Laboratory Investigation on Efficiency of Model Stone Column Groups

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Abstract

As in piles, the efficiency of a group (**E_g**) of stone columns is defined as the ratio between the capacity of the group to the capacity of each stone column in the group multiplied by single stone column capacity. In this paper, the group efficiency of 24 model stone columns installed in soft clay is considered. These groups consist of 2, 3 and 4 columns. The tests were conducted on stone columns with length to diameter ratio (L/D) of 6 and 8. A laboratory setup was manufactured in which two proving rings were 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, respectively. The spacing between all holes equals twice the stone column diameter (D), center to center.

The stone column capacity is taken as the load corresponding to a settlement equals to 50% of the diameter of stone column. The results illustrated that the group efficiency decreases with increasing the number of stone columns, also the stone columns with L/D of (8) provided higher efficiency than those with L/D of (6).

Keywords: Stone columns, group, efficiency, laboratory model, soft clay.

بحث مختبري عن كفاءة نموذج من مجاميع الأعمدة الحجرية

الخلاصة

تعرف كفاءة المجموعة من الأعمدة الحجرية كما هو الحال في الركائز بأنها النسبة بين قابلية تحمل المجموعة و مجموع قابليات تحمل الأعمدة الحجرية المنفردة في المجموعة.

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في هذا البحث تم اعتبار كفاءة المجموعة ل (24) نموذج مختبري من الأعمدة الحجرية المشيدة فـــي تـــرب طينية رخوة. تتألف هذه المجاميع من عمودين و ثلاثة و أربعة على التوالي. و قد أجريت الفحـــوص علـــى أعمدة حجرية ذات نسبة طول إلى قطر (L/D) مقدارها (6) و (8). و تم تصنيع نموذج مختبـــري يحتـــوي على مقياسين للقوة لقياس الحمل المسلط على منظومة التربة-العمود و كذلك الحمل المنتقـــل مباشـــرة إلـــى العمود الحجري. الألواح الحديدية المستعملة للأسس كانت دائرية ذات قطر (220) ملم و ســـمك (5) ملـــم و تحتوي على فتحة واحدة أو فتحتين أو ثلاث أو أربع فتحات دائرية بحيث أن المسافة بين كل فتحتين تـــساوي ضعف قطر الفتحة مقاسة من مركزي الفتحتين.

و تم اعتبار قابلية تحمل العمود الحجري بأنها الحمل الذي يسبب هبوطا يمثل (50 %) مـــن قطـــر العمود الحجري. و قد بينت النتائج أن كفاءة المجموعة تتناقص مع زيادة عدد الأعمدة الحجرية. كمـــا بينـــت النتائج أيضا أن استعمال حجر مكسر في الأعمدة و بنسبة (L/D) مساوية إلى (8) أعطى كفاءة أعلـــى مـــن الأعمدة ذات (L/D) مساوية إلى (6).

Introduction

The principle of reinforcing soft ground with granular columns was followed in ancient cities in Mesopotamia such as Ur and Babylon. Recently, stone columns were first employed in Europe in the 1830's and have been used there extensively since the late 1950's. The practice was adopted in U. S. A. since the early 1970's. This technique was proven, in general, to increase the bearing capacity within (150-300) % and reduces the settlements within (30-80) %, (Pribe, 1995).

The stone column technique of ground treatment has proven to be successful also in (Barksdale and Bachus, 1983):

(1) improving slope stability of both embankments and natural slopes,
(2) reducing the liquefaction potential of sands, and
(3) increasing the time rate of settlement.

In practice, stone columns are usually constructed fully penetrating a soft soil layer overlying a firm stratum. It may be constructed also as floating stone columns with their tips embedded within the soft clay layer. Stone columns may fail individually or as a group. Stone columns are often used as groups. The behaviour of stone columns is considered similar to that of piles including group action.

In this paper, experimental work has been carried out to study the efficiency of stone columns constructed in soft clays.

Testing program

The total of 24 model tests of stone columns were carried out in test tank to study the efficiency of stone column groups. Load tests were carried out on single column and groups of 50 mm diameter. The length to the diameter (L/D) ratios of stone column were taken equal to of 6 and 8.

Materials Used

I. Soil Used

Soil samples were collected from a depth of 0.50 m from the soil surface of a site in the vicinity of Al-Musaib Technical Institute in Babylon Governorate. The soil was subjected to routine laboratory tests to determine its properties. These tests include:

1- Grain size distribution (sieve analysis and hydrometer tests) according to ASTM D422 specifications.
2- Atterberg limits (liquid and plastic limits) according to ASTM D423 and D424 specifications.

The test results show that the soil consists of 10% sand, 42 % silt, and 48 % clay. According to the unified soil classification system, the soil is inorganic sandy silty clay designated as (CL). Table (1) shows the physical properties of the soil.

II. Crushed Stone

The natural calcium carbonate, $CaCO_3$ (limestone), crushed stone was used as a backfill material. The size of the crushed stone was chosen in accordance with the guidelines suggested by **Nayak** (1983), where the particle size is about **(1/6 to 1/7**) of the diameter of stone columns. The minimum particle size is 4 mm and the maximum particle size is 10 mm.

Figure (1) illustrates the grain size distribution of the crushed stone used in the tests.

Steel Container

The model tests were carried out in a test tank manufactured of steel with dimensions of 1100 mm * 1000 mm *800 mm, made of steel plates (6 mm in thickness) as shown in Figure (2). The container is sufficiently rigid and exhibited no lateral deformation during the preparation of the bed of soil and during the tests.

The Foundation Plates and Accessories

Figure (3) shows details of the foundation plates and accessories used for carrying out the loading tests. The foundation plates have 220 mm diameter and 5 mm thickness. These plates contain 1, 2, 3 and 4 holes, respectively. The spacing between all holes equals twice the stone column diameter (D), center to center.

