Strength Improvement of Soft Soil Treated Using Stone Columns

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Abstract

A total number of 12 models tests were carried out on models of soft clays of different values of undrained shear strength varying from 8 to 18 kPa. The tests consist of twelve models of stone columns, single column, two-column group, three-column group, four-column group, five-column group and six-column group, in addition to one model of untreated soil.

The undrained shear strength has been measured using portable vane shear before testing and after failure of model. It was noticed that the undrained shear strength of model stone columns increased by about (5.6 -20) % due to the construction of stone columns. The provision of stone column in soft clay bed caused an increase in the bearing capacity of the foundation bed by (1.76 - 2.91) times for floating stone columns and (2.13 – 3.15) times for end bearing columns.

Keywords: Stone columns, soft clay, undrained shear strength, improvement.

تحسين مقاومة التربة الطينية الضعيفة المعالجة بالاعمدة الحجرية

الخلاصة:

تم اجراء الأختبارات على اثني عشر موديلا لتربة طينية ضعيفة تتراوح قيمة مقاومة القص غير المبزول فيها بين (8- 18) كيلوباسكال وتتضمن الأختبارات عمود حجري واحد و عمودين و ثلاثة اعمدة و أربعة أعمدة و خمسة أعمدة وستة أعمدة بالأضافة الى موديل لأساس على تربة طينة ضعيفة فقط.

تم قياس مقاومة القص غير المبزول بأستخدام جهاز فحص القص بالأرياش المختبري قبل الفحص وبعد حصول الفشل لكل موديل. و قد لوحظ بأن مقاومة القص غير المبزول تزداد بنسبة تتراوح بين (5.6 - 20) % وذلك بسبب انشاء الأعمدة الحجرية وأن قابلية تحمل التربة تزداد بنسبة تتراوح بين (1.94 – 1.32) للأعمدة الحجرية الطافية وتزداد بنسبة (1.7 – 2.5) للأعمدة الحجرية ذات التحمل عند النهايات.

INTRODUCTION

Soft soil is extensively located especially in coastal areas and they exhibit poor strength and compressibility. Two main problems are encountered when undertaking construction in soft soil deposits, excessive settlement and low shear strength, (Barksdale and Bachus, 1983; Bergado et al., 1996).

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According to Terzaghi, 1943 (as cited by Brand and Brenner, 1981), they are defined as clays, normally or lightly over consolidated, with liquidity index greater than 0.5.

There are several methods for the improvement of soft soil among of them is the stone columns. There are different methods for the installation of stone columns and one of the most frequently used installation methods of stone columns is the bottom feed vibro-displacement method, where compressed air is used to flush a vibrating probe into the ground and the pile is inserted by displacing the soil. Sand or gravel is filled through an inner tube into the probe while a lock closes the probe to the top against the inner air pressure.

Geotechnical Studies of Stone Columns:

Malarvizhi and Ilamparuthi (2007) carried out a series of experimental studies and reported that the bearing capacity of a footing on encased stone column was 1.5 to 2 times that on ordinary stone column for length to diameter ratio of encased stone column equal to 9 and area ratio equal to 17%. The comparison between the end bearing column and floating column revealed that the footing on end bearing column has load carrying capacity twice that on floating column. Also analysis showed that the stress concentration in encased stone column is higher than the conventional stone column, which was attributed to the mobilization of hoop stresses in the geogrid. Rahil (2007) based on the analysis of the 45 model tests performed on untreated soil and soil treated with ballast layer with or without stone columns under both monotonic and repeated loadings, came to the following; the bearing ratio decreases with increasing undrained shear strength, Cu, the bearing improvement ratio decreases with increasing undrained shear strength. For models tested at Cu = 9 kPa and 16 kPa, the bearing improvement ratio have peak values at nearly S/B = 1% (S is the settlement and B is the footing width) followed by rapid drop, while for models tested at cu = 25 kPa, the bearing improvement ratio increases rapidly at S/B = 1% then remains nearly constant till the end of the test. This difference in behavior may be attributed to the gradual change in the mode of failure, and a decrease in settlement reduction ratio is observed with increasing bearing ratio and optimum reduction ratio was observed when Cu=9 kPa.

Fattah et al. (2011) carried out laboratory experiments to study the value of the stress concentration ratio, n, which is defined as the ratio of vertical stress acting on the stone column to that acting on the surrounding soil. A laboratory setup was manufactured in which two proving rings are used to measure the total load applied to the soil-stone column system and the individual load carried directly by the stone column. The foundation steel plates have 220 mm diameter and 5 mm thickness. These plates contain 1, 2, 3, and 4 holes. The spacing between all the holes equals twice the stone column diameter, D, center to center. The stone columns made of crushed stone were installed in very soft clays having undrained shear strength ranging between 6 and 12 kPa. Two length to diameter ratios L/D were tried, namely, L/D=6 and 8. The testing program consisted of 30 tests on single, two, three, and four columns to study the stress concentration ratio and the bearing improvement ratio (qtreared/ q untreated) of stone columns. The experimental tests showed that the stone columns with L/D=8 provided a stress concentration ratio n of 1.4, 2.4, 2.7, and 3.1 for the soil having a shear strength cu=6 kPa, treated with single, two, three, and four columns, respectively. The values of n were decreased to 1.2, 2.2, 2.5, and 2.8 when the L/D=6. The values of n increase when the shear strength of the treated soil was increased to 9 and 12 kPa.

