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# Behaviour of Encased Floating Stone Columns

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**Abstract**

In this paper, the finite element method is utilized as a tool for carrying out different analyses of stone column–soil systems under different conditions. A trial is made to improve the behaviour of stone column by encasing the stone column by geogrid as reinforcement material .

The program CRISP2D is used in the analysis of problems. The program adopts the finite element method and allows prediction to be made of soil deformations considering Mohr–Coulomb failure criterion for elastic-plastic soil behaviour.

A parametric study is carried out to investigate the behaviour of ordinary and encased floating stone columns in different conditions. Different parameters were studied to show their effect on the bearing improvement and settlement reduction of the stone column. These include the length to diameter ratio (L/d), shear strength of the surrounding soil and, the area replacement ratio ($a_s$) and others.

It was found that the important increase in strength of stone column occurs when it is encased by geogrid for (length/diameter) L/d = 8 while in case of L/d = 4, a slight increase in the bearing improvement ratio at the early stages of applying the load is obtained and then the value of (q/Cu) for both ordinary and encased stone columns is the same.

**Keywords**: Stone columns, Encased, Improvement, Finite elements.

# تصرف الأعمدة الحجرية الطافية المغلفة

**الخلاصة**

في هذا البحث تم استخدام طريقة العناصر المحددة كأداة لأجراء تحليلات مختلفة على منظومة الأعمدة الحجرية-التربة بظروف مختلفة. أجريت محاولة لتحسين تصرف الأعمدة الحجرية بواسطة تغليف الأعمدة باستخدام المشبكات (geogrid) كمادة تسليح. تم استخدام برنامج CRISP2D لإجراء هذه التحليلات و الذي يعتمد طريقة العناصر المحددة ويمكن من خلاله الحصول على التشوه المتوقع من خلال اعتماد معيار فشل Mohr–Coulomb لتصرف التربة المرن - اللدن.

أجريت دراسة للمعاملات لتحري تصرف الأعمدة الحجرية لظروف مختلفة. تمت دراسة عدة معاملات لبيان تأثيرها على تحسين قابلية التحمل والهبوط للأعمدة الحجرية وهذه المعاملات هي نسبة طول الركيزة إلى قطرها, مقاومة القص غير المبزولة للتربة المحيطة بالركيزة وكذلك نسبة المساحة التعويضية مساحة العمود الحجري/مساحة الأساس الكلي) لكل من الأعمدة الحجرية العادية والمسلحة.

وقد وجد أن الزيادة المهمة في قوة العمود الحجري تحدث عند تغليفه بمشبك التسليح لحالة (L/d) الطول/القطر) تساوي (8) أم في حالة (L/d) تساوي (4) فيحدث تحسن بسيط في نسبة تحسن التحمل في مراحل التحميل الأولى و بعدها يصبح التحسن لحالتي العمود الحجري الاعتيادي و المغلف متشابها.

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**Introduction:**
Stone columns were well known in 1830 to French military engineers to support the heavy foundation of iron work at the artillery arsenal that was founded on soft soil. The columns were (2 m) long and (0.2 m) in diameter constructed by driving stakes into ground withdrawing them then backfilling the hole with crushed stone, but they are not ideal for behaviour of foundation stone column system. Stone columns were then forgotten until the 1930's when they were rediscovered as by product of the technique of vibroflotation for compacting granular soils. In the last part of 1950's, the use of compacted stone column in soft clay deposits was started in Germany, and the construction of sand compaction pile was developed in Japan by Murayama in 1957 **(Tanimoto, 1973)**, Although stone columns are stiffer than compacted sand piles, the sand is cheaper than stone, so it is more economical to use sand instead of stone especially if large volume of weak soil is required to be replaced.

In recent years, a new kind of sand/gravel column appeared and called geotextile or giogrid encased sand/gravel column. It is primarily used for improvement of foundation in many countries around the world; they are placed in regular patterns through the soft soil down to lower bearing stratum **(Kempfert and Gebreselassi, 2006)**.

Al-Recaby (1999), carried out field load tests on stone column of (0.5 m) diameter and (3 m) length. These tests were performed in Al-Rahman mosque project in Baghdad city. The material of stone ccolumn was stabilized with 5% lime (dry or slurry) and reinforced by special pattern consisting of steel disk plates to be put in horizontal arrangement at specified depth. The results showed that increase in bearing ratio (q/Cu where Cu is the undrained shear strength) and reduction in the settlement ratio (S/d where d is the stone column diameter) can be obtained when the stone columns are reinforced.

Al-Qyssi (2001), performed seven field tests in Baghdad city to investigate the bearing improvement ratio and the settlement reduction ratio in case of ordinary stone column and when reinforcement of steel discs is used in the upper part of the column. The tests were carried out with area ratio (which is defined as the ratio between the area of stone column cross-section and the area of clay surrounding it) of (0.042) to (0.18). The results showed that addition of reinforcement in the upper half revealed an improvement of bearing ratio of (0.16) and (1.78) for two and three discs of reinforcement with corresponding settlement reduction ratios of (0.25) and (0.2), respectively.

**Geogrid Encased Stone Column:**
The foundation system with geotextile/geogrid encased sand or gravel columns (GEC) is a new soil improvement method and it is primarily used for improvement of foundations of road embankments in Germany, Sweden and the Netherlands since the last decade **(Kempfert and Gebreselassi, 2006)**. Basically, this method is an extension of the well known stone column and sand compaction pile foundation improvement techniques. The only difference is that the column in this new method is encased with geotextile of high tensile strength. Recently, it is also used in dike constructions and land reclamation such as the dike of roubust Airbus A380 in Hamburg, Germany which was founded on over 60,000 getextile – encased sand columns of diameter of (0.8 m) and (4 to 14 m) length below the base of the dike foot reached up to the relatively load bearing sand layer.

The geogrid/geotextile system can be used in very soft clay (Cu < 20 $kN/m^2$), because when used in sensitive clay, stone columns have certain limitations. There is increase in settlement of the bed because of absence of resistance. The clay particles get clogged around the stone column thereby reducing radial drainage. To overcome these limitations, and to increase the efficiency of the stone column with respect to strength and compressibility, stone columns are encased (reinforced) using geogrids to improve the lateral support.

In this paper, geogrid reinforced stone columns are analyzed using the finite element method.

**Computer Program Used:**

CRISP is a 2D finite element program. CRISP Windows interface is currently restricted to 2D plane strain and axisymmetric problems.

**Types of Analysis:**

The program can deal with undrained, drained or fully coupled (Biot) consolidation analysis of two-dimensional plane strain or axisymmetric (with axisymmetric loading) solid bodies.

**Finite Element Geometry:**

The basic axisymmetric finite element mesh used for geogrid encasement parametric study is shown in Figure (1).