The Loading Frame

Figure (4) shows details of the complete set up which consists mainly of steel container, loading frame, dial gauges and accessories.

Model Preparation and Testing

Preparation of the Bed of Soil

Prior to the preparation of the bed of soil, a relationship was obtained between the water content and the undrained shear strength of the soil as shown in Figure (5). The shear strength was measured using the Swedish fall cone pentrometer shown in Figure (6).

Following this stage, the bed of the soil was prepared as follows:

(1) The natural soil was first crushed with a hammer to small sizes and then left for (24) hours for air-drying. Further crushing was carried out using a crushing machine.
(2) The air-dried soil was divided into 10 kg groups. Each group was mixed gradually and thoroughly with sufficient amount of water corresponding approximately to the water content range of (24-35) %. This range of water content was chosen from Figure (5)**.**
(3) After mixing with water, the soil was placed in layers inside the steel container and each layer was tamped with a special tamping hammer of (50 mm * 50 mm) in size. The final thickness of each layer was about 50 mm. The procedure was continued until the final thickness of the bed of soil.
(4) After the completion of the preparation of the bed of soil, it was covered tightly with nylon sheets and left for four days as a curing period.

Construction of Stone Columns

At the end of curing period, the following steps were used in construction of the stone columns:

(1) The top of the soil bed was levelled.

(2) The position of the stone column(s) to be placed was properly marked with respect to the loading frame. A hollow PVC tube, with external diameter (52) mm and (2) mm in thickness, coated with petroleum jelly was inserted vertically to the required depths (40 mm in fully penetrated stone column or L/D = 8 and 30 mm in partially penetrated stone column or L/D = 6), [the critical length is usually about four times the column diameter (Greenwood and Krisch, 1983). The tube was then slowly withdrawn and twisted during the lifting process.

(3) The soil was removed from the tube and samples of the soil at different depths were taken for water content measurement.

(4) The crushed stone with or without sand or cement was poured into the hole in layers and each layer was compacted gently using a (30 mm) in diameter tamping rod. The unit weight of the compacted crushed stone was measured to be 16.3 kN/m^3.

Model Testing Procedure

The model tests were carried out according to the testing program as follows, (Al-Waily, 2007):

(1) First of all, the proving rings used in testing program were calibrated by applying various known static loads and recording the readings of dial gauges. This procedure was repeated for many times to get the more accurate readings.

(2) The footing assembly (220 mm diameter) consists of two plates (1 and 2 in Figure 4), one of them on the stone column(s) and the other on the surrounding soil. These plates were placed in position so that the center of the footing coincides with the center of the hydraulic jack.

(3) Two proving rings (3 and 4 in Figure 4) with accuracy of (0.01 mm/division) were set such that the total load applied to the model footing, and the load applied to the stone column can be measured alone.

(4) Three dial gauges (5, 6 and 7 in Figure 4) with accuracy of (0.01 mm/division) were fixed in position to measure the settlements of both plates.

(5) Loads were then applied through a loading disk in the form of load increments.

(6) During each load increment, the readings of the two dial gauges corresponding to two proving rings (1 and 2 in Figure 4) were recorded.

(7) The dial gauges (5, 6 and 7 in Figure 4) readings were recorded at the end of the period of each load increment.

(8) Each load increment was left for (2.5) minutes.

(9) The load increments were continued until the total settlement reached 50 mm (100% of the stone column diameter).

For comparison purposes, the loading tests were performed in the container for the untreated soil only.

Results

I. Bearing Improvement Ratio

In this paper, the capacity is taken as the load corresponding to a settlement equals to 50% of the diameter of stone column based on the work of Al-Mosawe et al., (1985).

Figures (7, 9, 11, 13, 15 and 17) relate the bearing ratio (q/cu) with the deformation ratio (S/B) for untreated soil and soil treated with single, two, three and four stone columns having (L/D) ratio of 6 and 8, respectively. The surrounding soil was prepared at undrained shear strength of (cu=6 kPa, 9 kPa and 12 kPa), respectively. These models were tested 24 hours after preparation. The figures demonstrate that the stone column in all bearing ratios shows significant difference in the behaviour corresponding to (S/B) ratio.

The figures also indicate that when the shear strength of the soil decreases, the effect of stone column becomes more visible and a clear increase in (q/cu) ratio is noticed. This behaviour is attributed to the truth that the calculation of stresses is dependent on the stress applied on the soil replaced from the zone of stone column only, disregarding the stress applied to the soil surrounding the column. Thus the effect of improvement seemed clearly in the treated soil of low shear strength.

The bearing improvement ratio achieved by stone columns is presented by the relationship between the ratio ($q_{treated}$ / $q_{untreated}$) and the (S/B) ratio. It can be noticed from ($q_{treated}$ / $q_{untreated}$) in Figures (8, 10, 12, 14, 16 and 18) that the bearing improvement ratio ($q_{treated}$ / $q_{untreated}$) ranges from 1.20 to 2.18 for the soil having (cu = 6 kPa) treated with single stone column with (L/D = 6) and with four stone columns of (L/D = 6) respectively at S/B=11% (Figure 8). The ratio ($q_{treated}$ / $q_{untreated}$) ranges from 1.18 to 1.88 for soil having (cu = 9 kPa) treated with single stone column of (L/D = 6) and with four stone columns of (L/D = 6), respectively (Figure 10).

The ratio ($q_{treated}$ / $q_{untreated}$) ranges from 1.19 to 1.62 for soil having (cu=12 kPa) treated with single stone column with (L/D = 6) and with four stone columns (L/D = 6), respectively (Figure 12).

It can be concluded from the previous values that the bearing improvement ratio is increased with increasing the number of stone columns by a percentage ranges between (20%) and (100%).

