Int. J. of GEOMATE, Sept., 2012, Vol. 3, No. 1 (Sl. No. 5), pp. 343-350
Geotec., Const. Mat. & Env., ISSN:2186-2982(P), 2186-2990(O), Japan

A Study on the Behaviour of Geogrid Encased Capped Stone Columns by the Finite Element Method

Mohammed Y. Fattah [1] and Qutaiba G. Majeed [2]
[1]Building and Construction Eng. Dept., University of Technology, Baghdad, Iraq
[2]Civil Engineering Department, University of Diyala, Iraq.

ABSTRACT: 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 columns by encasing them by geogrid as reinforcement material. The program CRISP-2D is used in the analysis of problems. The program 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 are 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), the area replacement ratio (a_s) and thickness of the stone cap layer. It was found that for encased stone column, the bearing improvement ratio increases with the increase of length to diameter (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 strength of stone column increases when encased with geogrid compared with ordinary stone column and the increasing in bearing capacity (q treated /q untreated) is higher when (L/d) increases. The use of stone cap above the stone column increases the bearing improvement ratio and decreases the settlement for all L/d ratios. The increase in stone cap thickness increases the bearing improvement ratio and decreases settlement for all L/d ratios.

Keywords: Stone columns, Finite elements, Geogrid reinforcement, Stone cap.

1. INTRODUCTION

Stone columns in soft soil improve bearing capacity because they are stiffer than the material which they replace and compacted stone columns produce shearing resistances which provide vertical support for overlying structures or embankments. Also the stone columns accelerate the settlement in the native surrounding soil and improve the load settlement characteristics of foundation.

Of many techniques of ground improvement, stone column has gained lots of popularity since it has been properly documented in the middle of the last century. As in most new ground improvement techniques that were developed in the world, experience has preceded the development of theory and comprehensive guidelines. The stone column technique of ground treatment has proven successful in improving slope stability of both embankments and natural slopes, increasing bearing capacity, reducing total and differential settlements, and increasing the time rate of settlement.

Granular piles or stone columns are composed of compacted sand or gravel inserted into the soft clay foundation by displacement method. The term “granular piles” refers to the component of compacted gravel and/or sand piles. It also refers to those known as stone columns. The ground improved by compacted granular piles is termed as composite ground. When loaded, the pile deforms by bulging into the subsoil strata and distributes the stresses at the upper portion of the soil profile rather than transferring the stresses into the deeper layers, thus causing the soil to support it. As a result, the strength and bearing capacity of the composite ground can be increased and compressibility reduced (Bergado et al., 1996) [5].

The diameter of column is in the range (0.6 - 0.8) m, but in some cases, it becomes up to (2.0) m (Aboshi et. al., 1979) [1]. Sand compaction piles of diameters of less than (1.0) m have usually been used when constructed on land while larger diameters have been used for reclamation of land from the sea, i.e. offshore application (Mitchell, 1981[11]; Baraksdale and Bachus, 1983[4]). The sand columns are usually placed at spacing of (1.5– 2.2) m c/c depending on the load condition and finer content of the soil being treated (Tanimoto, 1973). The performance of composite ground is best investigated in terms of ultimate bearing capacity, settlement, and general stability.

A new soil improvement method uses geotextile sand or gravel column. The column is encased with geotextile which has high tensile strength. This type of stone column is used in very soft clay (Cu<15 kN/m^2) such as peat or very soft silt\clay (Kempfert and Gebreselassi, 2006) [9].

Balaam and Poulos (1978) [3] used the finite element method for prediction of the load-settlement response of single stone column in which limiting adhesive column-clay interface strength can be specified. Both the stone column and the clay were treated as elasto-plastic material. Dual nodes were inserted at the column-clay interface and limiting nodal forces can be specified at these nodes. The effect of relative stiffness (stiffness of column/stiffness of surrounding soil), was studied. It was found that the increase in relative column stiffness causes an important settlement improvement.

Schweiger and Pande (1986) [14] presented a new approach of analyzing stone columns reinforcing soft clay. The constitutive model for an equivalent material consists of soil and columns. It was assumed that the influence of the columns is uniform and homogeneous. The elasto-plastic material laws, the critical state model and the Mohr–Coulomb criterion for clay and columns respectively were applied to take into account plastic deformation in column and surrounding soil including dilatancy effects. The model was incorporated in a finite element code using viscoplastic algorithm. It was suggested that the design practice is often based on stress concentration ratio η. The value of η in the analysis varied between 2 and 8 depending on the load level and the location within the columns. These ratios include the initial stress state and compare well with published results. If the initial stress state is not taken into account, stress concentration ratio η is somewhat higher.

