Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 5, No. 3, March, 2019

Improvement of Soft Soil Using Linear Distributed Floating Stone Columns under Foundation Subjected to Static and Cyclic Loading

Mahdi Karkush [a*], Anwar Jabbar [b]

[a] *Assistant Professor, Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq.*

[b] *M.Sc. Student, Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq.*

Received 22 December 2018; Accepted 02 March 2019

Abstract

A stone column is one of the soil improvement methods that are mainly used for improving the geotechnical behavior of soft soils. For deep improvement of soft soil, the floating stone columns are considered the best and effective economically which provide lateral confinement and drainage and longitudinal skin friction. In this study, six tests were carried out on the natural soft soil of undrained shear strength of 5.5 kPa improved by single and two linear distributed floating stone columns. The stone column dimensions are 30 mm in diameter and 180 mm in length and the stone column material is sand of high internal friction angle of 48°. The natural and improved soil samples are tested under isolated raft foundation of dimensions 120×120 mm subjected to vertical static and cyclic loading of frequency 2Hz and continued for 50 seconds. The results showed a significant improvement in soil bearing capacity when reinforced with stone columns despite the small area replacement ratio, where the bearing capacity of improved soil increased by 120 to 145%. The compressibility of improved soil decreased by 57 to 86% in comparison with that of natural soft soil. Also, the floating stone columns reduced the porewater pressure, where the stone columns considered efficient in providing short drainage pathways. This can be one of the reasons why soil reinforced with floating stone columns hold higher cyclic and static stresses regardless the end bearing of stone columns.

Keywords: Floating; Stone Column; Soft Soil; Axial Loading; Cyclic Loading.

---

1. Introduction

Most of the soils located in the middle and southern parts of Iraq are considered as soft to very soft cohesive soils especially in areas close to the marshes. Many projects are planned to be constructed in these areas, in the next coming years, it is expected to construct more than 1400 km of new railway networks and rehabilitation of the current network [1]. Soft clay soil is alluvial sediment formed in the last 10,000 years on a flat surface [2]. The soil is recognized by its high compressibility index ranged (0.19-0.44), the low shear strength (c_u<40 kPa), and high moisture content (40-60) %. One of the challenges that facing the geotechnical engineers is building on soft soil and meet the design project requirements. Mitchell and Jardine [3] recommended alternative method using additional appropriate materials rather than soft soil, relocating the projects to pass the poor area or using deep foundation, redesign the plant to satisfy the weak soil specification or modification of weak natural soil properties to adapt to the design specification of the facility. A stone column is one of the soil improvement methods that is used to increase soil strength, decrease the compressibility of soil, accelerate the consolidation rate and reduce the liquefaction potential of soils, they are mainly used for improving soft soils. Shivani et al. [4] studied the geosynthetic-encased stone columns with combination of ring model footing

* Corresponding author: mahdi_karkush@coeng.uobaghdad.edu.iq

http://dx.doi.org/10.28991/cej-2019-03091280

resting on clay reinforced with stone columns in a square tank testing and observed increase in bearing capacity and reduction in settlement are achieved as compared to ordinary stone column due to increasing confining pressure provided by encapsulating reinforcement. Fahmi et al. [5] investigated the behavior of the soft soil of 15 kPa shear strength and reinforced with ordinary and encased stone columns with geogrid under cyclic loading. Also, they used PLAXIS 3D software for verification of the enhanced method of utilizing stone columns and field load exams. They concluded that the models subjected to cyclic loading under the rate of loading 10 mm/sec reached the failure level faster than models tested under the rate of loading 5 mm/sec. The results of the PLAXIS 3D of settlement compared with the measured settlement in the laboratory yield a reasonable comparable value up to 50% of the design load. Afterwards, the recorded settlements show up to 60% higher values in compare with the results of the finite element analyses. Shehata et al. [6] studied numerically the effects of construction system of stone columns in soft clay on the load-settlement behavior of the treated ground, where High radial displacements of the soil particles associated with the installation process of the stone columns to achieve their target diameter, significantly alter the surrounding soil properties and affect the overall performance of the improved soil. Different radial excitations have been considered in the analyses to mimic the construction procedure. Aspects of the two- and three-dimensional numerical analyses are combined in this study to overcome the local numerical instabilities.

Zukri and Nazir [7] presented short review about the material used in construction the stone columns. Stone columns are considered the most “natural” soil treatment method or foundation system, where replacement of some soft or loose soil with those of more density will increase the confinement pressure leading to increase the strength of soil and reduce the compressibility of soil. Also, in saturated cohesive soil will increase the time rate of consolidation. For the deep improvement of soft soils, when the depth is greater than 25 meters and the columns do not reach the bearing layers, the built-up stone columns are called floating stone columns [8]. Floating stone columns are considered the best and effective economically technique used in improvement of soft and loose soils [9]. The stone columns had been widely used in the reinforcement and stabilization the railways constructed on the soft soils to control deformation and excessive porewater pressure [10]. Previous studies such as [11, 12] focused on improving the soil by end bearing stone columns and their behavior under the static loads, but the information remains limited about the floating stone columns when subjected to cyclic loads. In this study, six tests are carried out on the natural soft soil of undrained shear strength (5.5 kPa) improved by single and linear two floating stone columns which have 30 mm diameter and 180 mm length to increase the bearing capacity of soil, reducing the expected settlement of soil, and increasing the time rate of porewater dissipation.

2. Material and Methods

2.1. Natural Soft Soil

The soil is brought from a depth of 9 meters underground surface from Al Nahrawan city which is located 35 km to east of Baghdad city. The disturbed and undisturbed samples had been taken from a depth under groundwater table. The undisturbed samples are taken by Shelby tubes to study the mechanical properties of natural soil, while the disturbed sample of natural soil was used to determine the chemical and physical properties and then used in the physical model setup to measure the bearing capacity and compressibility properties of soil. The physical and chemical properties of the natural soft soil are listed in Table 1.