Eight-node isoparamtric elements were used to model the soil and stone column. The reinforcement material (geogrid material) is modelled by three-node bar elements which mobilize axial loads only. Due to symmetry, only half of the axisymmetric problem is considered. The boundary conditions of the axisymmtric problem domain are shear free with no radial movement at the lateral sides and prevent the bottom boundary from both radial and vertical movement. The thickness of soil below the tip of the stone column was taken according to the bulb of stresses which disappear at a distance equal to (6 d) below the column tip (where d is the diameter of the stone column), therefore the thickness of the soil below the tip of the stone column is (10 m), for more safety, (Majeed, 2008).

According to (2:1) stress distribution method, the stress reaching the lateral distance from the center of the stone column equals to (d+L)/2, thus for a length (L) equal to (12 m) and (d) equals (1 m), the lateral distance is taken to be (18 m), for more safety. The water table is assumed to be at the ground level. An isolated concrete footing of (0.5 m) thickness was placed at the top of the stone column and a uniform load was applied on the footing gradually.

The settlement is calculated at the top of footing at node number (479) for the mesh used to study the effect of geogrid encasement as shown in Figure (1).

**Material Characteristics and Modelling:**

Elastic-perfectly plastic Mohr-Coulomb model for undrained condition has been assumed to model the behaviour of the soil and stone column materials, while linear elastic bar element was used for geogrid material modelling.

The stone column material properties are given in Table (1). The geogrid used in this study is warp knitted fiberglass geogride (FGG 140). The geogrid properties are given in Table (2).

The study was carried out using Poisson's ratio (0.45) for clay. The modulus of elasticity (E) of the clay is assumed to be = Cu × 250 (E = 200 to 500 × Cu) (**Bowles, 1996**). The unit weight, ($\gamma$) = 16 $kN/m^3$, the angle of internal friction ($\phi$) of clay = 0.

**Effect of L/d and ($a_s$):**

The area replacement ratio of stone column plays an effective part in improving the strength of soft clay treated by stone column; also the length of stone column affects directly stone column strength.

Figures (2) to (7) show the relation between L/d (length of stone column / diameter of stone column) and the bearing improvement ratio (q treated /q untreated) for L/d (3-12), for ordinary floating stone column and encased floating stone column. In these figures, Cu = 20 kPa of surrounding soft soil was adopted. These figures show that for ordinary stone column, the strength of column increases with the increase in the length of stone column. The effective length to diameter ratio of stone column is found to be L/d = (7-8) for all area ratios and after L/d of 8, there is no effect on (q treated /q untreated) value. It can also be seen that for encased stone column, the bearing improvement ratio increases with the increase of (L/d) even when (L/d) ratio becomes more than 8 for all area replacement ratios. This means that in case of encased stone column, there is no limitation on the effective (L/d) ratio.

The figures also indicate that the strength of stone column increases when encased with geogrid compared with ordinary stone column and the increasing in (q treated /q untreated) is higher when (L/d) increases.

Figures (2), (3), and (4) reveal that the stone column is not improved when it is encased by geogrid when L/d =3, actually the improvement is starting from L/d = 6 for $a_s$ = 0.1 and 0.15, while the increasing in (q treated / q untreated) for $a_s$ = 0.25 is starting from L/d = 5. On the other hand, the improvement in stone column when it is encased started from L/d = 4 for $a_s$ = 0.3 and L/d = 3 for $a_s$ = 0.35.

Figures (8) and (9) show the relation between the bearing ratio (q/Cu) and (S/B) settlement/footing diameter for L/d = 4 and 8, respectively for untreated soil and soil treated by ordinary and encased floating stone columns. Figure (9) shows that the important increase in strength of stone column occurs when it is encased by geogrid for L/d = 8 while in case of L/d = 4, a slight increase in (q/Cu) at the early stages of applying the load is obtained and then the value of (q/Cu) for both ordinary and encased stone columns is the same as shown in Figure (8).

Figures (10) and (11) show the relation between (S/B) and (q treated /q untreated) to study the improvement in bearing ratio with the settlement increase for L/d = 4 and 8, respectively, when $a_s$ = 0.25 and Cu = 20 kPa for ordinary and encased stone columns. Figure (10), which is drawn for L/d = 4, shows that the bearing improvement ratio (q treated / q untreated) is initially higher for encased stone column than ordinary stone column at S/B less than 0.06 and after this value, the (q treated / q untreated) becomes the same for both the ordinary and encased stone columns.

Figure (11), which is drawn for L/d = 8, shows that for ordinary stone column, the bearing improvement ratio (q treated /q untreated) increases with S/B and after S/B = 0.1, the (q treated / q untreated) becomes constant, while for encased stone column, (q treated /q untreated) starts with high value and decreases with the increase in (S/B) till reaching the value of S/B = 0.1, and above this limit, the value of (q treated / q untreated) becomes constant with (S/B) increasing.

Figure (12) shows the relation between the area replacement ratio ($a_s$) (which is defined as the ratio between the area of stone column cross-section and the area of clay surrounding it) and (q treated / q untreated) for ordinary and encased floating stone columns. This figure shows that (q treated / q untreated) increases with increase in ($a_s$) for both ordinary and encased stone columns, the increase in ($a_s$) is more efficient for encased stone column than ordinary stone column especially when ($a_s$) is more than 0.25.

Figures (13) and (14) show the relation between bearing ratio (q/Cu) and (S treated / S untreated) (settlement of treated soil /settlement of untreated soil) for L/d = 4 and 8, respectively, when $a_s$ = 0.25 and Cu = 20 kPa. Figure (13) shows that the settlement reduction ratio (S treated / S untreated) for L/d = 4 is improved when the stone column is encased by geogrid but when (q/Cu > 8), the (S treated / S untreated) becomes the same for ordinary and encased stone columns. Figure (14) shows that for L/d = 8, the settlement reduction ratio (S treated / S untreated) is improved when the stone column is encased by geogrid and the improvement increases with the increase in (q/Cu) and becomes constant when (q/Cu) is greater than 10.

Figure (15) shows the relation between ($a_s$) and (S treated / S untreated) for ordinary and encased floating stone columns. It is demonstrated that the (S treated /S untreated) value decreases with the increase in $a_s$. It is also noted that the settlement improvement increases when ($a_s$) increases.

**Effect of the Undrained Shear Strength (Cu) of Surrounding Soil:**

Figures (16), (17), and (18) show the relation between the bearing improvement ratio (q treated /q untreated) and (L/d) (length of stone column/diameter of stone column) of ordinary and encased floating stone columns having ($a_s$) = 0.25. The undrained shear strength of the surrounding soil is Cu = 10, 30, and 40 kPa, respectively. These figures illustrate that the use of geogrid to encase the stone column leads to increase the strength of stone column. These figures also illustrate that the improvement in bearing ratio when the stone column is encased by geogrid is more efficient with increase in Cu. Figure (16), which is drawn for Cu = 10 kPa, shows that the encased stone column starts to give more strength than ordinary stone column after L/d = 6, while for Cu = 40 kPa as shown in Figure (18), the increase in (q treated /q untreated) starts from L/d = 4.

