative density, while the acceleration at the base is higher than the inlet acceleration, and the decrease in acceleration amplification was 6% and 20% at depth (10 and 30 cm) respectively, while the acceleration amplification value at the base increased by 65% in untreated sandy soil.

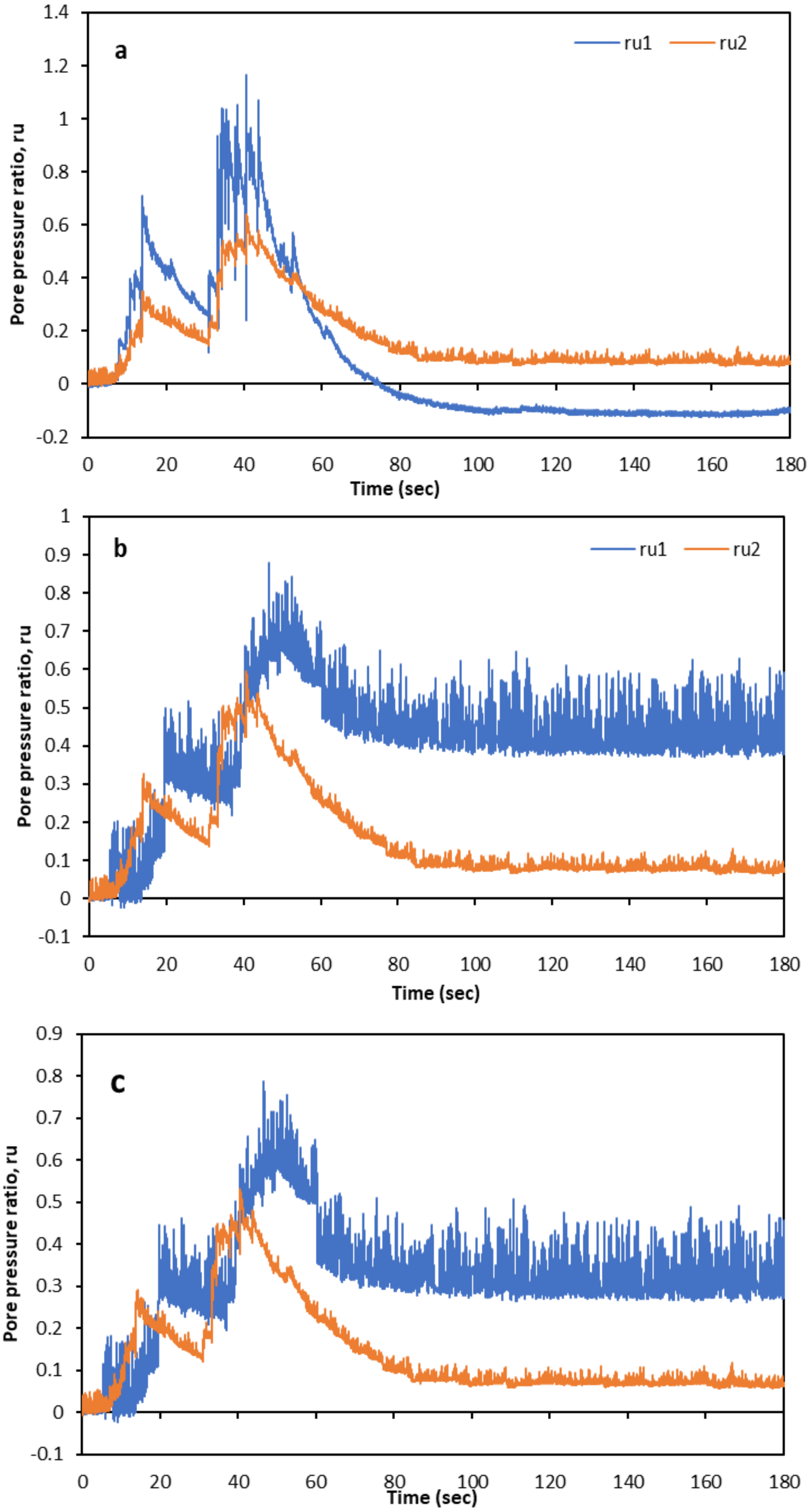
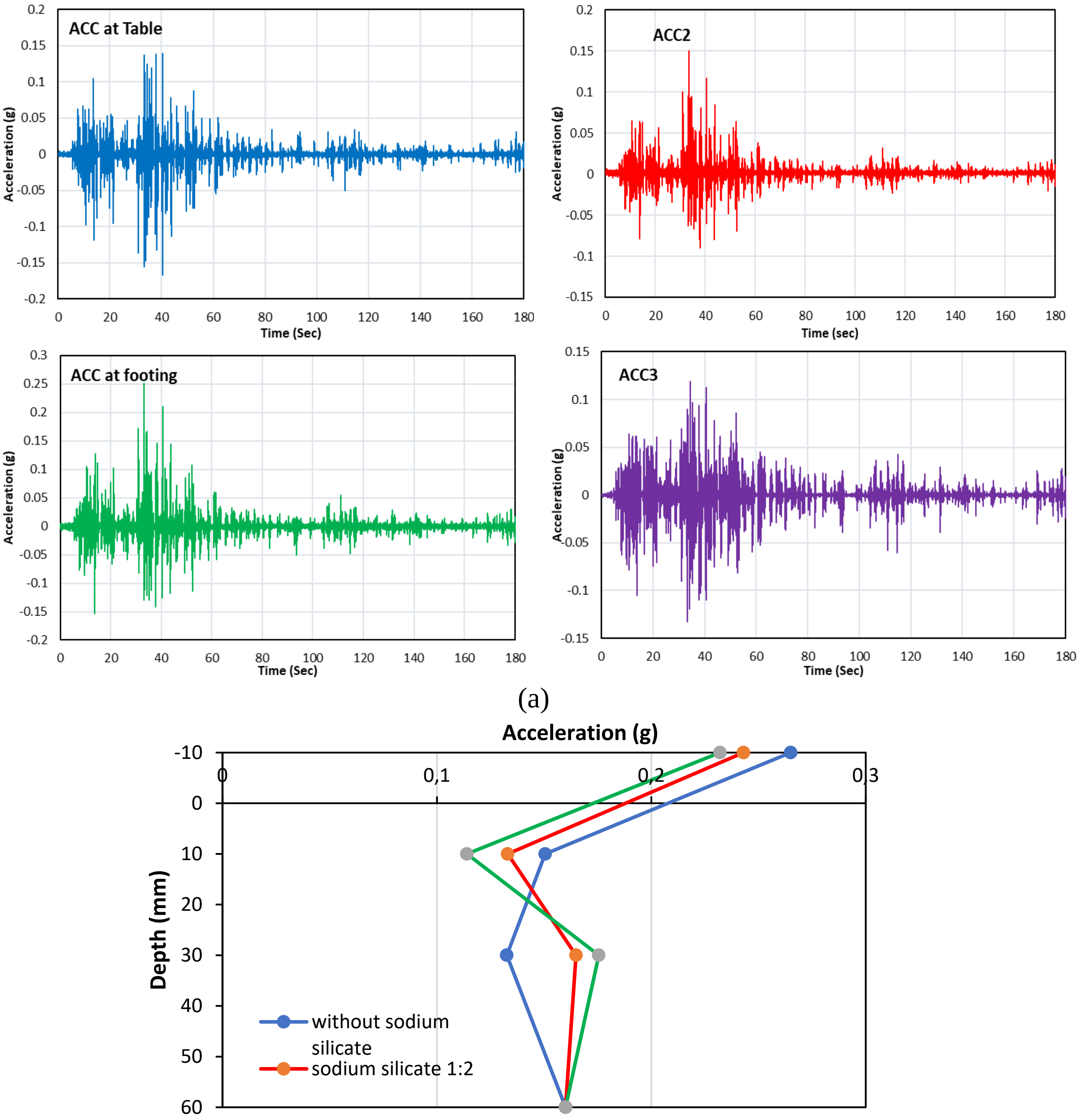