Table 1. The physical and chemical properties of natural soft soil

Property index	Value	Standards	Property index	Value	Standards
Liquid limit, %	35	ASTM D 4318	Sand content, %	10.0	ASTM D 422
Plastic limit, %	19	ASTM D 4318	Silt content, %	50.0	ASTM D 422
Plasticity index, %	16	ASTM D 4318	Clay content, %	40.0	ASTM D 422
Liquidity index, %	0.625	ASTM D 4318	TSS, %	5.72	B.S. 1377:1990 [13]
Specific gravity (Gs)	2.7	ASTM D854	SO_3, %	1.799	B.S. 1377:1990
Maximum dry unit weight (kN/m^3)	17.2	ASTM D1557	Cl^{-1}, mg/l	0.126	B.S. 1377:1990
Optimum moisture content, %	19.0	ASTM D1557	OMC, %	0.782	B.S. 1377:1990
Soil symbol according to USCS	CL	-	Gypsum, %	3.868	B.S. 1377:1990
			pH	7.11	B.S. 1377:1990

2.2 Stone Column Material

Sand is chosen to simulate the stone column material because it has an appropriate friction angle (more than 35°) and used by 50% of the researchers. The properties of the used sand are listed in Table 2, these properties are determined in accordance with (ASTM, 2003) [14]. The relative density of floating column material was selected as 65% because Shahu and Reddy [15] showed that if the density is greater than 80%, it would be very difficult to obtain a regular stone column at construction. After choosing the column diameter and length, it's necessary to select an appropriate particle size of stone column material. Wood et al. [16] emphasized that the typical ratios of column diameter to particle diameter (D/d) ranged from 12 to 40%. Al-Shaikhly [17] also emphasized that the maximum value of improvement occurred when D/d ranged from 11 to 40%. Therefor the size of sand particles was selected within the measurement of ranges between (0.7-2.5) mm which resulted D/d ratios ranged from 12 to 43 that is mean the sand particles passing through the sieve #8 and kept on sieve #25. The distribution of particle size of the natural soft soil was determined by a hydrometer according to ASTM D 422 and the particle size distribution of the sand used in the stone columns was determined using a dry sieving analysis method as shown in the Figure 1.

Table 2. The properties of stone column material

Property index	Value	Standards
Maximum dry unit weight (kN/m^3)	19.1	ASTM D4253
Minimum dry unit weight (kN/m^3)	14.4	ASTM D4254
Dry unit weight (kN/m^3) at Dr =65%	17.2	-
D_{10} (mm)	0.9	ASTM D422
D_{30} (mm)	1.3	-
D_{50} (mm)	1.75	-
D_{60} (mm)	2.0	-
Coefficient of uniformity (Cu)	2.22	-
Coefficient of curvature (Cc)	0.94	-
Suitability number (S_N)	3.0	-
Specific gravity (Gs)	2.65	ASTM D854
Angle of internal friction φ (°)	48.5	ASTM D3080

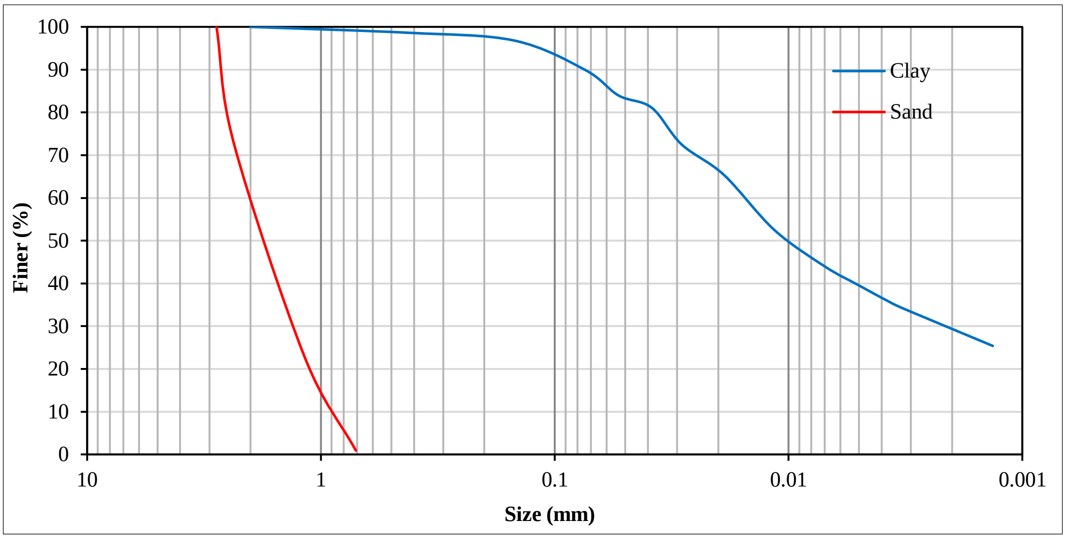

Figure 1. The particle size distribution curves of the natural soft soil and stone column sand

2.3 Compressibility and Shear Strength of Soft Soil

The compressibility characteristics of natural soft soil are measured by conducting 1-D consolidation test according to the procedure recommended by ASTM (D2435-70). The diameter of the consolidated ring was 50 mm and 20 mm high. The coefficient of volume compressibility (m_v) ranges from 0.07 to 1.07 m^2/MN and the coefficient of consolidation (c_v) equals to 0.05 cm^2/sec. The direct shearing test was determined in accordance with ASTM D 3080-98 for sand used in stone columns and natural soft soil. The minimum width of sample must be more than at least ten times the maximum particle size and the sample thickness must be more than at least six times the maximum particles, so the dimensions of the box used in the test are 60×60×30 mm. The undrained shear strength (c_u) of soft soil is 8 kPa and the internal angle of friction is 9.5° due to the presence of 10% of sand in the soft clay soil. The unconfined compression strength test was performed and determined according to ASTM D 2166-00 standard. The sensitivity (S_t) of the natural soil sample equals to 1.13 which calculated according to Equation 1. Accordingly, the soft clay soil can be classified as slightly sensitive [18].

$$S_t = \frac{q_u(undisturbed)}{q_u(remolded)} \quad (1)$$

Where q_u is the unconfined compression strength of soil. Also, the undrained shear strength of soil is measured by conducting the unconsolidated undrained triaxial test on natural soft soil. The undrained shear strength (c_u) calculated by applying confining pressures of (100, 200, and 300) kPa is equal to 11 kPa. The results of compressibility and shear strength parameters of soft clay soil sample are given in Table 3.