Fattah et al. (2014) investigated the behavior of embankment models resting on soft soil reinforced with stone columns. Model tests were performed with different spacing distances between stone columns and two lengths to diameter ratios of the stone columns, in addition to different embankment heights. A total number of 21 model tests were carried out on a soil with undriained shear strength ≈ 10 kPa. The models consisted of stone columns embankment at spacing to diameter ratio equal to 2.5, 3 and 4. Three embankment heights; 200 mm, 250 mm and 300 mm were conducted. Three earth pressure cells were used to measure directly the vertical effective stress on column at the top of the middle stone column under the center line of embankment and on the edge stone column for all models while the third cell was placed at the base of embankment between two columns to measure the vertical effective stress in reinforced soft soil directly. The embankment models constructed on soft clay treated with ordinary stone columns at spacing ratio equal 2.5 revealed maximum bearing improvement ratio equals (1.21, 1.44 and 1.7) for 200 mm, 250 mm and 300 embankment heights, respectively and maximum settlement improvement ratio equals (0.78, 0.67 and 0.56) for 200 mm, 250 mm and 300 embankment heights, respectively.

The main objective of this paper is to investigate the gain in shear strength of the soft clay surrounding stone columns due to installation of these columns. The undrained shear strength is measured in the soil surrounding the stone columns before and after completion of the loading test using the vane shear device.

Experimental Work:

A total number of 12 model tests were carried out in models of soft clays of different values of undrained shear strength Cu varying from 8 to 18 kPa.

The series consists of twelve models of stone columns, single column, two-column group, three- column group, four-column group, five-column group and six-column group as shown in Plate (1). Tests on these groups were carried out with two different conditions of stone columns; end bearing and floating in addition to one model of untreated soil.

Material Used

Soft soil

Soil used in this study was obtained from Al-Sader city east of Baghdad governorate. The physical and chemical properties of the soil are summarized in Table (1). According to the Unified Soil Classification System (USCS); the soil is classified as (CL). The soil consists of 17% sand, 35% silt and 48% clay as shown in the grain size distribution of Figure (1).

A sample of the remolded clay was extracted from the bed of soil, and standard consolidation test was conducted on the extracted sample according to ASTM D2435-02, the properties of clay from consolidation test are shown in Table (2).

The crushed stone material which is used for the stone columns was obtained from a crushing stone factory. It is produced as a result of crushing massive stones, angular in shape. The particle size distribution is shown in Figure (2). The crushed stone is of a uniform size, considered as poorly graded. Direct shear test was performed on samples prepared at relative density 73% according to (ASTM D-3080-2003). The test revealed that the angle of internal friction is 40^o. The physical properties are presented in Table $_{(3).}$

Preparation of Model Test

Preparation of bed of soil

Prior to the stage of preparation of the bed of soil, trial tests were performed to control the efficiency of the method of preparation. Control tests were carried out to determine the variation of shear strength at different water contents (or at different liquidity indices) with time. Several trials were made and the undrained shear strength was measured by the vane shear device.

To accomplish this point, three samples were prepared individually and placed in five layers inside CBR molds. Each layer was tamped gently with a special hammer to extract any entrapped air. The samples were then covered with polythene sheet and left for a period of 7 days for curing. The undrained shear strength and the water content were measured after the curing period. The variation of the undrained shear strength with time for different water contents is shown in Figure (3). The variation of shear strength measured after 5 day curing with liquidity index is shown in Figure (4), the shear strength of soil decreases with increasing the value of water content or liquidity index.
The natural soil was first dried and crushed with a hammer to small sizes; further crushing was carried out using a crushing machine.

The natural soil was mixed with enough quantity of water to get the desired consistency. The mixing operation was conducted using a large mixer (120 liter capacity) each 25 kg of dry soil was mixed separately till completing the whole quantity. After thorough mixing, the wet soil was kept inside tightened polythene bags for a period of 24 hours to get uniform moisture content.

The soil used for model tests was placed in a manufactured steel container in layers with a thickness ranging between (50-75) mm for each layer, each layer was leveled gently using a wooden tamper, and then the leveled layer was tamped gently with a metal hammer of 9.87 kg and dimensions of (150 x 150) mm in order to remove any entrapped air. This process continues for each layer till reaching a thickness of 500 mm of soil in the steel container for floating stone column models, 400 mm for end bearing stone column models and 300 mm for soil replacement models.

After completing the final layer, the top surface was scraped and leveled to get as near as possible a flat surface, then covered with polythene sheet to prevent any loss of moisture. A wooden board of similar area to that of the surface area of bed soil (600 x 600) mm was placed on the bed of soil. The bed of soil was subjected to seating pressure of 5 kPa for 24 hours to regain part of its strength. The bed of soil was covered and left for a period of curing time of (five days) before the testing time.

The tests were carried out using a steel container with internal dimensions of (750 x 750 x 600 mm) which is used for the stone columns group. The steel container is made of steel plates (4 mm) thick; Plate (4) shows the steel container.

Steel foundation

All steel foundations are 10 mm in thickness and the dimensions of the foundation for the different cases are as follows:

1- The diameter of foundation is 64.6 mm for the stone column.
2- Rectangular footing (125*250 mm) for the two stone columns.
3- Square footing (250*250 mm) for the three and four stone columns.
4- Square footing (375*375 mm) for the five stone columns.
5- Rectangular footing (250*375 mm) for six stone columns.

It could be observed that the increase of spacing of stone columns decreases the bearing pressure of the foundation. The increase in bearing pressure, when the spacing reduces from 3.5d to 2.5d is substantially high beyond which further increase in bearing capacity is marginal. Hence the optimum spacing of the stone columns can be taken as 2.5 d (Bora and Dash, 2010).

Steel loading frame was manufactured by Majeed (2012) to support the hydraulic jack (see Plate (3a)). These arrangements for square plates allow the piston to move horizontally along the beam as shown in Plate (3b). At the sides of columns, holes were made to help in controlling vertically the distance between the jack and the container surface.