II. Efficiency (E_g) of Stone Column Groups

As in piles, the efficiency of a group (**E_g**) of stone columns is defined as the ratio between the capacity of the group to the capacity of each stone column in the group multiplied by single stone column capacity. Group efficiency has been calculated by taking the net load carried by the single column taken directly from the reading of the proving ring mounted on the plate test on stone column, after that the net load was taken by the group of stone column, according to the following formula proposed by Rao et al. (1997).

$$\textbf{Efficiency } (E_g) = \frac{\textbf{Load (single)}}{\textbf{(Load (group)/ No. of columns)}}$$

Tables (2) to (4) show the calculations of group efficiency for all model tests. In all model tests, the capacity is taken as the load corresponding to a settlement equals to 0.11 times the diameter of loading plate or 50% times the diameter of stone column. It can be seen from these tables that the group efficiency is decreased with increasing the numbers of stone columns. The group efficiency of two, three and four stone columns are (1.01, 0.86, 0.81) for soil having (cu = 6 kPa) treated with stone columns (L/D=6). The results also show that the group efficiency values are (1.03, 0.86 and 0.81) in soil treated with two, three and four stone columns respectively at length to diameter ratio of stone column, L/D = 8.

These tables demonstrate that when the shear strength decreases, the group efficiency increases. These tables also illustrated that the crushed stone with (L/D = 8) provided higher efficiency than those with (L/D= 6).

The results obtained from tables (2) to (4) are in agreement with Al-Mosawi et al. (1985), Rao et al., (1997), and Al-Qyssi, (2001).

Conclusions:

The following points are drawn from the tests:

(1) The value of the bearing improvement ratio decreases with increasing the shear strength of the treated soil.
(2) The crushed stone columns with (L/D = 8) provided an increase in the bearing improvement ratio ($q_{treated}/q_{untreated}$) of (1.25, 1.7, 1.94 and 2.28) for the soil of shear strength (cu=6 kPa) treated with single, two, three and four columns, respectively. The values of ($q_{treated}/q_{untreated}$) are decreased to (1.20, 1.58, 1.80 and 2.18) when (L/D= 6).
(3) The group efficiency decreased with increasing the numbers of stone columns
(4) For the efficiency of stone column group $\mathbf{E_g}$, it is indicted that their values decrease with increasing the shear strength of the treated soil.
(5) The crushed stone with (L/D = 8) provided higher efficiency than those with (L/D= 6).

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Table (1) Physical properties of the used soil.

Property	value
Liquid limit (LL)	44%
Plastic limit (PL)	22%
Plasticity index (PI)	22%
Specific gravity (G_S)	2.72
% Passing sieve No. 200	90%
Sand content	10%
Silt content	42%
Clay content < 0.005 mm	48%
Maximum dry unit weight kN/m^3	17.8
Symbol according to Unified Soil Classification System	CL

Table (2) Summary of group efficiency (E_g) from various model tests
(cu = 6 kPa). Stone columns with L/D = 6

No. of columns	Ultimate load (N)	Load on soil (N)	Load on group of stone columns (N)	Load on single stone column (N)	Group Efficiency
Single	1291.00	1035.00	256.00	256.00	
Two	1678.30	1159.00	519.30	259.65	1.01
Three	1936.50	1276.00	660.50	220.17	0.86
Four	2323.80	1490.20	833.60	208.40	0.81

Stone columns with L/D = 8

No. of columns	Ultimate load (N)	Load on soil (N)	Load on group of stone columns (N)	Load on single stone column (N)	Group Efficiency
Single	1356.00	1058.00	298.00	298.00	
Two	1872.00	1260.00	612.00	306.00	1.03
Three	2066.00	1299.00	767.00	255.67	0.86
Four	2453.00	1489.00	964.00	241.00	0.81

Table (3) Summary of group efficiency (E_g) from various model tests (cu = 9 kPa).

Stone columns with L/D = 6

No. of columns	Ultimate load (N)	Load on soil (N)	Load on group of stone columns (N)	Load on single stone column (N)	Group Efficiency
Single	1743.00	1347.00	396.00	396.00	
Two	2259.00	1539.00	720.00	360.00	0.91
Three	2776.00	1821.00	955.00	318.33	0.80
Four	3098.00	2001.00	1097.00	274.25	0.69

Stone columns with L/D = 8

No. of columns	Ultimate load (N)	Load on soil (N)	Load on group of stone columns (N)	Load on single stone column (N)	Group Efficiency
Single	1936.00	1492.00	444.00	444.00	
Two	2453.00	1611.00	842.00	421.00	0.95
Three	2905.00	1774.00	1131.00	377.00	0.85
Four	3163.00	1822.00	1341.00	335.25	0.76

Table (4) Summary of group efficiency (E_g) from various model tests (cu = 12 kPa).

Stone columns with L/D = 6

No. of columns	Ultimate load (N)	Load on soil (N)	Load on group of stone columns (N)	Load on single stone column (N)	Group Efficiency
Single	2001.00	1498.00	503.00	503.00	
Two	2517.00	1608.00	909.00	454.50	0.90
Three	2776.00	1636.00	1140.00	380.00	0.76
Four	3550.00	2197.00	1353.00	338.25	0.67

Stone columns with L/D = 8

No. of columns	Ultimate load (N)	Load on soil (N)	Load on group of stone columns (N)	Load on single stone column (N)	Group Efficiency
Single	2066.00	1513.00	553.00	553.00	
Two	2711.00	1666.00	1045.00	522.50	0.94
Three	3098.00	1750.00	1348.00	449.33	0.81
Four	3550.00	2034.00	1516.00	379.00	0.69