Figure (19) shows the relation between Cu of the surrounding soil and the improvement ratio (q treated /q untreated) for encased and ordinary floating stone columns. It can be noticed that the use of geogrid encasement gives better results when Cu is higher, and increasing the value of Cu plays important role in ordinary stone column.

Figure (20) shows the relation between (q treated / q untreated) and (L/d) for ordinary stone column in soft clay having shear strength of Cu = 10, 20, 30, and 40 kPa. It can be noted that the value of (q treated / q untreated) is higher for lower Cu values; this means that the stone column is more efficient in very soft soil.

The reason for this behaviour is attributed to the change in the modular ratio (modulus of elasticity for stone column/ modulus of elasticity for soft soil). When Cu = 10 kPa, the modulus of elasticity = 2500 kPa (E for soft soil = 250 × Cu was used in this study) and hence the modulus of elasticity for stone column material is assumed to be 100000 kPa, then the modular ratio is 40, while the modular ratio for Cu = 40 kPa is only 10, and hence the efficiency of the stone column increases with increase in modular ratio as was shown by **Balaam and Poulos, (1978)**. Then the lower value of Cu gives better results than the higher Cu. Figure (20) also shows that for Cu = 20, 30, and 40 kPa, the effective length to diameter ratio (L/d) is (7-8), while for Cu = 10 kPa, the effective (L/d) is (10).

Figure (21) shows the relation between (S treated / S untreated) and Cu for ordinary and encased stone columns. This figure illustrates the effect of Cu on settlement which is better improved when Cu is decreased for both ordinary and encased stone columns.

Figure (22) shows the relation between (q treated / q untreated) and (L/d) for ordinary stone column in soft clay having shear strength of Cu = 10, 20, 30, and 40 kPa. It can be noted that the value of (q treated / q untreated) is higher for lower Cu values; this means that the ordinary stone column is more efficient in very soft soil.

**Conclusions:**

From the finite element analysis carried out in the previous sections, the following conclusions can be drawn:

**Ordinary Floating Stone Columns:**

1. The area replacement ratio has great effect on bearing improvement ratio for soft soil improved by stone column.
2. The undrained shear strength (Cu) of the surrounding soil has a significant effect on bearing improvement ratio and settlement reduction. When the undrained shear strength (Cu) of the surrounding soil is decreased, the bearing improvement ratio is increased and the settlement is decreased.
3. The maximum effective length to diameter (L/d) ratio is between (7-8) for Cu between (20 - 40) kPa and between (10 - 11) for Cu = 10 kPa.

**Encased Floating Stone Columns:**

1. The increase in the area replacement ratio increases the bearing improvement ratio especially when the area replacement ratio is greater than (0.25).
2. The bearing improvement ratio and settlement increase with increasing the undreamed shear strength (Cu) of the surrounding soil.
3. The geogrid encasement of stone column greatly decreases the lateral displacement compared with ordinary stone column. The use of geogrid encasement gives better results when Cu is higher, and increasing the value of Cu plays important role in ordinary stone column.
4. The important increase in strength of stone column occurs when it is encased by geogrid for L/d = 8 while in case of L/d = 4, a slight increase in (q/Cu) at the early stages of applying the load is obtained and then the value of (q/Cu) for both ordinary and encased stone columns is the same.
5. The bearing improvement ratio (q treated / q untreated) increases with increase in the area replacement ratio ($a_s$) for both ordinary and encased stone columns, the increase in ($a_s$) is more efficient for encased stone column than ordinary stone column especially when ($a_s$) is more than 0.25.

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**[8]-Tanimoto, K., (1973),** "Introduction of the Sand Compaction Pile Method as Applied to Stabilization of Soft Foundation Grounds", Common Wealth Scientific Industrial Research Organization, Australia.

**Table (1) Material Properties of Stone Column Used in the Parametric Study of the Problem.**

| Parameter | Value |
|---|---|
| **Angle of internal friction,** f **(degrees)** | 40 |
| **Unit weight, $\gamma$ (kN/m$^3$ )** | 17 |
| **Poisson's ratio,** u | 0.30 |
| **Modulus of elasticity (kN/m$^2$)** | 100000 |

**Table (2) Geogrid Properties Used in Stone Column Encasement (Shenzhen Ktyu Insulation CO., Ltd.)**

| Parameter | Value |
|---|---|
| Tensile strength (kN/m) | 140 |
| Elongation (%) | 4 |
| Weft diameter (mm) | 5 |
| Hole size (mm × mm) | 25.4 × 25.4 |
| Elastic modulus (GPa) | 76 |