The axial load is applied through a hydraulic jack system as shown in Plate (3). The maximum load that can be applied is about (10 ton) according to hydraulic jack catalogue. At the right column of frame, a manual system is fixed to control hydraulic intensity.

At the top of hydraulic jack, a pressure gage is connected to measure the axial force (pressure). Plastic tube is used to pump the hydraulic from the manual system to the piston. Abreaction system is used to expel the air from the hydraulic. A load cell with a digital weighting indicator as shown in Plate (4) was used to measure the axial net load on footing.

Construction of stone columns

After preparing the bed of soft soil, the following steps were followed for construction of stone columns. The length to diameter ratio (L/D) of 6 was chosen for floating stone column and (L/D) of 8 for the end bearing stone columns as proposed by Al-Waily (2007). The area replacement ratio (a_s) which is different for each case. Table (4) illustrates the details of the stone columns cases.

1. After the preparation of the bed of soft soil, the center of the footing and the center of each stone column were located on the surface of the soil bed.
2. The undrained shear strength of the soil bed was measured at the center of each stone column at 150 mm depth by using the Portable Vane Shear Device.
3. A hole was made in the center of each stone column by pushing plastic pipe (PVC) into the soil gradually till the required depth.
4. The soil was removed from the plastic pipe by using a small auger.
5. The crushed stone is placed in the hole by using a plastic cone in 3 layers for the floating stone column (L/D = 6) and 4 layers for the end bearing stone column (where the end bearing stone column where L/D = 8 is supported by the container base) each layer is 130 mm thick and compacted by using a small hammer to reach the desirable dry unit weight of approximately 15.1 (kN/m^3).
6. After finishing the construction of the stone columns, the soil was covered and left for a period of curing time of (24 hours) before the testing.

Testing procedure for the stone columns

After the completion of the curing period, the following steps were followed:

1. The steel footing was placed over the stone columns.
2. The loading frame was placed in position so that the center of the loading piston coincides with the center of the footing or the single stone column as shown in Plate (5).
3. Loads were applied through a loading jack in the form of load increments. Each load increment was left till the dial gauge nearly stopped or a penetration rate of 0.01 to 0.05 in. or 0.25 to 1.25 mm/min is reached according to (ASTM D-1143, 2000).
4. Dial gauge readings were recorded before the addition of the next load increment.
5. The load increments continued until failure was achieved.
6. After completion of the load test, the undrained shear strength of the soil bed was measured between the stone columns at 150 mm depth by using the Portable Vane Shear Device.

Results and Discussion:

Twelve model tests are conducted and analyzed to examine the behavior of each case. The cases include single stone column and groups of columns consisting of two, three, four, five and six columns.

The analysis of results of all model tests regarding the applied stress and the corresponding settlement is illustrated in terms of (q_u/Cu) vs (S/B). The (q_u/Cu) represents the ratio of applied stress to undrained shear strength of the bed of saturated soft clay, denoted as "bearing ratio" and (S/B) represents the corresponding vertical settlement as a percent of the model footing width, denoted as "settlement ratio".

Definition of Failure

Most researchers consider the stone column behave as a pile. Therefore, the criterion proposed for defining the failure load of the pile can be adopted for stone columns. There are many approaches proposed to define the ultimate bearing capacity and failure of stone column. The most important five of them are:-

(1) De Beer (1967) the bearing capacity is taken at break point of two interesting straight lines of different slopes after plotting the load-settlement relationship in log-log plot. This break point represents failure. This criterion was adopted by Al-Qyssi (2001).

(2) Terzaghi (1947) proposal, where failure is defined as the load corresponding to 10% of the model footing width (or pile diameter). This criterion is adopted by Zakaria (2001).

(3) Tangent proposal, in which definition of failure based on the intersection of the two tangents of load-settlement curve. The first tangent to the initial part of the curve while the second is tangent to the lower flatter portion of the curve.

(4) Hughes and Withers (1974) proposal. The ultimate load carrying capacity (true failure, equals to 26 times the undrained cohesion of the clay) was reached at vertical displacement of 58% of the stone column diameter. Al-Mosawe et al., (1985) found that the ultimate load carrying capacity was reached at a vertical displacement of 60% of the diameter of the stone column.

(5) Roa et al., (1997) proposal. The capacity is taken as the load corresponding to a settlement equal to 0.1 times the diameter of the stone column.

In this paper, Terzaghi criterion is adopted for all models.

Model Tests on Untreated Soft Soil

One model test was performed on a bed of saturated clay. The footing was placed on the surface of the bed of soil and loaded gradually up to failure. The results of bearing ratio q_u/Cu versus settlement ratio $S/D_{footing}$ are shown in Figure (5).

Model Tests on Soft Soil Treated with Stone Columns

Figures (6) to (11) demonstrate the relationship between q_u/Cu and S/B for different cases of stone column groups.

Table (5) illustrates the bearing capacity ratio (q_u/Cu) and the bearing improvement ratio ($q_{treated}/q_{untreated}$) of different cases of stone columns.

Confinement, and thus stiffness of the stone, is provided by the lateral stress within the weak soil. Upon application of vertical stress at the ground surface, the stone and weak soil move downward together resulting an important concentration of stress within the stone column being stiffer than the soil.

An axial load applied at the top of single stone column produces a large bulge to a depth 2 to 3 diameter beneath to surface. This bulge in turn, increases the lateral stress within the clay which provides additional confinement for the stone. An equilibrium state is eventually reached resulting in reduced vertical movement when compared to the unimproved soil. Stone column groups loaded over entire area undergo less bulging than for single stone column. After the threshold limit of deformation, the shear resistance of the soil starts getting mobilized leading to increased load carrying capacity. Therefore, test was carried out after 24 hours of model preparation.