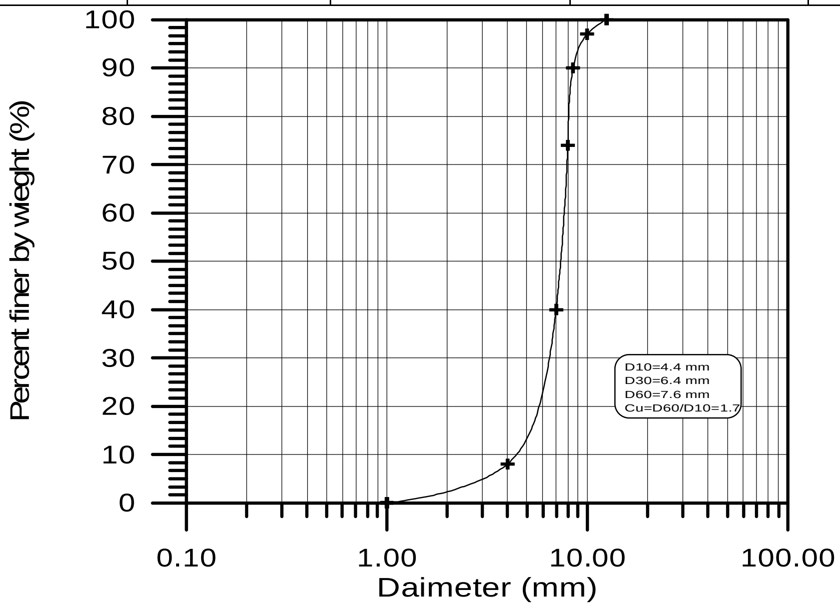

Figure (1) Grain size distribution of the crushed stone used in preparing the model tests.

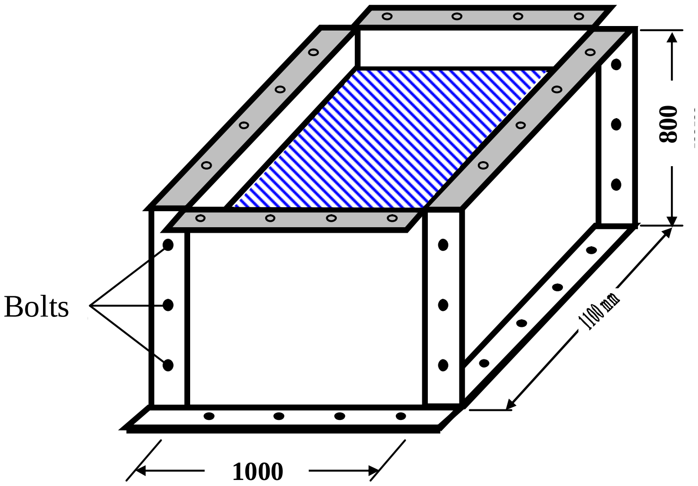

Figure (2) Steel container used in the tests.

Figure (3) Foundation plates and accessories.