Table 3. Compressibility and shear strength parameters of natural soft soil

Index property	Index value
Initial void ratio (e_o)	0.78
Compression index (c_c)	0.166
Swelling index (c_r)	0.027
Coefficient of consolidation (cv) (cm^2/sec)	0.05
Avg. coefficient of volume change (m_v) (m^2/MN)	0.49
Coefficient of permeability (k) (cm/min)	1.45E-08
Angle of internal friction for soft soil, φ (°) (direct shear test)	9.5
Undrained shear strength for soft soil, c_u (kPa) (direct shear test)	8.0
Undrained shear strength for undisturbed soft soil, c_u (kPa) (unconfined compressive strength test)	5.5
Undrained shear strength for remolded soft soil, c_u (kPa) (unconfined compressive strength test)	4.84
Undrained shear strength for undisturbed soft soil, c_u (kPa) (unconsolidated undrained triaxial test)	11

3. Experimental Study and Results

A laboratory physical model is designed for the purpose of studying the effects of the stone columns on the soil bearing capacity and compressibility of soil under static and cyclic loads. The steel container is (700×700×600) mm made of a 3 mm thickness steel plate supported by angles of 8 mm thickness at the corners. Also, there is a steel pipe welded to the angles to support and prevent any movement of lateral steel plates. At 100 mm apart from the container base there is a steel plate with holes of 5 mm each 50 mm apart. This plate was supported from the bottom to ensure no movement during vertical loading. The purpose of the plate is to act as filter plate and two pieces of geotextile was placed over the filter plate to allow drainage and prevent clay particles from passing through the filter plate. The dimensions of the tank (700×700) mm were chosen to achieve the free distance between the outer edge of the column and the tank wall as shown in Figure 2.

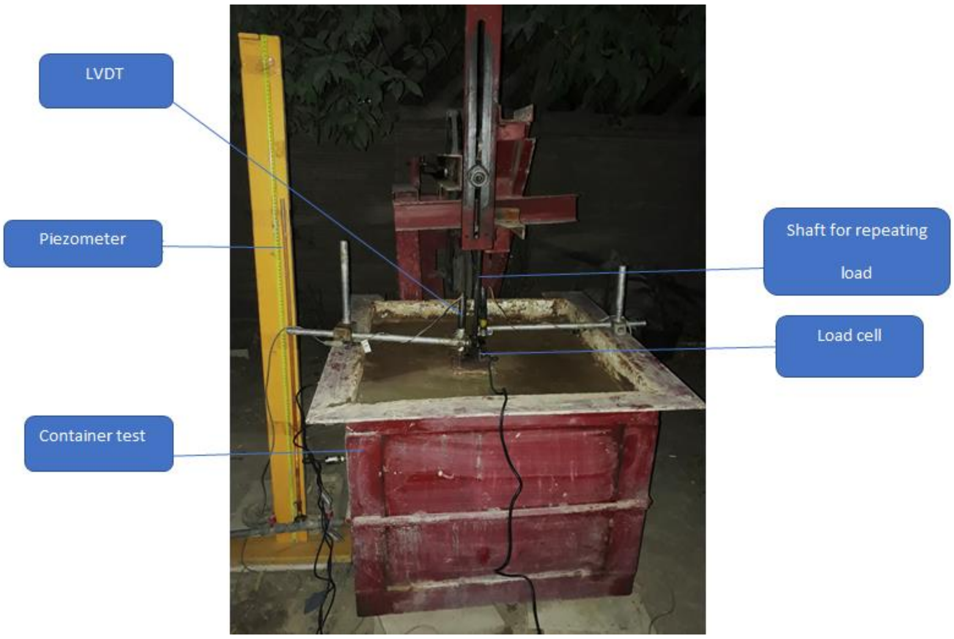

Figure 2. The physical model used in testing soil samples under cyclic loading

Steel loading frame is used to support the mechanical jack and axial loading system. The axial loading system is connected through a mechanical jack associated by an engine and AC drive (speed controller), which controls the speed of the engine. The most extreme load that can be connected is around 1 ton. At (1 mm/min) the loading rate is kept constant as suggested by ASTM D1143. The axial loading system consists of:

- Mechanical jack: The load that can be connected through the mechanical jack is around 2 tons in weight.
- Gear box: Is an engine with a high drive, it has the ability to apply high torque and can control the axis speed through AC motor (speed control). The shaft is connected by the mechanical socket.
- AC Drive (speed controller): The device is directly connected to gearbox to control the speed of the.

The natural and improved soil samples are tested under isolated raft foundation of dimensions 120×120 mm subjected to vertical static and cyclic loading. The required amount of soil was collected in a large container and mixed with the natural water content of 29%, The amount of soil required to fill the container was divided into 5 layers, after finishing the ending layer, the top surface had been scraped to get a flat surface then covered with polythene sheets to prevent any loss of moisture. The soil left in steel container covered with polyethylene sheets for (8-10) days to regain strength and get stable soil surface. Fattah et al. [12] stated that for curing the bed soil before test should covered and left for a period of 5 days. The diameter of stone column is selected to be 30 mm and spacing (centre to centre) is 75 mm. The typical length/column diameter ratio (L/D) is generally between 6 to 10, so the column length is chosen according to this ratio. Mckelvey et al. [19] stated that no respectable increase within the load carrying capability urged to be obtained beyond L/D ratio greater than 10. Each column instilled by drilling a hole by a suitable auger and filled with the predetermined mass of the sand mass which divided equally into groups and added into the hole with ramming until the desired densification is achieved. The pore pressure readings are recorded from the piezometer installed at the bottom of container during each load increment.