It can be noticed that with the provision of stone column in soft clay bed, the bearing capacity of foundation bed can be improved by (1.8-2.9) times for floating stone columns and (2.1-3.2) times for end bearing columns depending on the (L/D) ratio.

The Improvement of the Undrained Shear Strength of the Soil Bed

The undrained shear strength has been measured using (portable vane shear) before testing and after the failure of model. Table (6) shows the variation of the undrained shear strength for each case of the stone column and the soil replacement. It can be noticed that the undrained shear strength of the clay increased by about (5.6 -20) % due to the construction of stone columns. It can be concluded that the strength gain is greater as the undrained shear strength of the surrounding soil decreases. This means that construction of stone columns in very soft clays reveals two advantages: inserting columns of high stiffness within the soft clay and increasing the strength of the surrounding clay.

At higher stress levels, relative displacement (slip) may also occur between the stone column and surrounding soil. The occurrence of either lateral spreading or slip results in greater settlement of stone column improved ground than would otherwise occur.

Conclusions

From the experimental work carried out the following points have been concluded:

1- The measurements made before and after testing showed that the undrained shear strength of the clay surrounding the stone columns increased by about (5.6 - 20) % due to the construction of stone columns.
2- The provision of stone column in soft clay bed resulted in improvement of the bearing capacity of the foundation bed by about (1.76 - 2.91) times for floating stone columns and (2.12 - 3.15) times for end bearing columns.
3- The area replacement ratio has a significant effect on the bearing improvement ratio ($q_{treated}/q_{untreated}$) for a given stone column.

Table (1): Physical and chemical properties of the natural soft soil.

Index Property	Value	Specification
Liquid Limit (L.L) (%)	44	ASTM D 4318-00
Plastic limit (P.L) (%)	19	ASTM D 4318-00
Shrinkage limit (S.L) (%)	14	ASTM D 4318-00
Plasticity index (P.I) (%)	25	ASTM D 4318-00
Activity (A_t)	0.96	ASTM D 4318-00
Specific gravity (Gs)	2.69	ASTM D 854-00
Gravel (%)	0	ASTM D 422-00
Sand (%)	17	ASTM D 422-00
Silt (%)	35	ASTM D 422-00
Clay (%)	48	ASTM D 422-00
Classification (USCS)	CL	ASTM D 2487-00
Organic matter (O.M.) (%)	0.39	ASTM D 2974-00
Calcium oxide (CaO) (%)	0.36	BS 1377 test No.8
SO_3 content (%)	0.52	BS 1377 test No.9
Total dissolved salts % (TDS)	1.02	BS 1377 test No.10
pH value (%)	9.17	BS 1377 test No.11

Table (2): Compressibility characteristics of remolded clay obtained from consolidation test

Index Property	Value
Initial void ratio (e)	0.48
Coeff. of compressibility (a_v) (m^2/kN)	1.5×10^{-4}
Coeff. of volume change (m_v) (m^2/kN)	1.1×10^{-4}
Compression index (c_c)	0.21
Swelling index (c_r)	0.02
Preconsolidation pressure (p_c') (kN/m^2)	40
Dry unit weight (γ_{dry}) (kN/m^3)	15.5
Coeff. of consolidation (c_v) (m^2/min) at a pressure of (800) KPa.	3.344×10^{-5}

Table (3): Physical properties of the crushed stone material.

Index property	Index value
Max. dry unit weight (kN/m^3)	15.9
Min. dry unit weight (kN/m^3)	13.3
Dry unit weight (kN/m^3) at D_r = 73%	15.1
D_{10} (mm)	5.1
D_{30} (mm)	6.8
D_{60} (mm)	9
Specific gravity (G_s)	2.65
Coefficient of uniformity (C_u)	1.76
Coefficient of curvature (C_c)	1.00
Relative density (D_r%)	73
Angle of internal friction (ϕ^0) at D_r = 73%	40

Table (4) Details of stone column models.

Case No.	Type	L/D	No. of Columns	Diameter of Column (mm)	Dimensions of footing (mm)	Area replacement ratio
1	Floating	6	1	50	64.6	0.600
2	Floating	6	2	50	125*250	0.126
3	Floating	6	3	50	250*250	0.094
4	Floating	6	4	50	250*250	0.126
5	Floating	6	5	50	375*375	0.070
6	Floating	6	6	50	375*250	0.126
7	End Bearing	8	1	50	64.6	0.600
8	End Bearing	8	2	50	125*250	0.126
9	End Bearing	8	3	50	250*250	0.094
10	End Bearing	8	4	50	250*250	0.126
11	End Bearing	8	5	50	375*375	0.070
12	End Bearing	8	6	50	375*250	0.126

Table (5) the bearing capacity ratio (q_u/Cu) and the bearing improvement ratio ($q_{treated}/q_{untreated}$) of different cases of stone columns.

Case	q_u /Cu	$q_{treated}/q_{untreated}$
Single column floating	6	1.76
Single column End bearing	7.2	2.12
Two columns floating	6.2	1.82
Two columns End bearing	8	2.35
Three columns floating	6.6	1.94
Three columns End bearing	8.5	2.50
Four columns floating	6.8	2.00
Four columns End bearing	9.6	2.82
Five columns floating	8.8	2.59
Five columns End bearing	9.9	2.91
Six columns floating	9.9	2.91
Six columns End bearing	10.7	3.15

Table (6) Variation of the undrained shear strength before and after testing for the stone column cases.