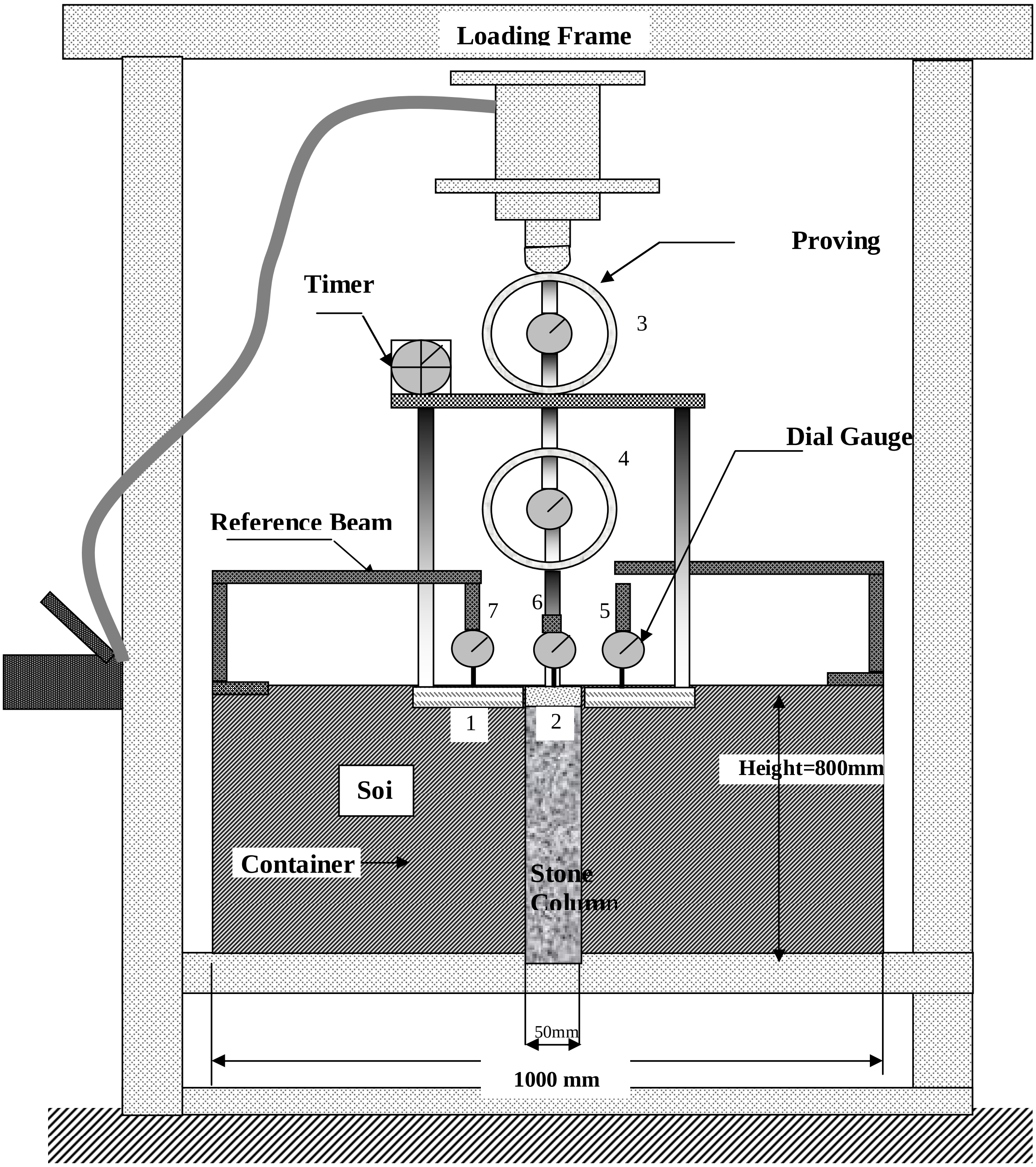

Figure (4) Schematic diagram of the experimental set-up.

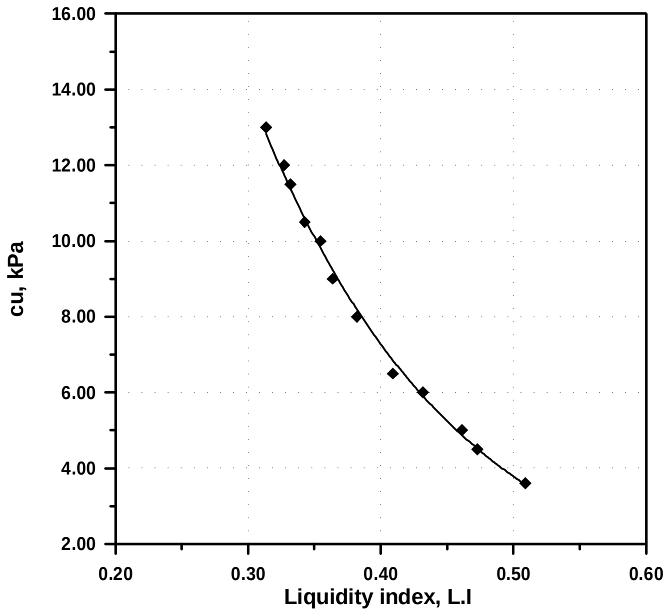

Figure (5) Shear strength-liquidity index, L.I. relationship.

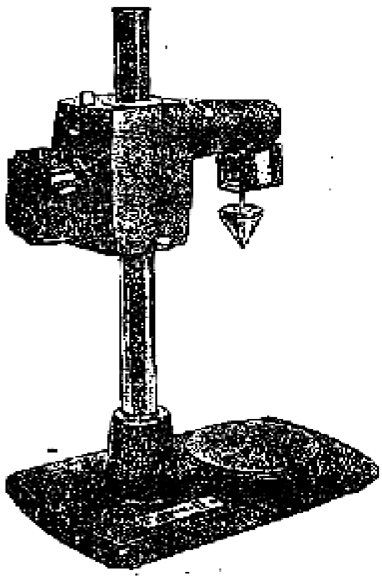

Figure (6) The Swedish fall cone penetrometer apparatus used for measuring the undrained shear strength.

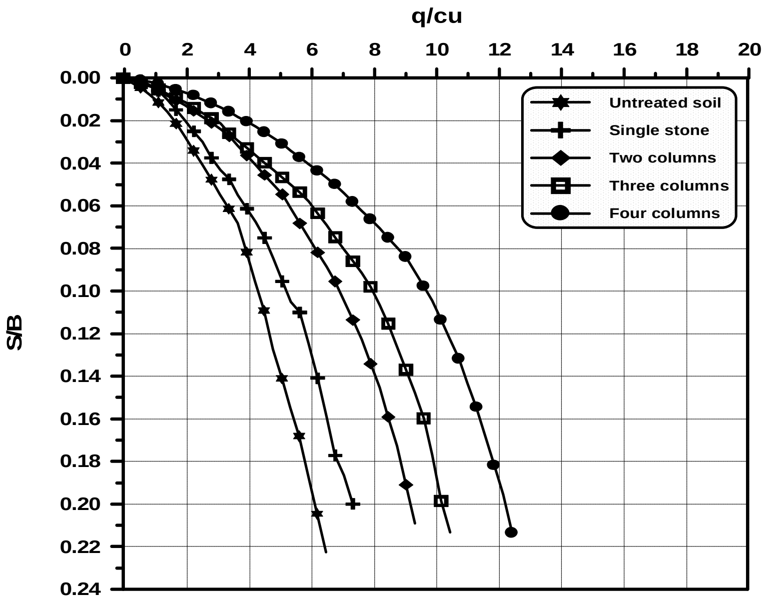

Figure (7) q/cu versus S/B for the soil treated with stone column, cu = 6 kPa and L/D = 6.

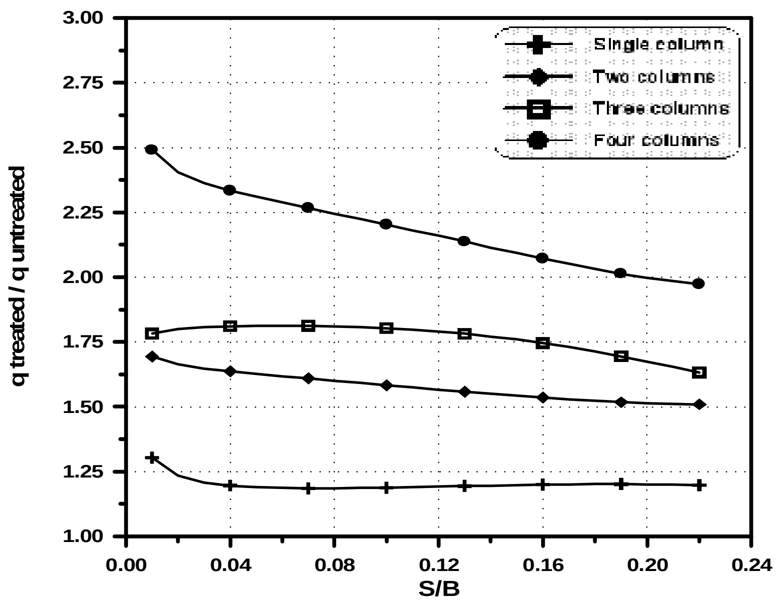

Figure (8) Bearing improvement ratio versus (S/B) for the soil treated with stone columns, cu = 6 kPa and L/D = 6.