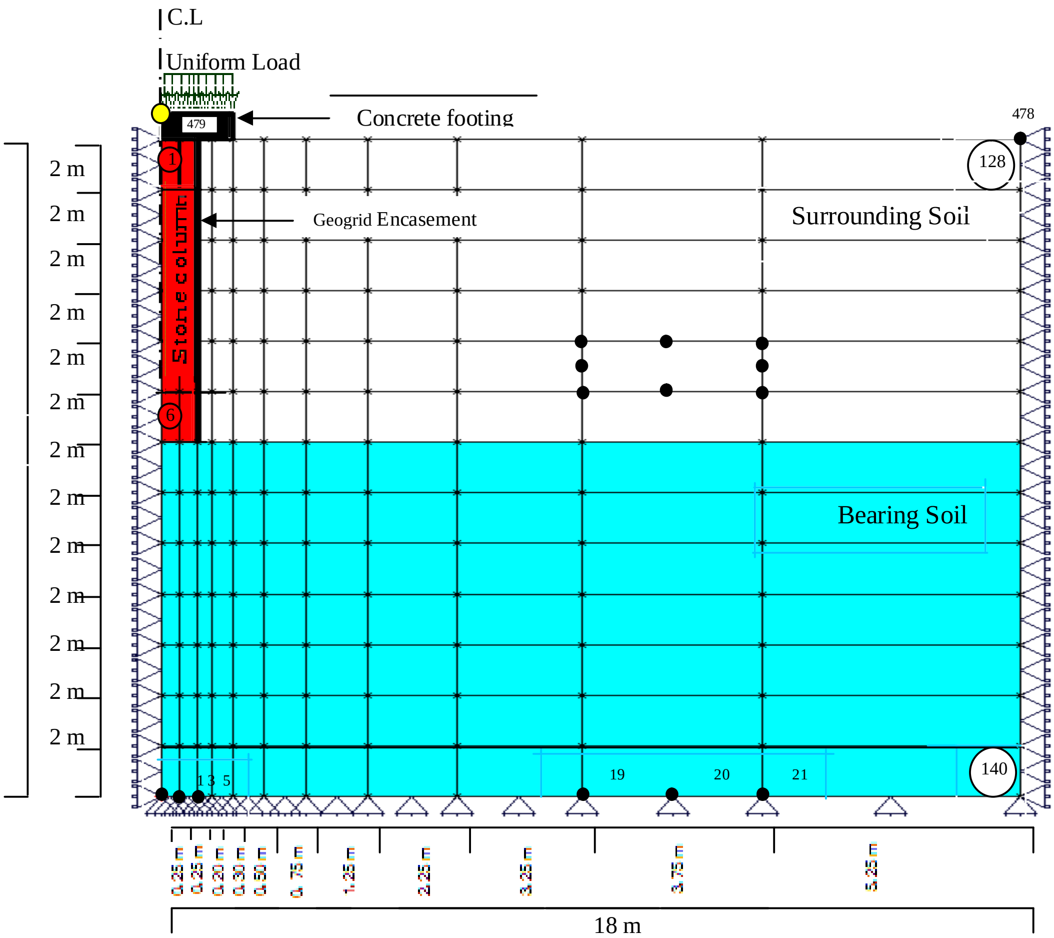


Figure (1) Basic Axisymmetric Finite Element Mesh Used for the Parametric Study.

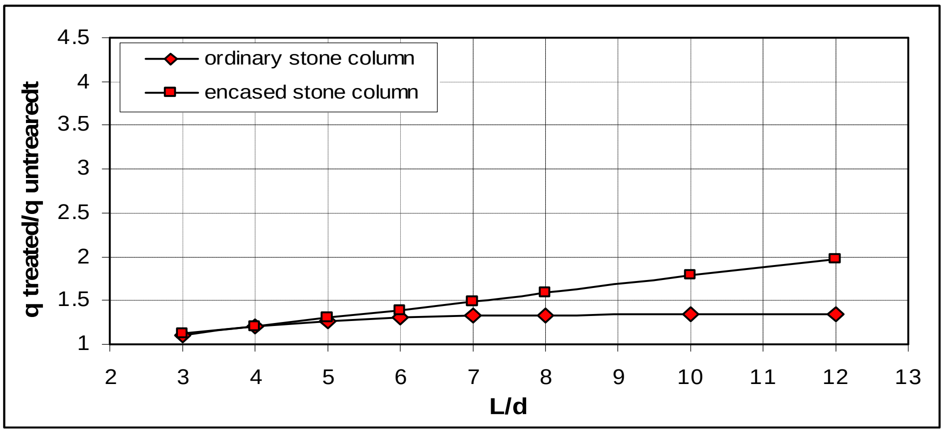


Figure (2) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio of Floating Stone Column (Cu=20 kPa, $a_s$ = 0.1).

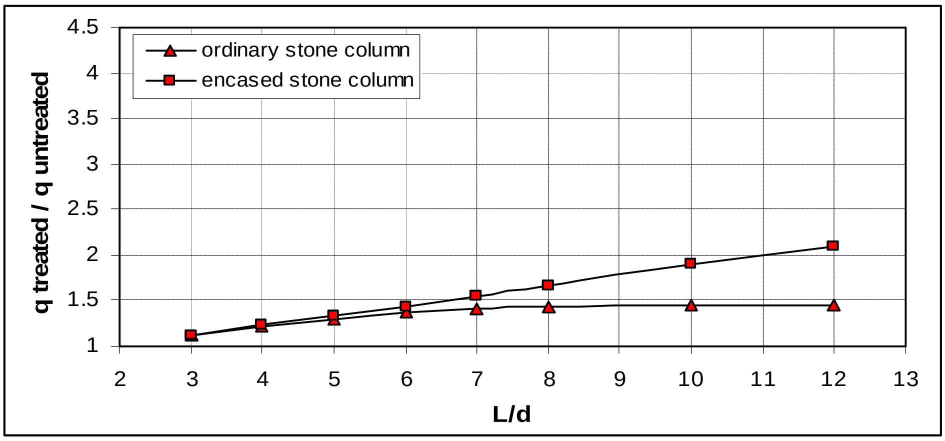


**Figure (3) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio of Floating Stone Column (Cu=20 kPa, $a_s$ = 0.15).**

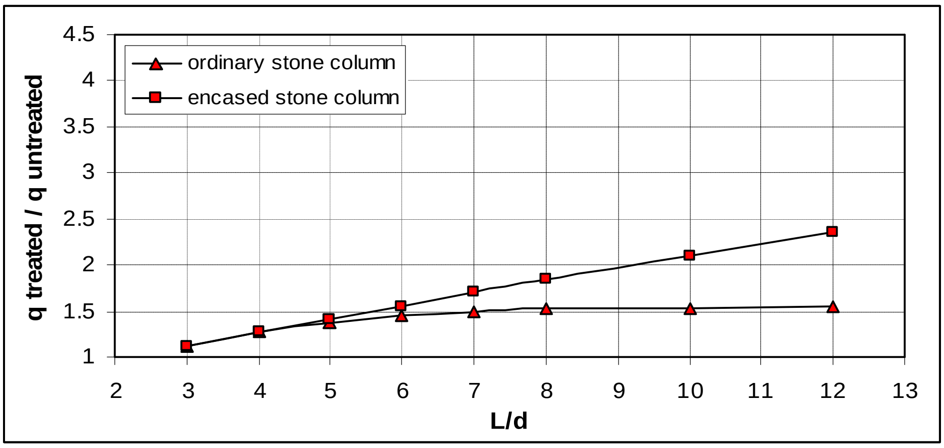


**Figure (4) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio of Floating Stone Column (Cu=20 kPa, $a_s$ = 0.2).**

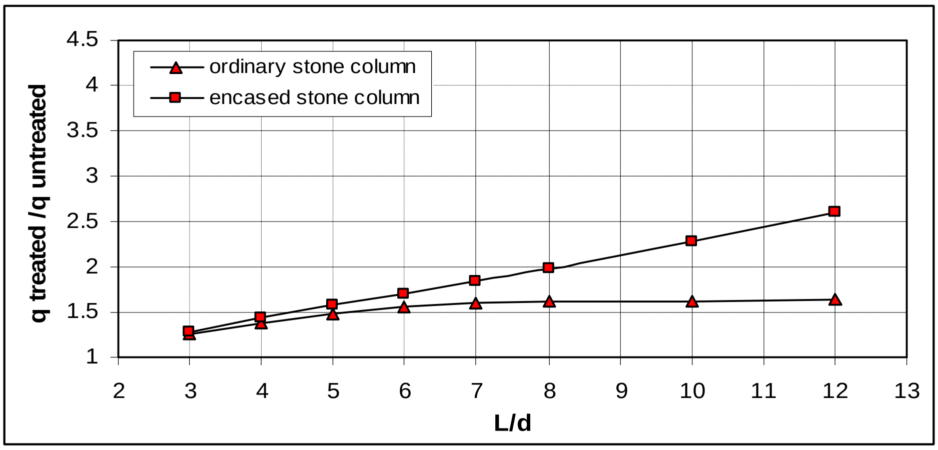


**Figure (5) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio of Floating Stone Column (Cu=20 kPa, $a_s$ = 0.25).**