Case	Cu before test (kPa)	Cu after testing (kPa)	Percentage of increase (%)
Single column floating	17	18	5.6
Single column End bearing	17	18	5.6
Two columns floating	16	17	5.9
Two columns End bearing	17	18	5.6
Three columns floating	15.5	16.5	6.1
Three columns End bearing	13.5	15	10.0
Four columns floating	14	16	12.5
Four columns End bearing	11	13	15.4
Five columns floating	12.5	14.5	13.8
Five columns End bearing	8	10	20.0
Six columns floating	15.5	17	8.8
Six columns End bearing	13.5	14.5	6.9

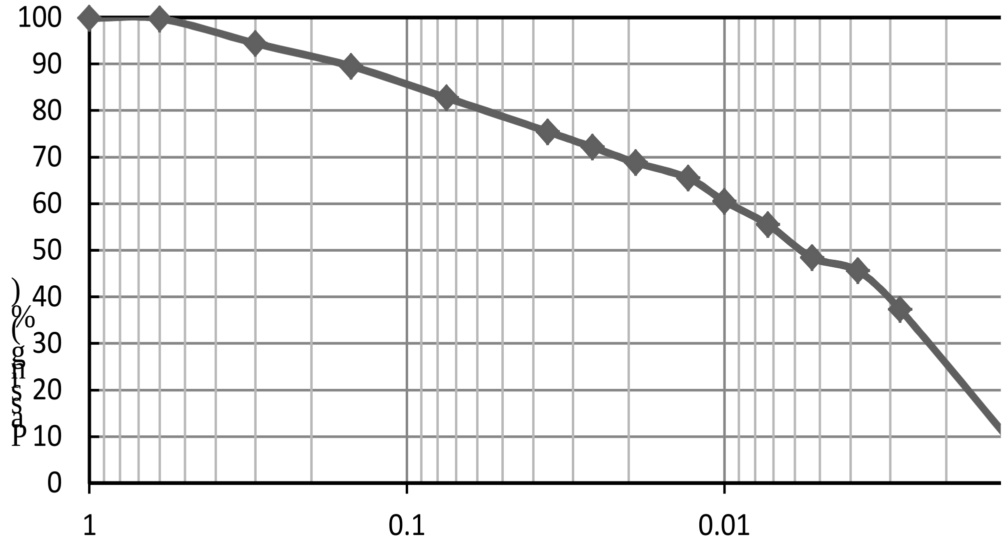


Figure (1) Particle size distribution of the soft soil used.

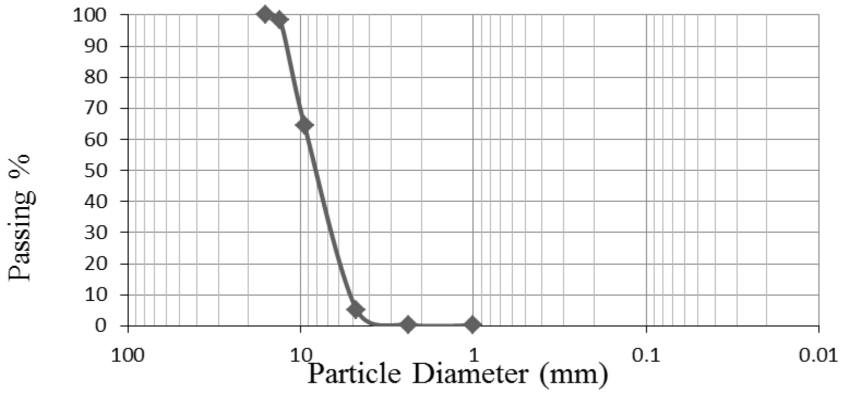


Figure (2) Grain size distribution of the crushed stone material.

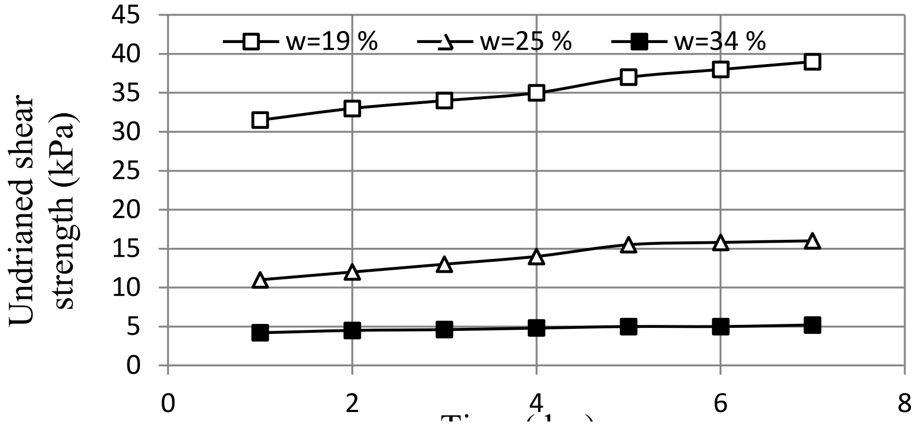


Figure (3) Variation of the undrained shear strength with time for different water contents of the remolded clay.

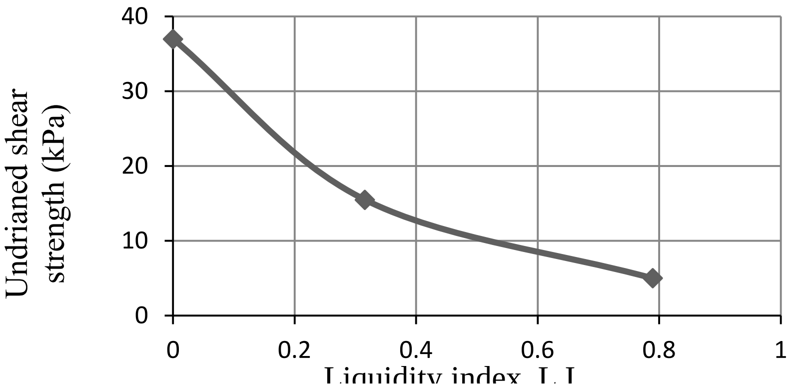


Figure (4) Variation of the undrained shear strength with liquidity index for the remolded clay after (5) days.