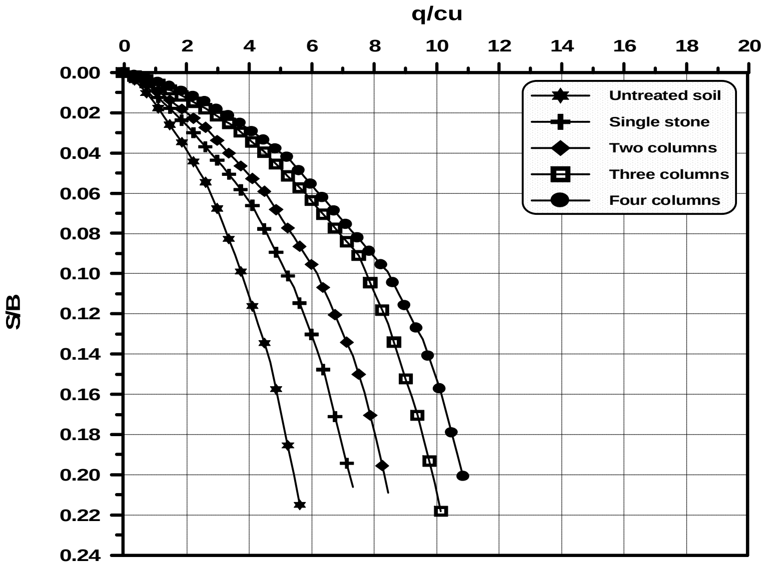

Figure (9) q/cu versus S/B for the soil treated with stone column, cu = 9 kPa and L/D = 6.

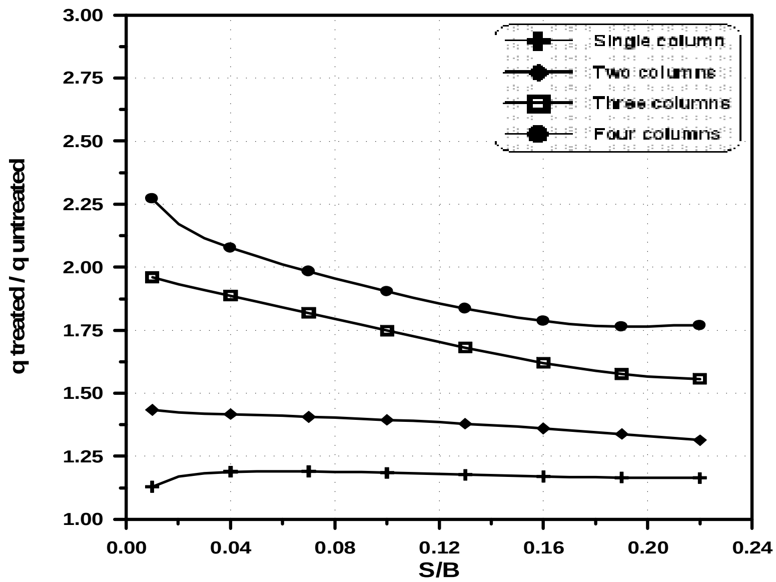

Figure (10) Bearing improvement ratio versus (S/B) for the soil treated with stone columns, cu = 9 kPa and L/D = 6.

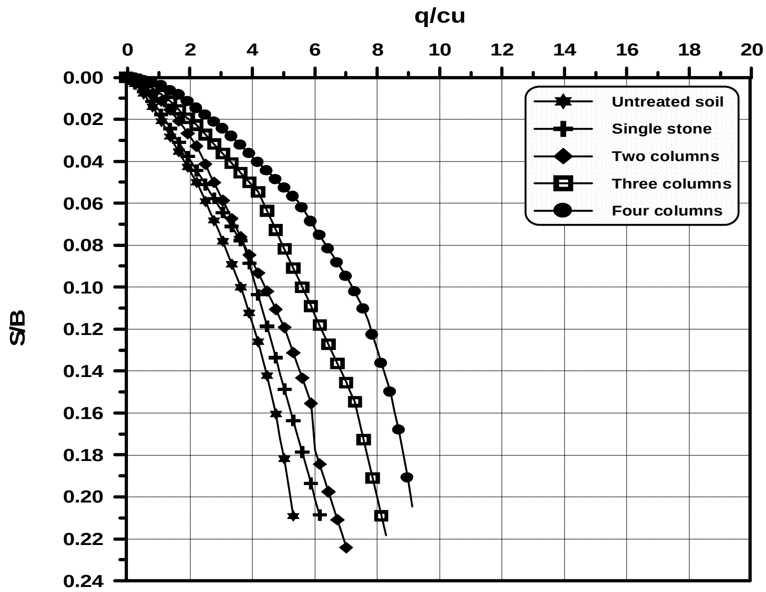

Figure (11) q/cu versus S/B for the soil treated with stone column, cu = 12 kPa and L/D = 6.