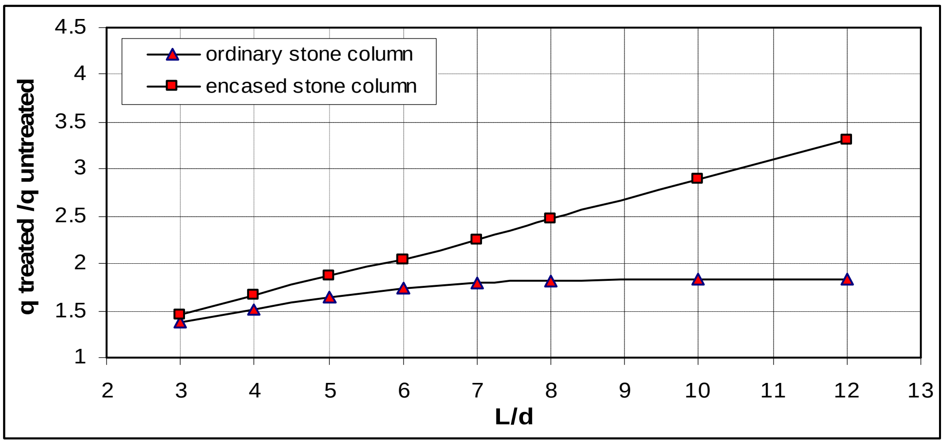


**Figure (6) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio of Floating Stone Column (Cu=20 kPa, $a_s$ = 0.3).**

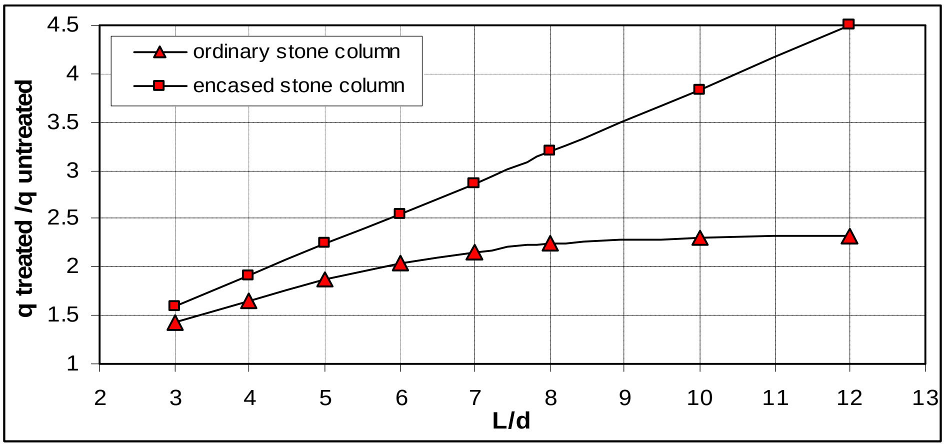


**Figure (7) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio of Floating Stone Column (Cu=20 kPa, $a_s$ = 0.35).**

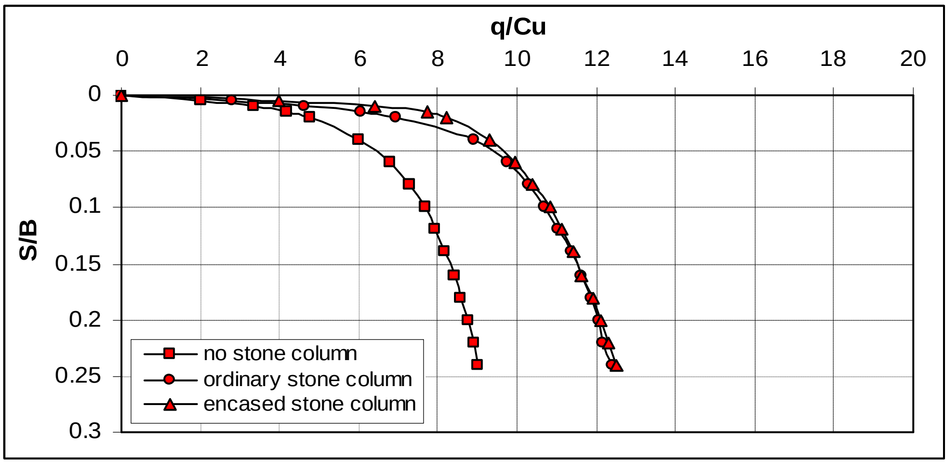


**Figure (8) Relationship Between the Bearing Ratio and Settlement Ratio of Floating Stone Column, (Cu=20 kPa, L/d=4, $a_s$ = 0.25).**

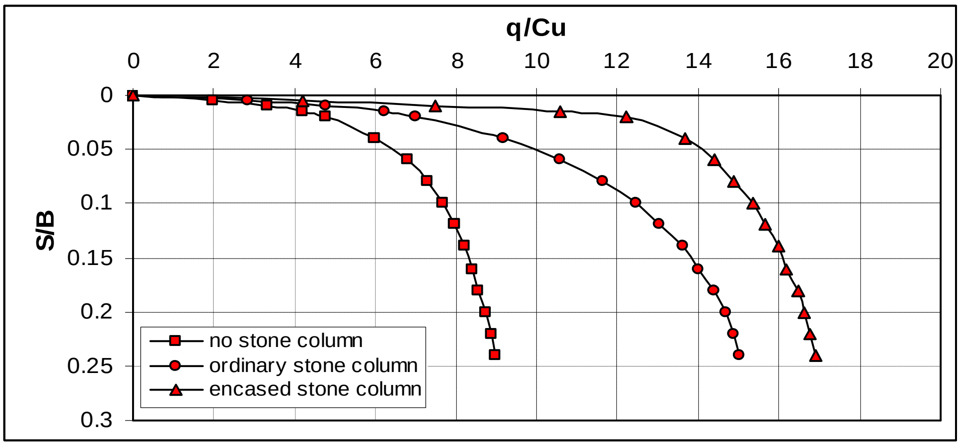


**Figure (9) Relationship Between the Bearing Ratio and Settlement Ratio of Floating Stone Column, (Cu=20 kPa, L/d=8, $a_s$ = 0.25).**