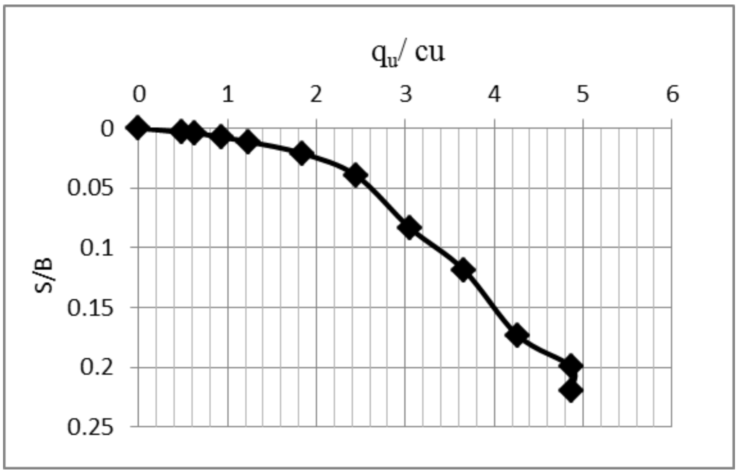


Figure (5) Pressure –settlement curve for a footing resting on untreated soil.

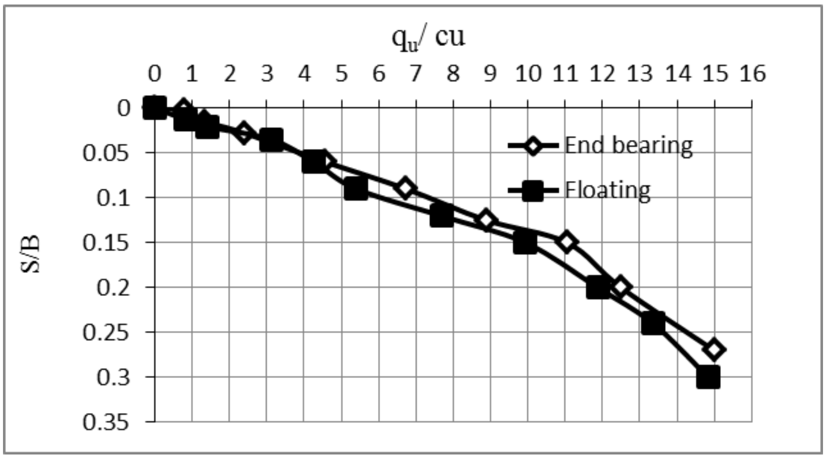


Figure (6) Pressure –settlement curve for a footing resting on soft clay treated by single stone column.

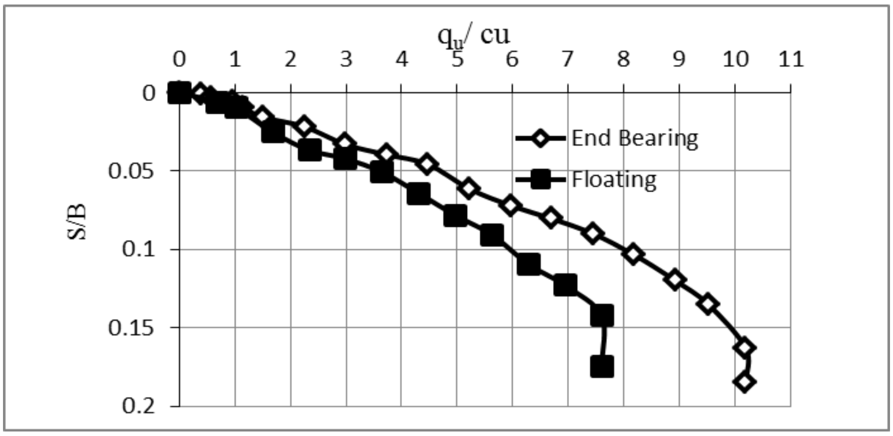


Figure (7) Pressure –settlement curve for a footing resting on soft clay treated by two stone column group.

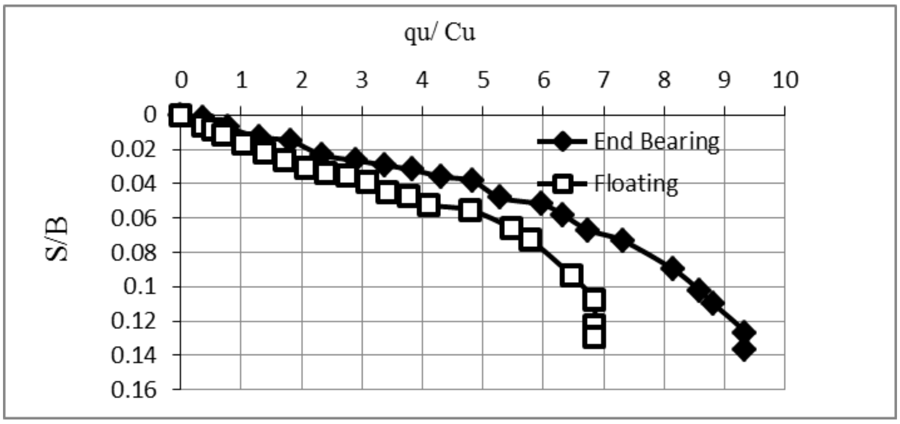


Figure (8) Pressure –settlement curve for a footing resting on soft clay treated by three stone column group.