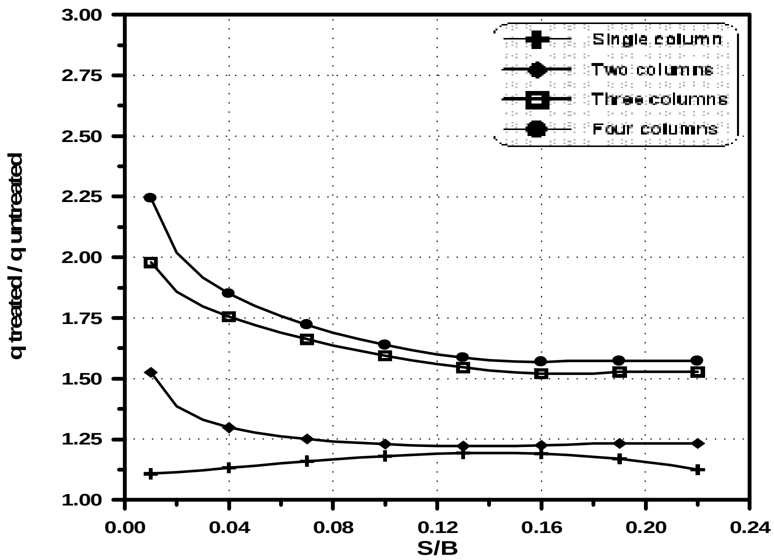

Figure (12) Bearing improvement ratio versus (S/B) for the soil treated with stone columns, cu = 12 kPa and L/D = 6.

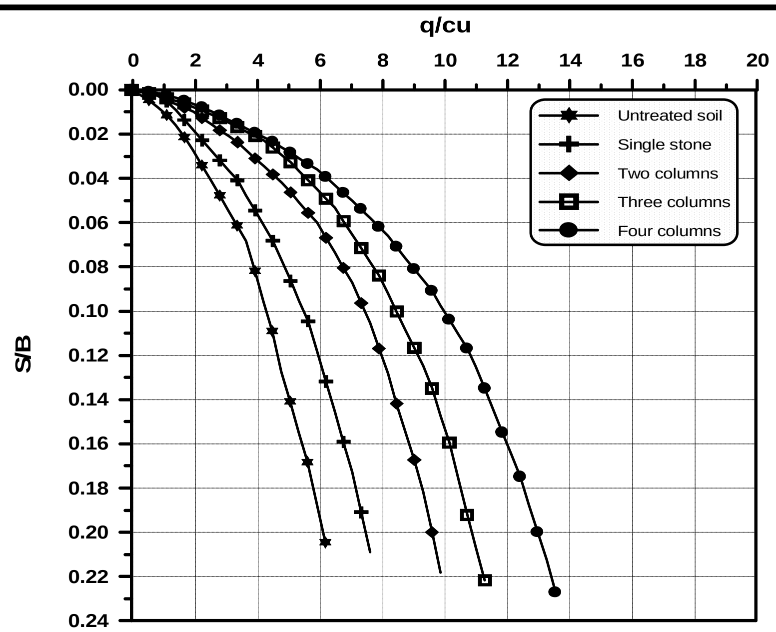

Figure (13) q/cu versus S/B for soil treated with stone column cu = 6 kPa and L/D = 8.

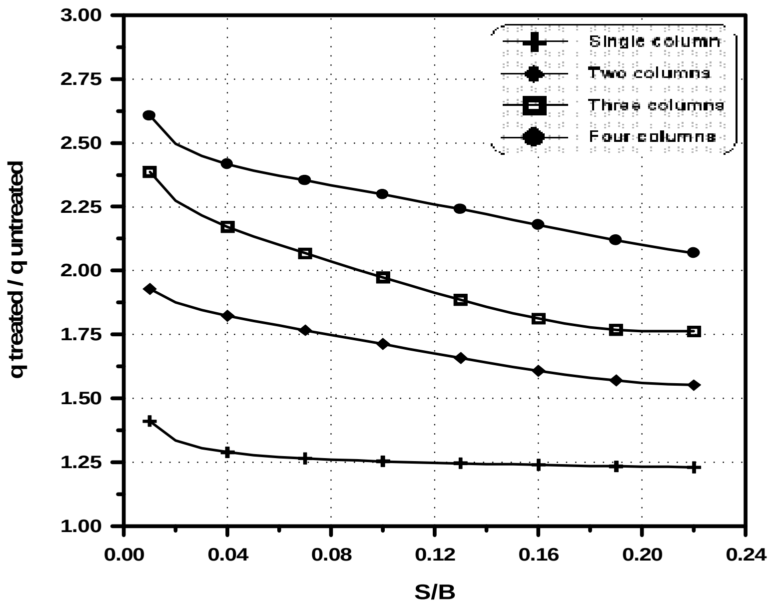

Figure (14) Bearing improvement ratio versus (S/B) for the soil treated with stone columns, cu = 6 kPa and L/D = 8.

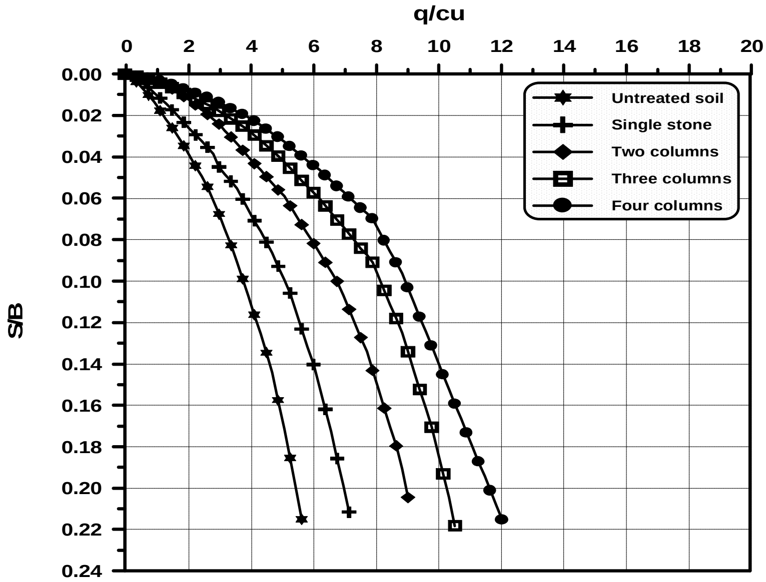

Figure (15) q/cu versus S/B for soil treated with stone column cu = 9 kPa and L/D = 8.