The instruments used in physical model are:

- Load cell with digital weighing indicator: Pressure/tension load cell is utilized to measure load with input accuracy of 50 g and capacity of 1 ton was calibrated locally.
- Porewater pressure transducers with digital indicator: The pore pressure electronic reading unit connected to the three pressure adapters. The transducers are connected at the side of test box at distances of (5, 20, 35) cm apart from the surface of soil.
- LVDTs data system: Two linear variable displacement transducer (LVDT) with digital indicator have been used to get accurate readings and measuring of movements as small as a few parts of millimetres. These sensor devices measured linear displacement and very accurate (calibrated as 1 mm = 0.172 V and 0.309 V) respectively.

3.1. Load-Settlement Relationship under Static Load

The loading capacity of natural soft soil (no column) was found to be around 0.44 kN which equivalent to bearing capacity of approximately 31 kPa. The measured value of bearing capacity (31 kPa) is well agreed with the bearing capacity of soil (28.27 kPa) calculated by Terzagh's equation.

$$q_{ult} = 5.14\ c_u \tag{2}$$

Where c_u is the undrained shear strength of the soft soil (5.5 kPa), 5.14 is the bearing factor for clay (N_c), and q_{ult} is the ultimate bearing capacity of soil. The ultimate bearing capacity of untreated soil (SL0) is compared with that of the reinforced soil with single floating stone column (SL1) and two floating stone columns (SL2) floating stone columns as shown in Figure 3. It was noted that the presence of the columns developed the bearing capacity of the weak soil. The ultimate bearing capacity of the soil was improved by 75% with one stone column and this increase is good for the area replacement ratio of 4.9%. Abdul Husain [20] and many researchers have reported that improvement in soil does not occur significantly except for the area replacement ratio greater than 15%. This significant improvement was due to the large angle of internal friction of the floating stone column (48°) compared to the rest of the studies.

$$A_r = \frac{A_C}{A_{foot}} \tag{3}$$

Where A_r is area replacement ratio; A_C is area of stone column cross; A_{foot} is area of isolated foundation. Table 4 shows a comparison between the ultimate bearing capacity of soil (q_{ult}) measured experimentally with those calculated theoretically by modified Davisson equation [21]. The results showed that the results obtained from Davison's equation are more conservative.

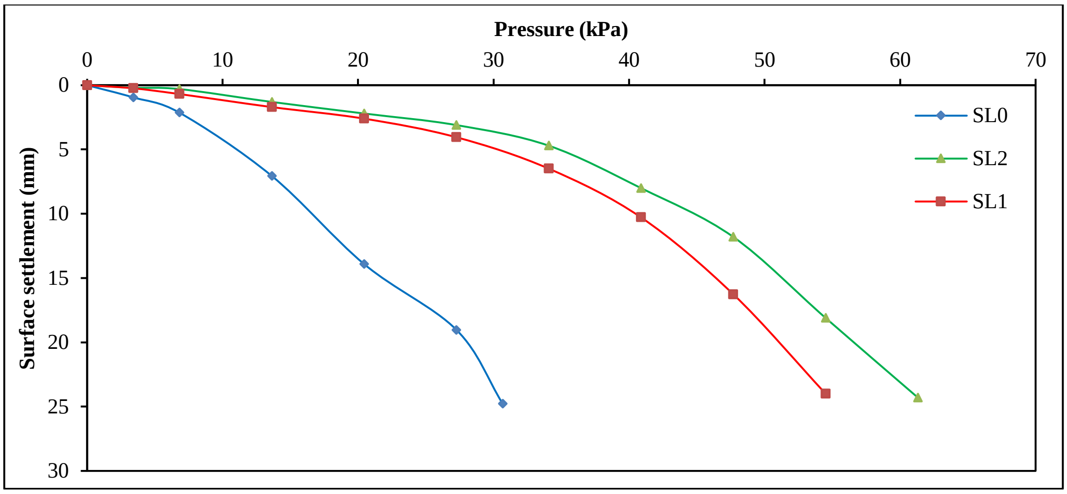

Figure 3. Pressure versus settlement under foundation subjected to static loading for untreated and reinforced soil samples

Table 4. Summary of the static bearing capacity values

Loading symbol	No. of stone columns	q_{ult} (kN/m^2)		% of Deviation
		Measured	Davisson Eq.	
SLO	-	28.27	31.0	9.6
SL1	1	47.7	54.5	14
SL2	2	50.0	61.0	22

3.2. Load-Settlement Relationship under Cyclic Loading

Cyclic loading tests carried out on natural soft soil (nonreinforced) (CL0) and two tests on soil reinforced with single floating stone column (CL1) and two floating stone columns (CL2). All tests were conducted under cyclic stresses of 100 cycles of frequency 2 Hz. The results of cyclic loading tests are shown in Figure 4 which shows cyclic stresses against settlement. Results showed the influence of cyclic stress levels (20.44, 27.25, 34.06, and 40.88 kPa) on the settlement of footing constructed on soft soil reinforced with floating stone columns.