Fig. 10. Under the Halabjah earthquake, the saturated sand soil's excess pore pressure was as follows: (a) without sodium silicate, (b) with sodium silicate 1:2 (S/W), and (c) with sodium silicate 1:1 (S/W)

It can be seen that when sodium silicate was injected into the soil at concentrations of 1:2 and 1:1, the acceleration amplification increased by 3% and 10% at a depth of 30 cm inside the soil column, while the acceleration amplification decreased by 40% and 20% at a depth of 10 cm near the soil surface. The decrease in acceleration amplification can be attributed to the solidification of sodium silicate and the bonding of soil particles with each other in this region, which could cause earthquake vibrations to be absorbed. It was also observed that the acceleration at the foundation decreased mainly at injection concentrations of 1:2 and 1:1 to 9% and 14%, respectively as shown in (Fig 11).



(a)

(b)

Fig. 11. (a) Acceleration time for untreated soil compared to various soil columns (b) Acceleration for untreated and sodium silicate-injected soil along the soil column

6. Conclusions

This study investigated the increase in soil resistance to liquefaction, being administered sodium silicate via a vibrating table method after being exposed to the 2017 Halabja earthquake. Several sensors were used to investigate both X and Y directions of lateral displacement, foundation stability, acceleration of sandy soil, and pore pressure. The following findings were obtained:

- The sodium silicate injection method shows great promise in treating liquefaction in sandy soils under shallow foundations. This technique offers several advantages over conventional methods, as it reduced the lateral displacement and stability of the foundation. The enhancement in the performance of the sand raised when the polymer concentration was 1:1 as it gave stiffness to the sandy soil by forming a silica gel matrix that binds the soil particles.

- The foundation's stability and both X and Y directions of lateral displacement were greater. when sodium silicate was not injected into the sandy soil as the ratios were 26.24 and 2.69 mm respectively.
- The foundation's lateral displacement was 26.24 mm larger than the Y axis's 2.69 mm because the X axis is the one that receives the seismic load.
- The ratio of excess water pressure in the sand layer's pores decreases significantly when sodium silicate is injected, especially when it is at a concentration of 1:1 (S/W) near the surface of the soil compared to the untreated soil. The Halabja earthquake caused the excess water pressure ratio in the pores to drop by about (25 and 33%) when injected at concentrations of 1:2 and 1:1 respectively.
- The acceleration of the sandy soil injected with sodium silicate at a concentration of 2:1 and 1:1 (S/W) doubles at the average depth through the sand column by 3% and 10% and begins to decrease at the soil surface by 40 and 20% and also at the foundation by 9% and 14% respectively.

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