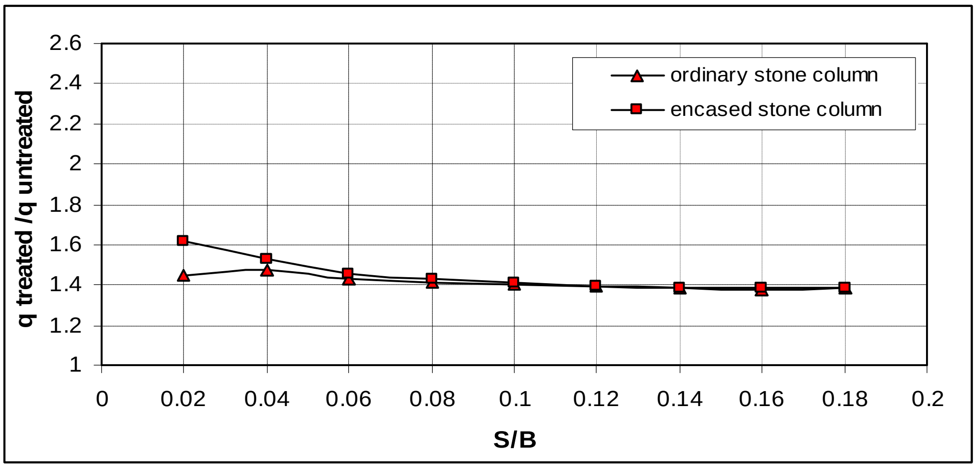


**Figure (10) Relationship Between the Bearing Improvement Ratio and Settlement Ratio of Floating Stone Column, (Cu=20 kPa, L/d=4, $a_s$ = 0.25).**

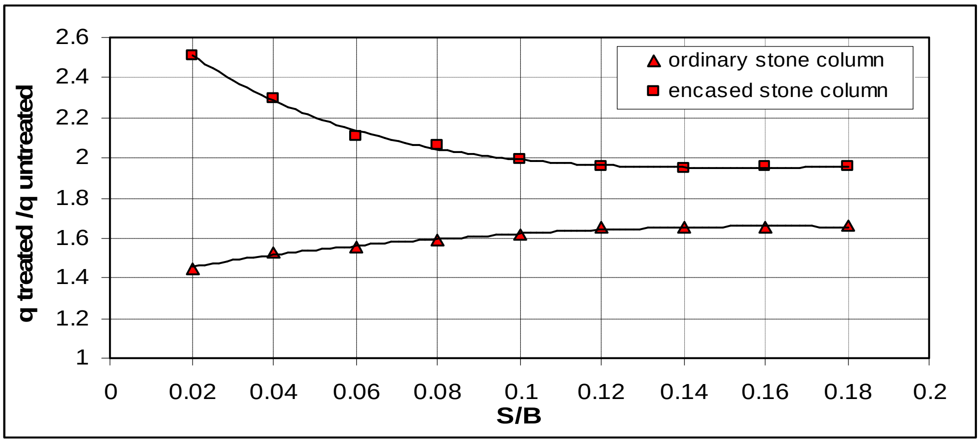


**Figure (11) Relationship Between the Bearing Improvement Ratio and Settlement Ratio of Floating Stone Column, (Cu=20 kPa, L/d=8, $a_s$ = 0.25).**

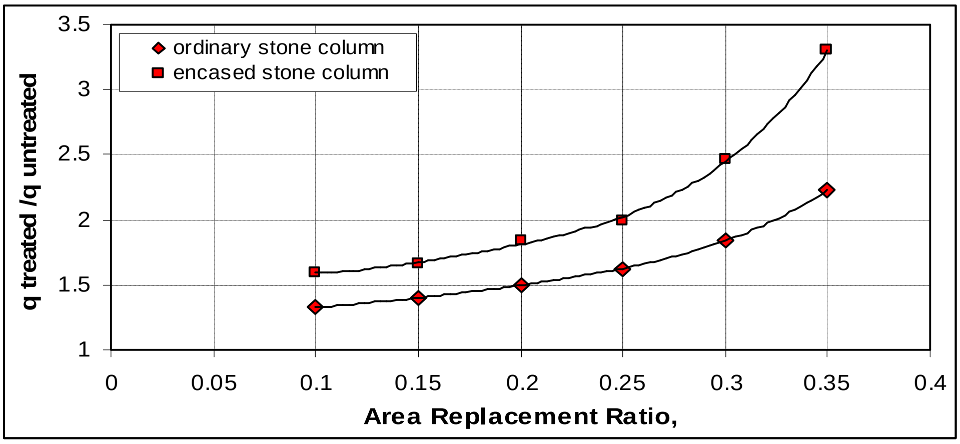


**Figure (12) Variation of the Bearing Improvement Ratio with the Area Replacement Ratio of Floating Stone Column (Cu=20 kPa, L/d=8, $a_s$ = 0.25).**

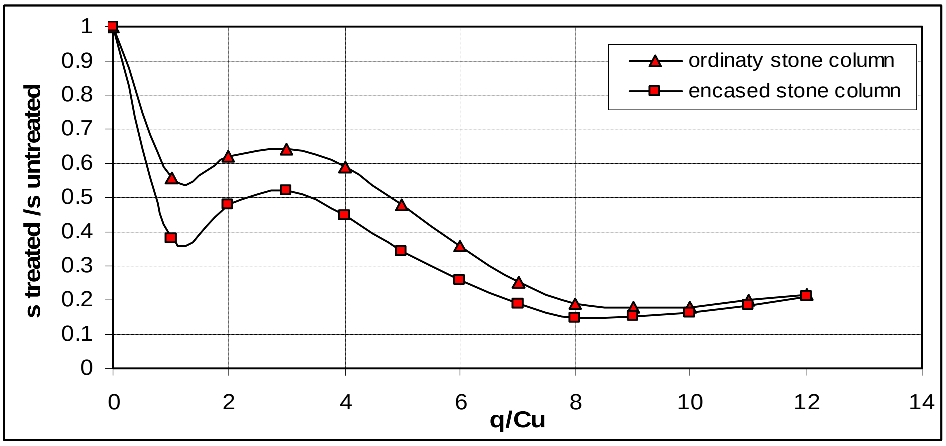


**Figure (13) Relationship Between the Settlement Ratio with the Bearing Ratio of Floating Stone Column (Cu=20 kPa, L/d=4, $a_s$ = 0.25).**