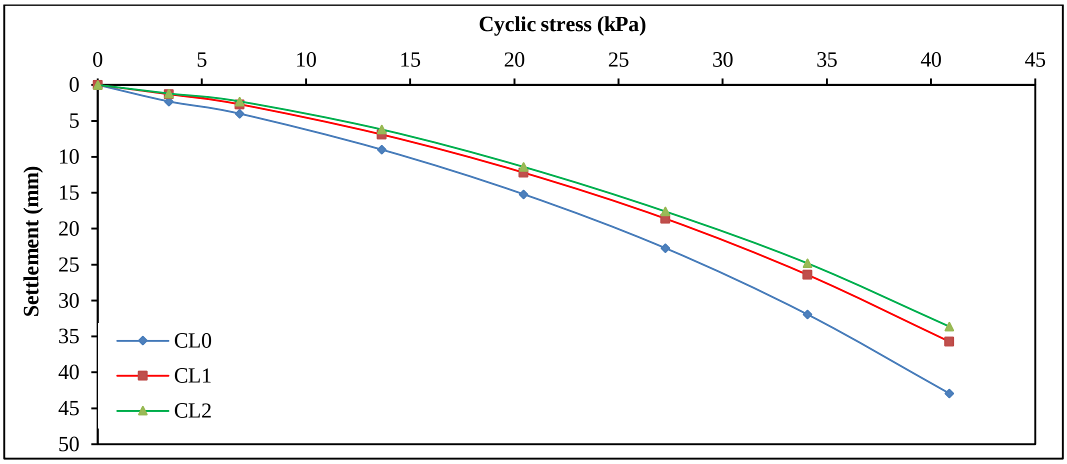

Figure 4. Relationship between cyclic stresses with surface settlement

Natural soft soil sample was more sensitive to loading change than the reinforced soil samples. For soft soils supported by stone columns under cyclic stress of 27.25 kPa, there was a reduction in the settlement in comparison with the natural soft soil by (17 and 22) % in soil specimens CL1 and CL2 respectively. Figure 5 shows the settlement against number of cycles, for natural soft soil (CL0) and soil reinforced with one column (CL1). Results showed the influence of cyclic stress levels (20.44 and 27.25) kPa on the deformation pattern of CL0 and stress levels (20.44, 27.25, and 34.06) kPa on the deformation pattern of CL1. It can be observed that for both soil samples (CL0 and CL1), the accumulative settlement growth was significantly affected by increasing the cyclic stresses. In the range of the loading examined, CL0 is more sensitive to increasing the number of loading cycles and cyclic stresses than CL1.

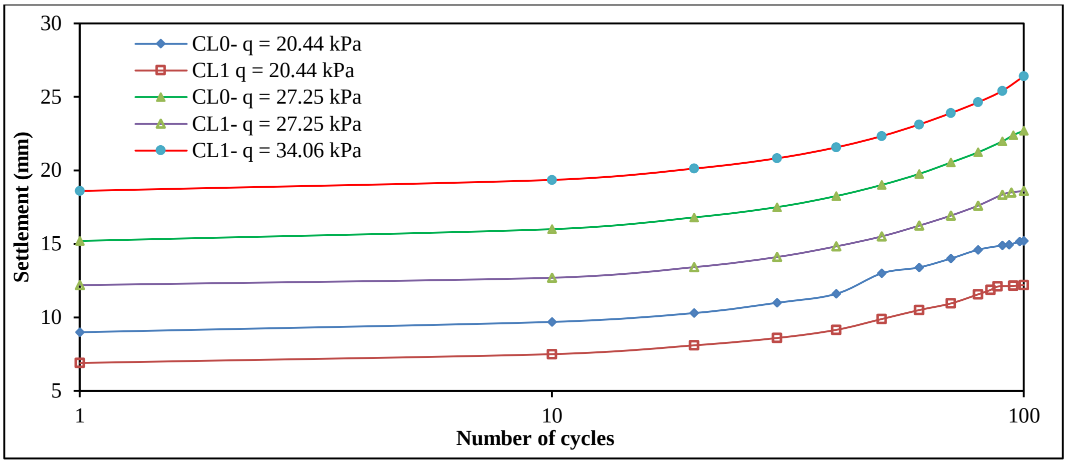

Figure 5. Variation of settlement with number of cycles for soil samples CL0 and CL1 under different cyclic stresses

When the tests were performed at cyclic stress of 20.44 kPa, the results showed that the soil sample (CL0) began to stabilize after 92 cycles because of cyclic loading was within soil capacity, so it will compact the soil particles and increase its strength. Otherwise, under cyclic stress of 27.25 kPa, the specimen settlement continues to increase. On the other hand, the sample with one stone column was tested under cyclic stresses of 20.44 kPa, the progress of the settlement began to stabilize approximately after 85 cycle at a value of 12.2 mm. This value increased to reach 18.6 mm by increasing the cyclic stress to 27.25 kPa and began to stabilize after 93 cycles. But, the soil sample (CL1) when tested under cyclic stress of 34.66 kPa, the specimen was failed in shear because the specimen continues to settle with increasing the number of cycles. While the specimen reinforced with two stone columns (CL2) was tested under cyclic stress of 27.25 kPa, the settlement after 80 cycles encountered to 17.6 mm as shown in the Figure 6.

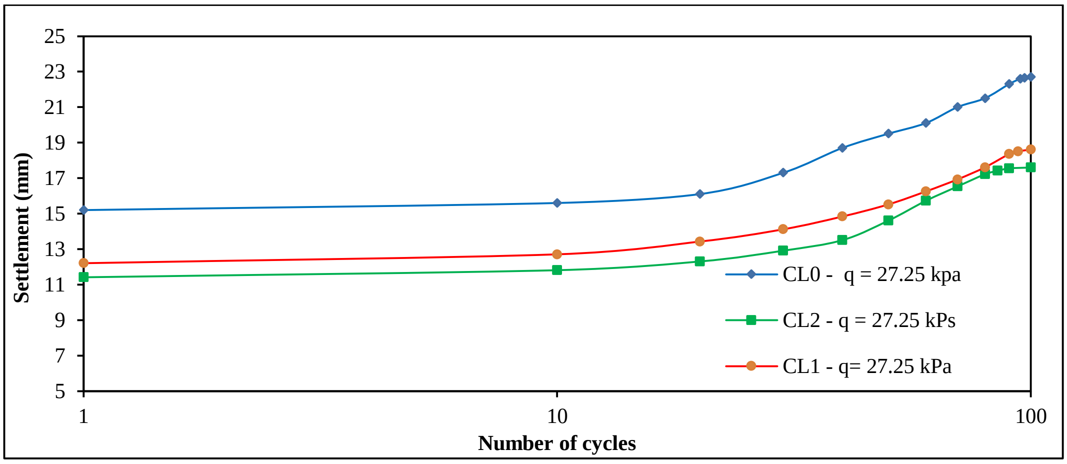

Figure 6. Variation of settlement with number of loading cycles for tested soils under cyclic stress level of 27.25 kPa