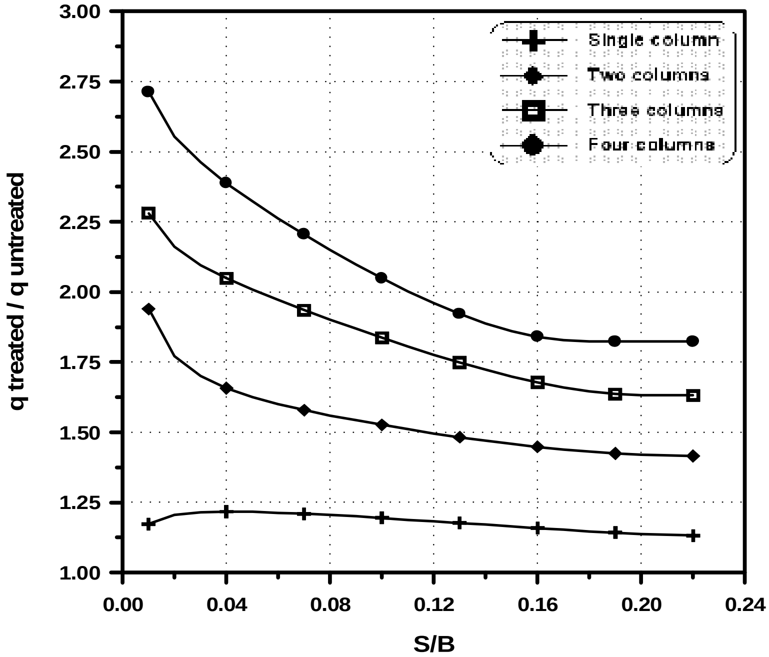

Figure (16) Bearing improvement ratio versus (S/B) for the soil treated with stone columns, cu = 9 kPa and L/D = 8.

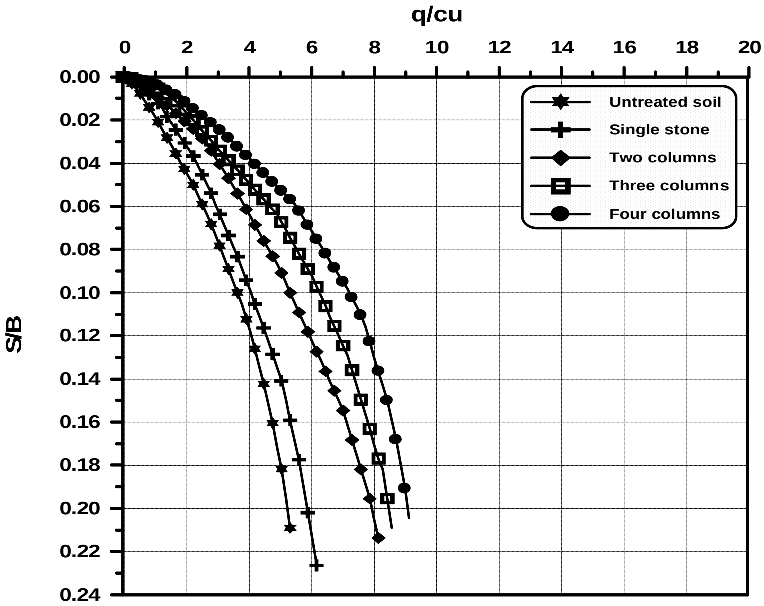

Figure (17) q/cu versus S/B for the soil treated with stone column cu = 12 kPa an L/D = 8.

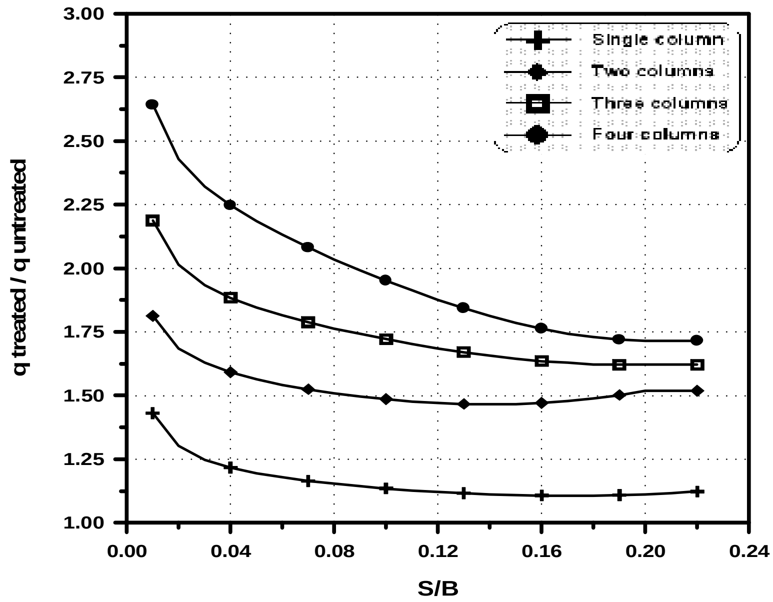

Figure (18) Bearing improvement ratio versus (S/B) for the soil treated with stone columns, cu = 12 kPa and L/D = 8.