Rasheed (1992) [12] used the finite element method to study the soft clay behaviour reinforced by stone column. Linear and non-linear hyperbolic model was adopted for both the soil and the stone column. Many parameters were studied and presented. The effect of the ratio of modulus of elasticity of stone column E_s to the modulus of elasticity of soft soil E_c was considered. Spacing to diameter of the column, length of stone column to the thickness of soft soil layer and effect of Poisson's ratio of the soil on settlement behaviour of the treated soft soil were also considered. The most effective parameter was found to be the ratio of spacing to diameter (s/d).

Buggy et al. (1994) [7] used finite element method through the program CRISP adopting a non-linear modified Cam clay model to perform settlement and horizontal deformation for barrel oil storage tank foundation on soft hydraulic fill soil improved using stone columns at port of Tampa, Florida. The analysis was based on the unit cell concept. The stresses in the stone column and surrounding soil can be estimated if reasonable value of stress concentration ratio η is assumed on previous measurement or estimated from theory.

Al-Saidi (2000) [2] studied the behaviour of stone column by two finite element programs; the first was for axisymmetric condition for single stone column using (unit cell) concept and the second program was three-dimensional which was used to investigate the effect of the group action. Many parameters were studied. The results showed that the depth of the bulging zone ranged between 2 to 3 times the diameter when the stone column was loaded alone and between 1.0 to 1.5 times the diameter when the load was distributed on stone column as well as the surrounding soil. The maximum ratio of L/d (length of stone column / diameter of stone column) was between (8 – 10) and there was no use increasing the ratio above this limit. It was found that the stone column behaviour can be improved by inserting concrete strike which leads to an improvement in the bearing capacity of the stone column by 350% and preventing bulging. Maximum efficiency of group of stone column can be obtained if the spacing becomes (3-3.5) diameter.

Fattah et al. (2010) [8] 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 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.

2. 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) [9]. 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. It is intended to make a comparison between the behaviour of geogrid encased and ordinary stone columns. In addition, the effect of using stone cap (a layer of granular material) on the stone column behaviour will be studied and discussed. The stone cap is proposed to be placed above the stone column and beneath the foundation. The stone cap material properties are assumed to be the same as the stone column material properties.

3. FINITE ELEMENT ANALYSIS

3.1 Program Used

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

3.2 Finite Element Geometry

The basic axisymmetric finite element mesh used for geogrid encasement parametric study is shown in Figure 1. Eight-node isoparamtric elements are 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) [10].

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.

3.3 Material Characteristics and Modeling

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 was used for geogrid material modeling. 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) [6]. The unit weight, γ = 16 kN/m^3, the angle of internal friction ϕ of clay = 0.

3.4 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. The area replacement ratio (a_s) or reinforcement ratio is defined as the ratio of stone column area to total unit cell area (Bergado et al., 1996) [5]:

$$a_s = \frac{A_s}{A_s + A_c} \qquad \text{……...…………..} \quad (1)$$

where:

As = area of stone column cross-section, and

Ac = area of clay in unit cell surrounding stone column.

Figures 2 to 7 show the relation between L/d (length / diameter of stone column) and the bearing improvement ratio (q treated /q untreated) for L/d (3-12), for both 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.

3.5 Use of Stone Cap above the Stone Column

A layer of granular material (stone cap) is proposed to be placed above the stone column (between the footing and the stone column). The granular layer is assumed to have the same properties of stone column material. The floating stone column case is chosen in this study to investigate the effect of using the stone cap above the stone column. The undrained shear strength for the surrounding soil is Cu=20 kPa and a_s = 0.25. The stone extension ratio represents (stone cap extension; from the face of footing/footing diameter) as illustrated in Figure 1.

Figures 8 and 9 show the relation between the strength ration q/Cu and the settlement ratio S/B for L/d = 4 and 8, respectively. The stone cap thickness is 0.5 m and stone extension ratio = 0.1.

Figures 10 and 11 show the relation between S/B and (q treated /q untreated) for L/d 4 and 8, respectively, when the stone extension ratio is 0.1. These figures show that the use of stone cap above the stone column improves the stone column strength efficiently.

Figures 12 and 13 show the relation between (q treated / q untreated) and L/d for ordinary stone column and stone cap stone column with stone cap thickness of 0.125 and 0.25 m, respectively. The stone cap extension ratio is 0 and 0.1. It can be noticed that the increase in (q treated /q untreated) is small and more or less there is no important effect when the stone extension ratio = 0. On the other hand, when the stone extension ratio = 0.1, a considerable improvement in bearing of stone column is obtained. These figures also show that the rate of increase in (q treated /q untreated) value is higher when L/d is less than 5 for both extending cases.