Das and Shin [22] pointed out that the initial rapid adjustment resulting from the application of cyclic load occurs during the first 10 cycles of loading, which constitute 60-80% of the total adjustment. Based on the final permanent settlement definition, the experimental value of the critical number of cycles (Ncr) (within 100 cycles) was determined, at which settlement stabilized for each test. The critical time and number of load cycles (Ncr) is shown in Table 5. Figure 7 shows the effect of the area replacement ratio (Ar) on the improvement in the soil under the effect of cyclic and static loads, where the results indicated that the settlement under cyclic loads is greater than the static load in all tests especially in light loads and this difference decreased with increasing the applied loads to be roughly equal in high load. The soil becomes more resistant to static loads. The notations used in Figure 6 are $A_{r1} = (\frac{A_c}{A_{fot.}})^2$= 4.9 % for test of single stone columns and A_{r2}= 9.82%. Where A_c is the column cross section and A_{foot} is the foundation area.

Table 5. The critical number and time of load cycles

load	Loading Symbol					
	CL0		CL1		CL2	
	No. of cycles	Time (sec)	No. of cycles	Time (sec)	No. of cycles	Time (sec)
20.44 kPa	92	46	85	43	-	-
27.25 kPa	-	-	93	47	80	40

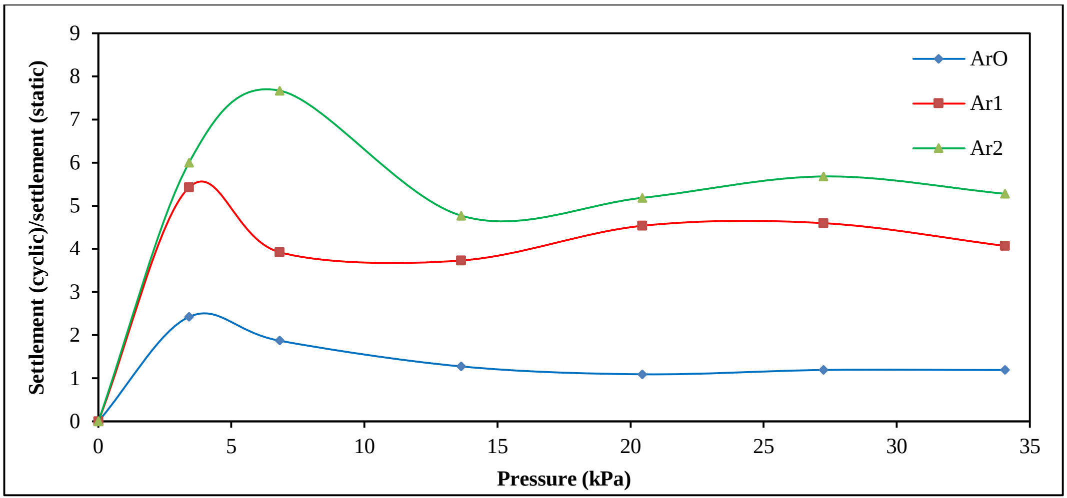

Figure 7. Ratio of settlement at acyclic/static loading for different area replacement ratio of floating stone columns

4. Effects of Stone Columns on Porewater Pressure

4.1. Static Loading

Porewater pressure (PWP) is measured during the static loading in two methods. The first one (PP1) includes installation of stand piezometric pipe at the bottom of soil layers and the second method (PP2) include installation of porewater pressure transducers at different levels on the side of container (5, 20, 35) cm. The distances are measured from the soil surface in the container of physical model. These transducers will be termed as ch1, ch2, and ch3 respectively. The transducer (ch1) didn't show any reading during the tests. Figure 8 shows the results of changes of PWP occurred during the static loading for all soil samples and under different levels of stress. The presence of stone columns helped to decrease the porewater pressure because they worked as drainage wells and shortening the drainage paths. The comparison of porewater pressure values at certain stress level, for example at loading 34.05 kPa, the porewater pressure was 4.99 kPa for SL1 and continue to decrease for SL2. These results indicate that the stone columns provide good and easy drainage pathways and reducing the porewater pressure.