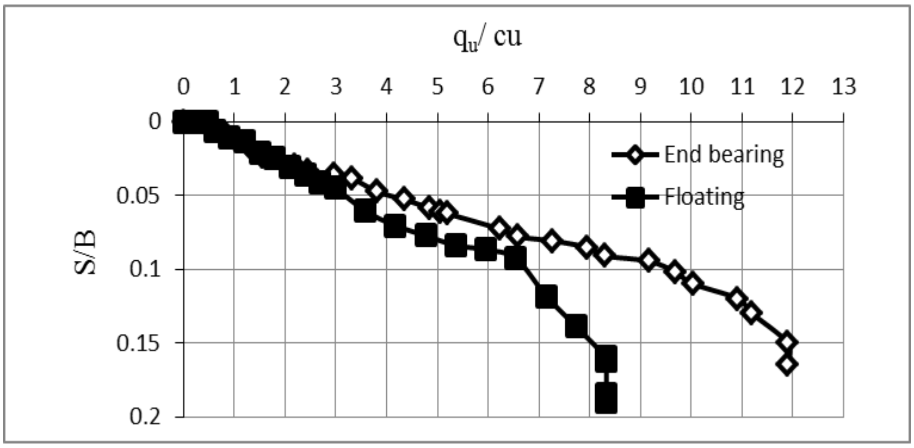


Figure (9) Pressure –settlement curve for a footing resting on soft clay treated by four stone columns group.

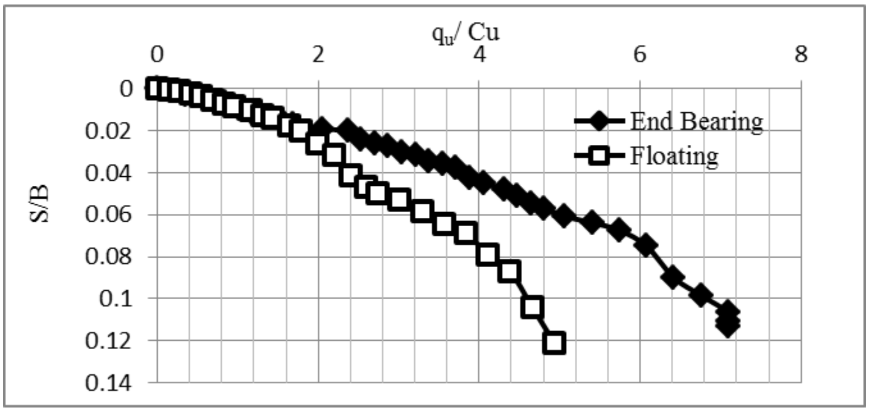


Figure (10) Pressure –settlement curve for a footing resting on soft clay treated by five stone column group.

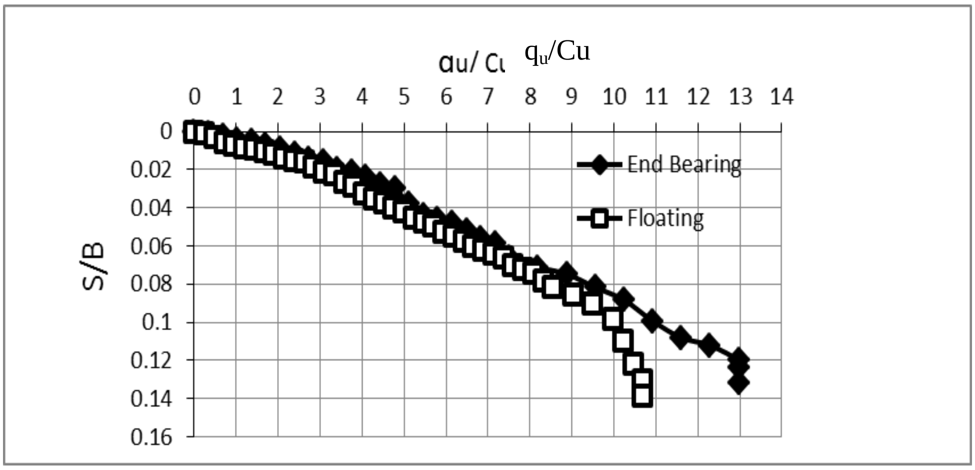


Figure (11) Pressure –settlement curve for a footing resting on soft clay treated by six stone column group.

Plate (1) Four-end bearing stone column group model.

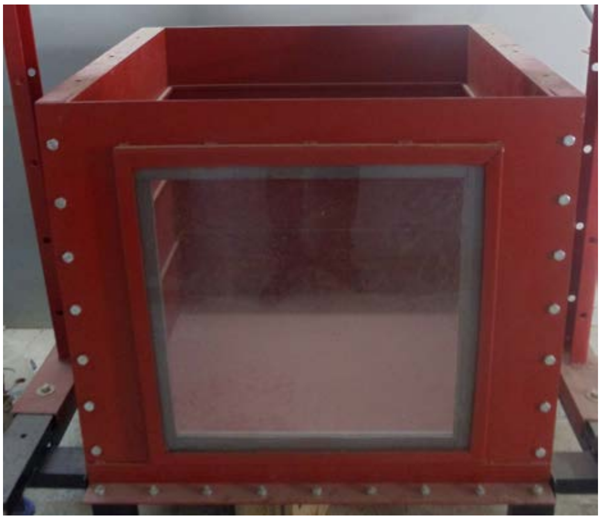
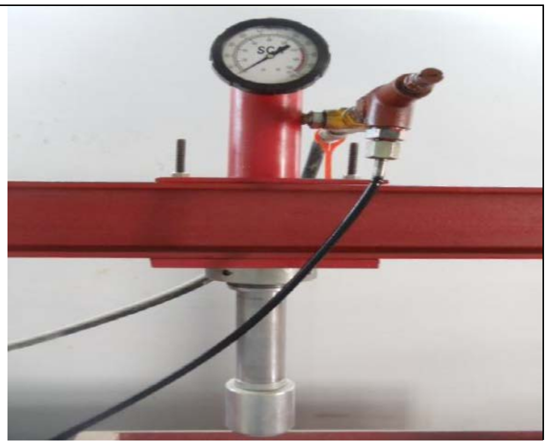


Plate (2) Steel container.