Figures 14 and 15 illustrate the relation between (q treated / q untreated) and L/d for ordinary stone column and stone cap stone column with 0.375 and 0.5 m layer thickness, respectively. The stone extension ratio is 0 and 0.1. When the stone cap extension ratio = 0.1, a higher (q treated /q untreated) value is obtained compared with stone extension ratio = 0.

Figures 12, 13, 14 and 15 show that the effective L/d ratio when stone cap is placed above the stone column is between (7-8). This is true for all values of cap thickness.

Figure 16 shows the relation between (q treated /q untreated) and the cap layer thickness when the stone extension ratio is 0.1 and L/d is 3, 4, 5, 6 and 7. The value of (q treated /q untreated) increases with the increase in layer thickness for all L/d ratios.

Figures 17 and 18 show the relation between the settlement reduction ratio (S treated /S untreated) and bearing ratio q/Cu for L/d of 4 and 8 and the stone cap thickness is 0.5 m with stone extension ratio = 0.1. The same relation is shown when ordinary stone column or stone columns with stone cap are used.

Figure 19 illustrates the relation between the thicknesses of stone cap and (S treated /S untreated) for stone cap extension ratio of 0.1. It is noted that the (S treated /S untreated) decreases with increase in the layer thickness.

Figure 20 shows the relation between the (q treated /q untreated) with the stone extension ratio. The value of (q treated /q untreated) increases with stone cap extension ratio increasing. It can be noted that a stone extension ratio of 0.4 gives a limit of increases in (q treated / q untreated) after which, the extending provides no effect on (q treated / q untreated) value.

4 CONCLUSIONS

From the finite element analysis, the following conclusions can be drawn:

1. 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.
2. 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.
3. 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.
4. The use of stone cap above the stone column increases the bearing improvement ratio and decreases the settlement for all L/d ratios.
5. The increase in stone cap thickness increases the bearing improvement ratio and decreases settlement for all L/d ratios. The stone cap extension (from the face of footing) has a significant effect on bearing improvement ratio, but there is no use of increasing the stone cap extension more than 0.4 the footing diameter. The maximum effective (L/d) ratio is between (7-8) for all stone cap thicknesses and stone cap extension/footing diameter.

Table 1: Material properties of stone column used in the parametric study of the problem.

Parameter	Value
Angle of internal friction, ϕ (degrees)	40
Cohesion, c (kN/m^2)	0
Unit weight, γ (kN/m^3)	17
Poisson's ratio, υ	0.30
Modulus of elasticity (kN/m^2)	100000

Table 2: Geogrid properties used in stone column encasement (Shenzhen Ktyu Insulation CO., Ltd.) [13].

Parameter	Value
Tensile strength (kN/m)	140
Elongation (%)	4
Weft diameter (mm)	5
Hole size (mm × mm)	25.4 × 25.4
Modulus of elasticity (kN/m^2)	76 x 10^6

5 REFERENCES

[1] Aboshi, H., Ichimoto, E., Enoki, M. and Harada, K., (1979), "The Composer- A Method to Improve Characteristics of Soft Clays by Inclusion of Large Diameter Sand Columns", Proceedings International Conference on Soil-Reinforcement; Reinf. Earth and Other Technique, Paris, pp. 211-216.

[2] Al-Saidi, A.A., (2000), "The Use of Stone Columns to Improve Soft Soils" M.Sc. thesis, College of Engineering, University of Baghdad, Iraq.

[3] Balaam, N.P., and Poulos, H.G., (1978), "Method of Analysis of Single Stone Column", Proceedings Symposium on Soil Reinforcing and Stabilizing Techniques Sydney, Australia, pp.497-512.

[4] Baraksdale, R.D., and Bachus, R.C., (1983), "Design and Construction of Stone Columns", Federal Highway Administration, Vol.1, School of Civil Engineering, Georgia Institutes of Technology, Atlanta (www.fhwa.dot.gov).

[5] Bergado, D. T., Anderson, L. R., Miura, N., Balasubramaniam, A. S., (1996), "Soft Ground Itnprovetnent in Lowland and Other Environments", Published by American Society of Civil Engineers, New York.

[6] Bowles, J.E., (1996), "Foundation Analysis and Design", 5th Edition, McGraw-Hill Book Company, p. 1175.