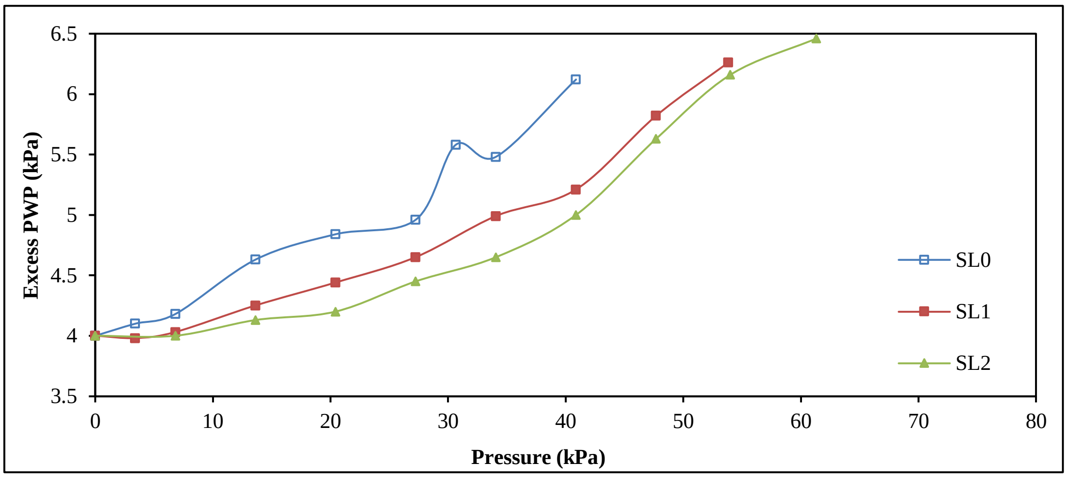

Figure 8. Variation of excess porewater pressure under static loading (PP1) in tested soil samples

4.2. Cyclic Loading

Porewater pressures were measured during cyclic loading at the bottom of the soil specimen by using piezometer. Figure 9 shows the values of PWP generated under cyclic stresses levels of (20.44 and 27.25) kPa where 20.44 kPa is the cyclic stress at which the natural soil has stabilized and 27.25kPa is the cyclic stress in which the reinforced soil has stabilized. Under application of cyclic loading, the excess pore water pressure was built up with increasing the cyclic stresses. The applied cyclic stresses will help in generation high porewater pressure and when enough drainage paths are available will help in decreasing this pressure quickly, but when the capacity of available drainage, stone columns, are not enough to dissipate the porewater pressure, this will help in raising the PWP. Figure 9 shows the relationship between the ratio of pore pressure in the case of cyclic loading/pore pressure in case of static loading with applied loads. From the results shown in Figure 10, it is clear that in the case of the small replaced area, as in tests CL1 and CL2. Increasing the loads lead to increase porewater pressure and PWP would decrease with increased replacement area ratio.

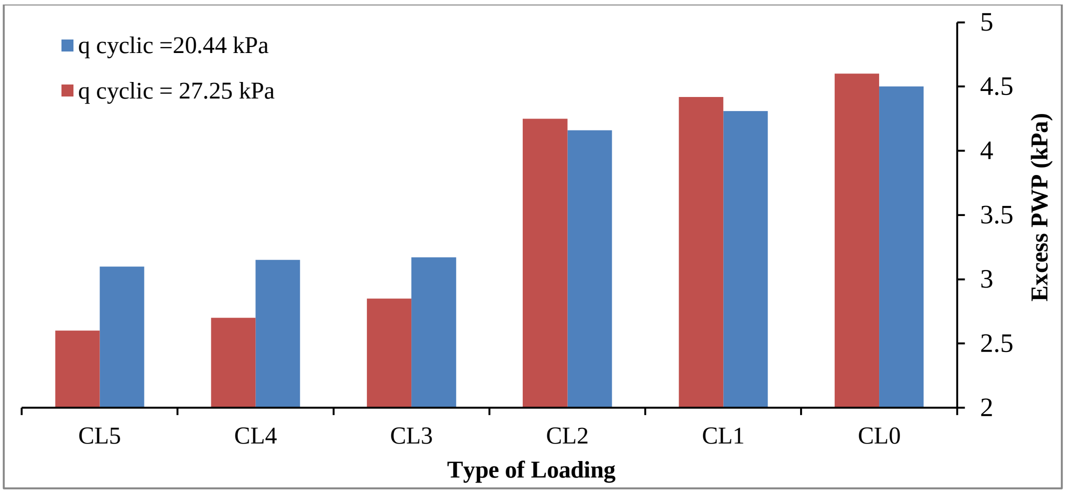

Figure 9. Values of excess PWP measured by piezometer for all soil samples under different cyclic loading levels

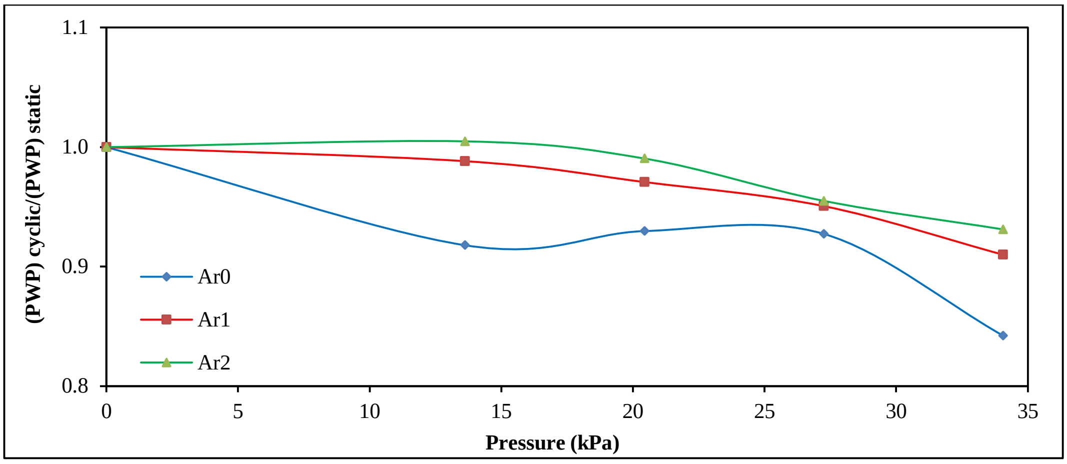

Figure 10. The ratio of PWP (cyclic)/PWP (static) and loading for different ratios of area replacement of stone columns

5. Conclusions

- Reinforcement the soft clay with floating stone columns lead to increase the bearing capacity of the soil by a factor of 120% (supposed the failure load corresponding to settlement equals 20% from the foundation width) for isolated columns and 145% times for group of columns.
- The floating stone columns lead to improve settlement through reducing the settlement corresponding to the failure load by 86% for the group of stone columns and by 57% for the single floating stone column.
- The results showed a significant improvement in soil bearing capacity under the influence of static loads despite the small area replacement ratio. For example, in SL1 test, the replacement area is 4.9 % and column materials of high friction angle (48°), the improvement rate was approximately 1.75 times that in the natural soft soil.
- The floating stone columns improves the threshold cyclic stress of soft soil, for example in CL2 test, the threshold cyclic stress rises from 20.44 kPa for the natural soft to be 27.25 kPa for the soil reinforced with two stone columns.
- The floating stone column reduces the porewater pressure under both static and cyclic loading to provide water drainage pathways. This can be one of the reasons why reinforced soil holds higher cyclic stresses.