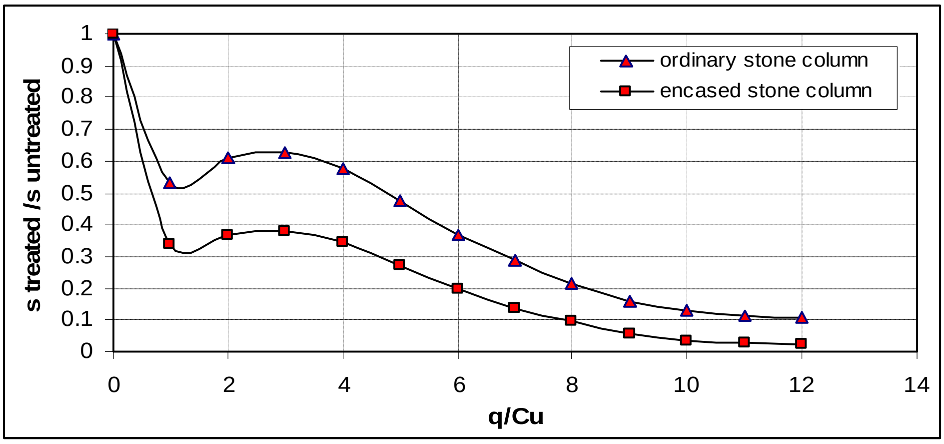


**Figure (14) Relationship Between the Settlement Ratio with the Bearing Ratio of Floating Stone Column (Cu=20 kPa, L/d=8, $a_s$ = 0.25).**

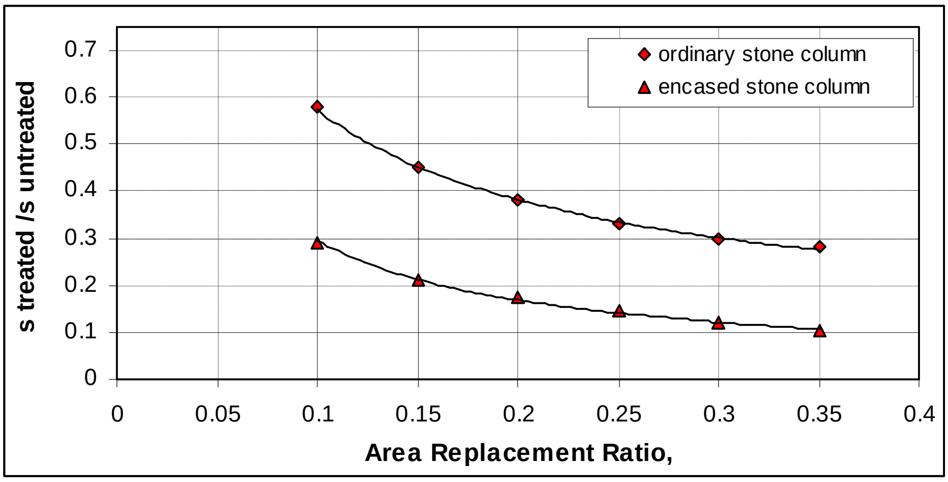


**Figure (15) Variation of the Settlement Ratio and Area Replacement Ratio of Floating Stone Column (Cu=20 kPa, $a_s$ = 0.25, L/d=8).**

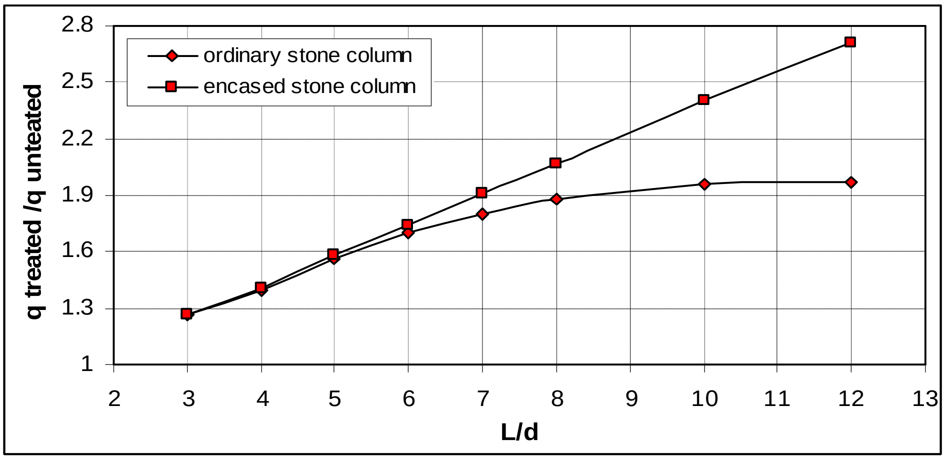


**Figure (16) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio of Floating Stone Column (Cu=10 kPa, $a_s$ = 0.25).**

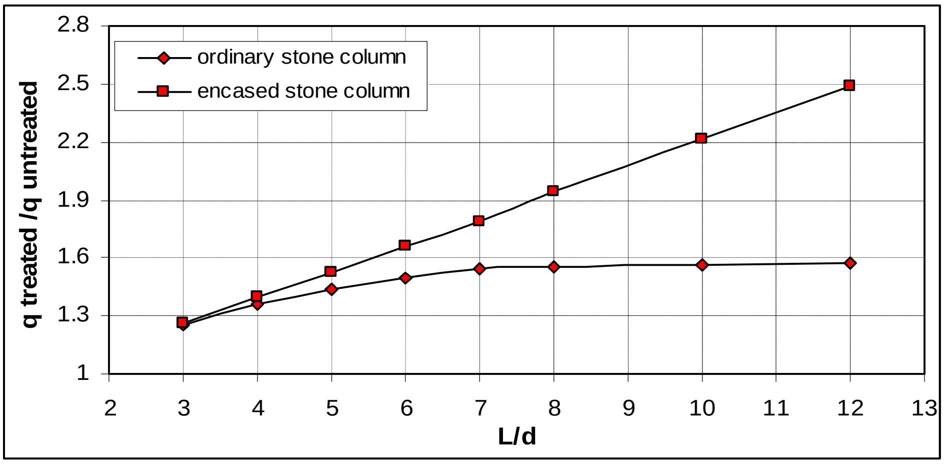


**Figure (17) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio of Floating Stone Column (Cu=30 kPa, $a_s$ = 0.25).**

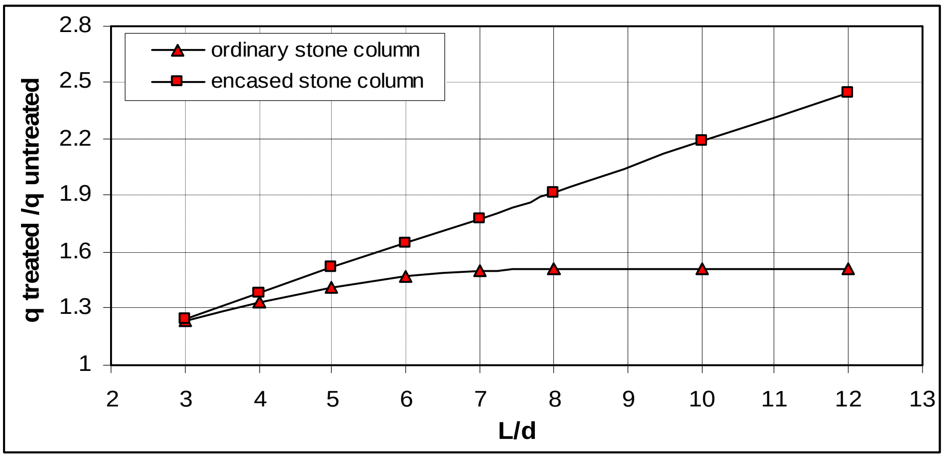


**Figure (18) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio of Floating Stone Column (Cu=40 kPa, L/d=8 $a_s$ = 0.25).**