[7] Buggy, F.J., Martinez, R.E., Hussin, J.D., and Deschamps, R.J., (1994), "Performance of Oil Storage Tanks on Vibroflotation Improved Hydraulic Fill in the Port of Tampa , Florida " , Vertical and horizontal Deformations of Foundation and Embankments , Proceeding of settlement 94 , American Society of Civil Engineers , New York , pp.548-560 .

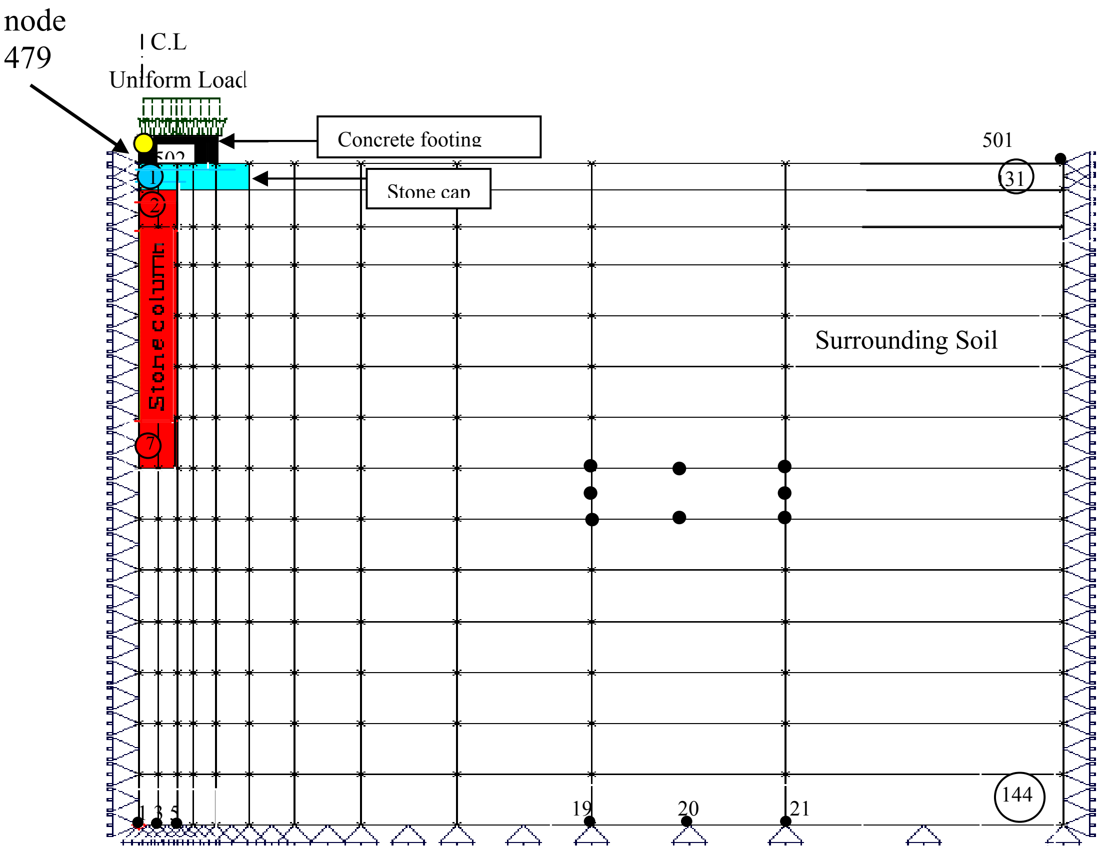

Figure 1: Basic axisymmetric finite element mesh used for the parametric study.

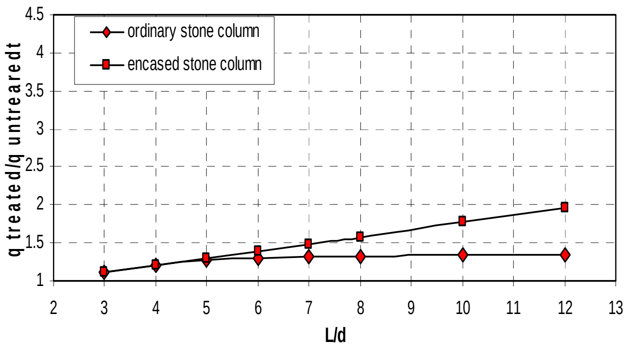

Figure 2: Relationship between the bearing improvement ratio and length to diameter ratio of floating stone column (Cu=20 kPa, $a_s = 0.1$).