6. Acknowledgement

The authors expressed their thanks and appreciation to the staff of soil mechanics laboratory at the Department of Civil Engineering/University of Baghdad for their assist in conducting laboratory tests.

7. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] Abbawi, Z.W. "Evaluation of improvement techniques for ballasted railway track model resting on soft clay" Ph. D. Thesis, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq (2010).

[2] Malarvizhi, S. N., and K. Ilamparuthi. "Load versus settlement of clay bed stabilized with stone and reinforced stone columns." In 3rd Asian Regional Conference on Geosynthetics, pp. 322-329. 2004.

[3] Mitchell, John Michael, and Finlay M. Jardine. A guide to ground treatment. Vol. 573. London: CIRIA, 2002.

[4] Verma, Shivani, Vikas Kumar, and Akash Priyadarshee. "An Experimental Test Study on Ring Footing Resting on Clay Bed Reinforced by Stone Column." Innovative Infrastructure Solutions 3, no. 1 (August 20, 2018). doi:10.1007/s41062-018-0169-9.

[5] Fahmi, Kwa Sally, Mohammed Fattah, and Alena Shestakova. "Behavior of Foundation Soil Improved by Stone Column under Cyclic Load." Edited by A.D. Abramov and V. Murgul. MATEC Web of Conferences 239 (2018): 05015. doi:10.1051/matecconf/201823905015.

[6] Shehata, H. F., T. M. Sorour, and A. L. Fayed. "Effect of Stone Column Installation on Soft Clay Behavior." International Journal of Geotechnical Engineering (May 25, 2018): 1–13. doi:10.1080/19386362.2018.1478245.

[7] Zukri, Azhani, and Ramli Nazir. "Sustainable Materials Used as Stone Column Filler: A Short Review." IOP Conference Series: Materials Science and Engineering 342 (April 2018): 012001. doi:10.1088/1757-899x/342/1/012001.

[8] Datye, K.R. "Settlement and bearing capacity of foundation system with stone columns." Int. Symp. on Soil and Rock Improvement Techniques Including Geotextiles, Reinforced Earth, and Modern Piling Methods, Asian Institute of Technology (1982).

[9] Sivakumar, V., Boyd, J.L, Black, J.A., and McNeil, J. A. "Effects of granular columns in compacted fills." Proceedings of the Institution of Civil Engineers - Geotechnical Engineering 163, no. 4 (August 2010): 189–196. doi:10.1680/geng.2010.163.4.189.

[10] Fatahi, B, H Khabbaz, and T Le. "Improvement of Rail Track Subgrade Using Stone Columns Combined with Geosynthetics." Advances in Transportation Geotechnics 2 (September 13, 2012): 202–206. doi:10.1201/b12754-26.

[11] Ashour, Samir. "The response of stone columns under the cyclic loading." PhD diss., University of Birmingham, 2016.

[12] Fattah, Mohammed Y., Mohammed A. Al-Neami, and Ahmed Shamel Al-Suhaily. "Estimation of Bearing Capacity of Floating Group of Stone Columns." Engineering Science and Technology, an International Journal 20, no. 3 (June 2017): 1166–1172. doi:10.1016/j.jestch.2017.03.005.

[13] BS 1377. "Methods of Test for Soils for Civil Engineering Purposes" British Standards Institution (BSI) (1975). doi:10.3403/30306957.

[14] ASTM. "Annual Book of American Society for Testing and Material Standards" ASTM Tech Publications (2003).

[15] Shahu, J. T., and Y. R. Reddy. "Clayey Soil Reinforced with Stone Column Group: Model Tests and Analyses." Journal of Geotechnical and Geoenvironmental Engineering 137, no. 12 (December 2011): 1265–1274. doi:10.1061/(asce)gt.1943-5606.0000552.

[16] Wood, D. Muir, W. Hu, and D. F. T. Nash. "Group Effects in Stone Column Foundations: Model Tests." Ground and Soil Improvement (January 2004): 119–128. doi:10.1680/gasi.31708.0016.

[17] Al-Shaikly, A. ,2000 "Effect of stone grain size on the behavior of stone columns" M.Sc. Thesis, Building and Construction Engineering Department, University of Technology, Iraq.

[18] Das, Braja M. "Advanced soil mechanics. Crc Press, 2013.

[19] McKelvey, D., V. Sivakumar, A. Bell, and J. Graham. "Modelling Vibrated Stone Columns in Soft Clay." Geotechnical Engineering 157, no. 3 (July 2004): 137–149. doi:10.1680/geng.157.3.137.42416.

[20] Abdual Husain, H. A. (2000), "The behavior of groups of stone columns in soft clay" M.Sc. Thesis, Building and Construction Engineering Department, University of Technology, Iraq.

[21] Davisson, M. T. "High capacity piles. in Innovations in Foundation Construction." Proceedings of a lecture series, Illinois Section ASCE, Chicago (1973).

[22] Das, Braja M., and E. C. Shin. "Laboratory model tests for cyclic load-induced settlement of a strip foundation on a clayey soil." Geotechnical & Geological Engineering 14, no. 3 (1996): 213-225. doi: 10.1007/BF00452948.