(a) Loading steel frame.



(b) Front view of the axial loading system.

(c) Side view of the axial loading system.

Plate (3) Stone columns loading assembly (after Majeed, 2012).

Plate (4) Load cell and digital weighting indicator.

Plate (5) Loading of four-stone column group.

References

[1]Al-Qayssi, M. R. M., (2001), "Unreinforced and Reinforced Behaviour of Single and Groups of Granular Piles". Ph.D. Thesis Presented to the Civil Engineering Department, Faculty of the Military, College of Engineering at Baghdad. pp.192.

[2]Al-Waily, M. J. (2007), "Stress Concentration Ratio of Model Stone Columns Improved by Additives", Ph.D. Thesis, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq.

[3]ASTM D 2487-00: “Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)”, American Society for Testing and Materials.

[4]ASTM D 2974-00: "Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils", Annual book of ASTM standards, Vol. 04.08, American Society for Testing and Materials.

[5]ASTM D 3080-98: "Standard Test Method for Direct Shear Test of Soils Unconsolidated Undrined Conditions", American Society for Testing and Materials.

[6]ASTM D 422-00: "Standard Test Method for Particle Size Analysis of soils", American Society for Testing and Materials.

[7]ASTM D 4253-00: "Standard Test Method for Maximum index Density and Unit Weight of Soils Using a Vibratory Table", American Society for Testing and Materials.

[8]ASTM D 4254-00: "Standard Test Method for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density", American Society for Testing and Materials.

[9]ASTM D 4318-00, "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils", American Society for Testing and Materials.

[10]ASTM D 854-00: "Standard Test Method for Specific Gravity of Soil Solids by Pycnometer", American Society for Testing and Materials.

[11]ASTM D 194-94: "Standard Test Method for Bearing Capacity of Soil for Static Load and Spread Footings", American Society for Testing and Materials.

[12] ASTM D1143-81 (1994), “Standard Test Method for Piles under Static Axial Compressive Load”, American Society for Testing and Materials.

[13] ASTM D2435-02, (2002), “Standard Test Methods for One-Dimensional Consolidation Properties of Soils,” Annual Book of ASTM Standards, Vol. 04.08, ASTM International, West Conshohocken, PA, pp. 1–10.

[14] Barksdale, R. D. and Bachus, R. C., (1983), “Design and Construction of Stone Columns, Volume I”, Prepared for the Federal Highway Administration, U.S. Department of Transportation. P.239.

[15] Bergado, D.T, Anderson, L.R, Miura N., Balasubramaniam A.S. (1996),"Soft Ground Improvement in Lowland and other Environments" 2^{th} Edition, American Society of Civil Engineering, New York.

[16]Bora, M. C. and Dash, S.K., (2010), "Load Deformation Behavior of Floating Stone Columns in Soft Clay", Indian Geotechnical Conference, December 16-18, 2010, Bombay, pp. 251-254.

[17] Brand, E.W. and Brenner, R.P., (1981),"Soft Clay Engineering", Elsevier Scientific Publishing company, Amsterdam, pp. 778.

[18]British Standard B.S: C.P. 8004 (1986), Code of Practice for Foundations, British Standard Institution, London, UK.

[19]De Beer, E. E., (1967), " Proefondervindelijke bijdrge tot de studie van het gransdraagvermogen van zand onder funderingen op staal; Bepaling von der vormfactor sb", Annales des, Annales des Travaux Publics de Belgique, 68, No.6, pp.481-506; 69, No.1, pp.41-88; No.4, pp.321-360; No.5, pp.396-442, No.6, pp.495-522.

[20] Fattah, Mohammed Y., Shlash, Kais T., Al-Waily, Maki J., (2011), "Stress Concentration Ratio of Model Stone Columns in Soft Clays", Geotechnical Testing Journal, ASTM, Vol. 34, No. 1, pp. 61-71, Paper ID GTJ103060Available online at: www.astm.org.

[21] Fattah, M. Y., Zabar, B. S., Hassan, H. A., (2014), "An Experimental Analysis of Embankment on Stone Columns", Journal of Engineering, University of Baghdad, Vol. 20, No. 7, pp. 62-84.

[22] Hughes, J. M. O., and Withers, N. J., (1974), "Reinforcing of Soft Cohesive Soils With Stone Columns", Ground Engineering, Vol. 7, No. 3, May, pp. 42 – 49.

[23] Malarvizhi, S.N. and Ilamparuthi, K., (2007), "Comparative Study on the Behavior of Encased Stone Column and Conventional Stone Column", Soils and Foundations Journal, 47, No. 5, pp. 873-885.

[24]Majeed A.A.,(2012),"Effect of Scaling Factor on Pile Model Test Results" M.Sc. Thesis, Building and Construction Engineering Department, University of Technology, Iraq.

[25]Rahil, F.H. (2007),"Improvement of Soft Clay Underneath a Railway Track Model Using Stone Columns Technique", Ph.D. Thesis, Building and Construction Engineering Department, University of Technology, Iraq.

[26]Rao, S.N., Reddy, K.M., and Kumar, P.H. (1997), "Studies on Group of Stone Column in Soft Clay", Geotechnical Engineering, Journal of Southeast Asian Geotechnical Society, Vol. 28, December, pp. 165-181.

[27] Terzaghi, K. (1943). Theoretical Soil Mechanics, John Wiley and Sons, NY.