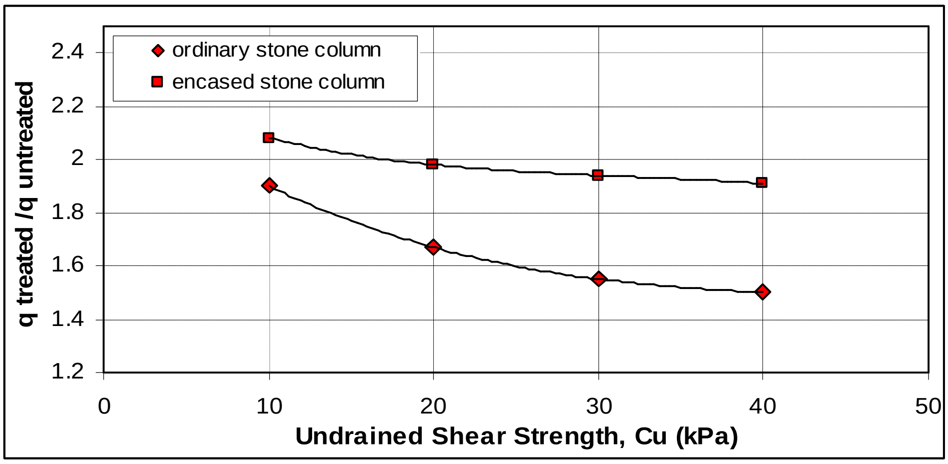


**Figure (19) Variation in the Bearing Improvement Ratio with the Undrained Shear Strength of Soft Soil for Floating Stone Column (L/d=8, $a_s$ = 0.25).**

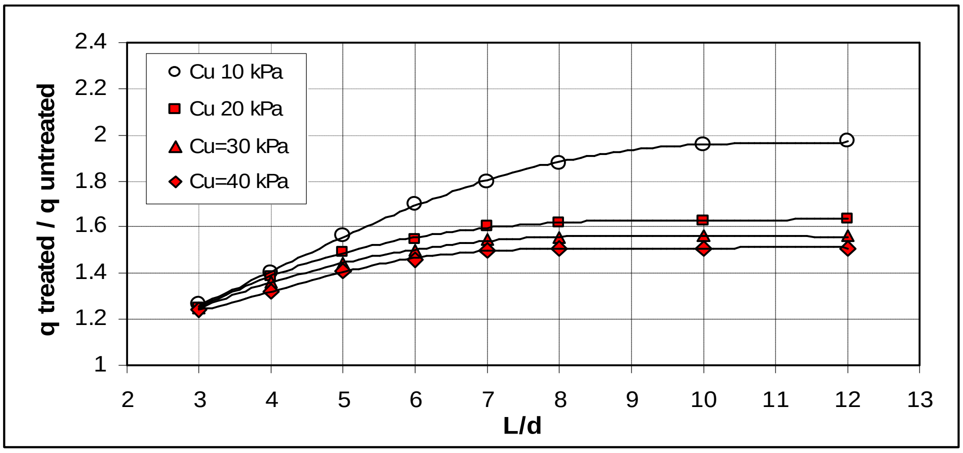


**Figure (20) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio for Different Undrained Shear Strengths of Ordinary Floating Stone Column, ($a_s$ = 0.25).**

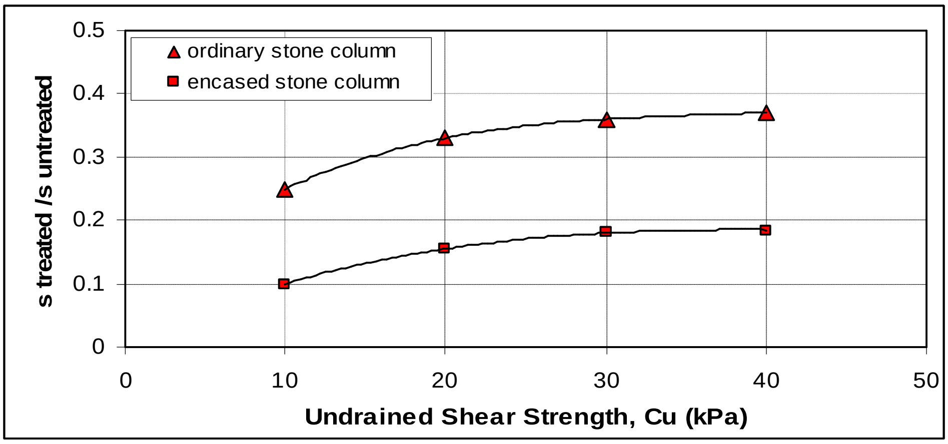


**Figure (21) Variation in the Settlement Ratio and Undrained Shear Strength of Soft Soil for Floating Stone Column ($a_s$ = 0.25, L/d=8).**

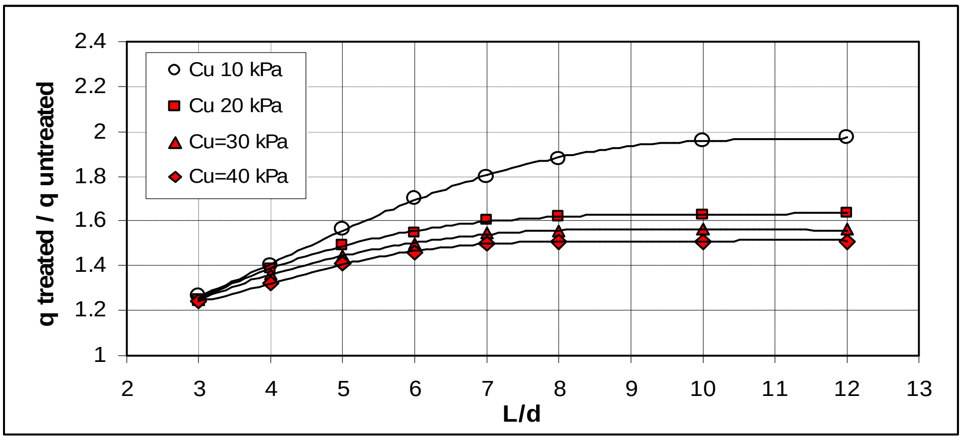


**Figure (22) Relationship Between the Bearing Improvement Ratio and Length to Diameter Ratio for Different Undrained Shear Strengths of Ordinary Floating Stone Column, ($a_s$ = 0.25).**