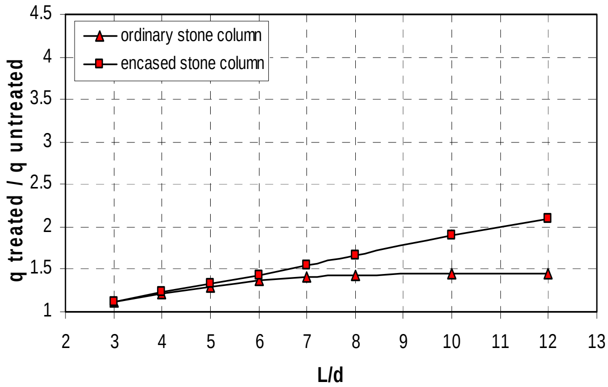

Figure 3: Relationship between the bearing improvement ratio and length to diameter ratio of floating stone column (Cu=20 kPa, $a_s = 0.15$).

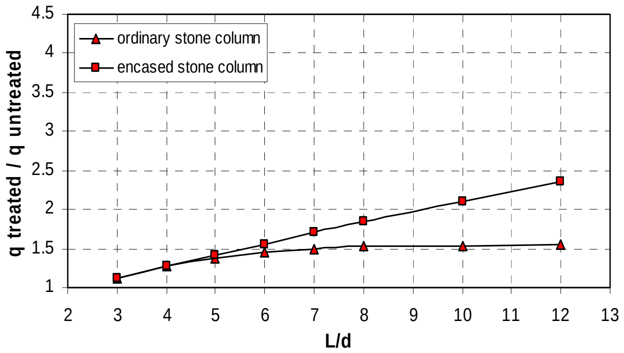

Figure 4: Relationship between the bearing improvement ratio and length to diameter ratio of floating stone column (Cu=20 kPa, a_s= 0.2).

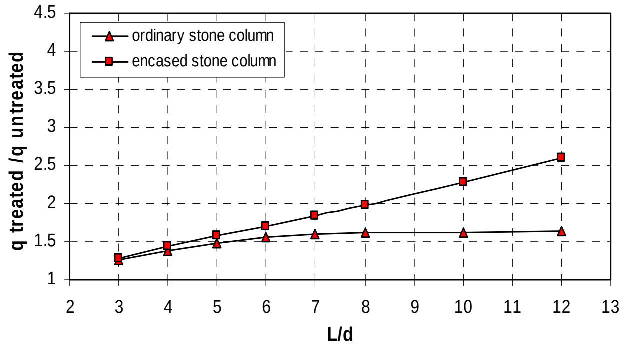

Figure 5: Relationship between the bearing improvement ratio and length to diameter ratio of floating stone column (Cu=20 kPa, a_s = 0.25).

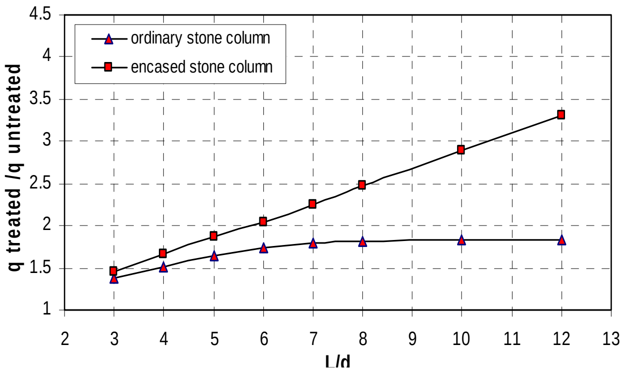

Figure 6: Relationship between the bearing improvement ratio and length to diameter ratio of floating stone column (Cu=20 kPa, a_s = 0.3).

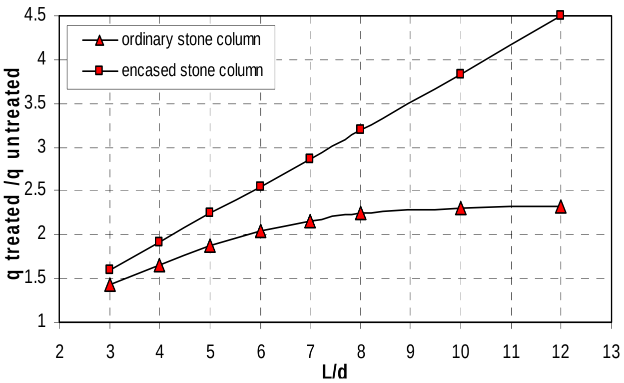

Figure 7: Relationship between the bearing improvement ratio and length to diameter ratio of floating stone column (Cu=20 kPa, a_s = 0.35).

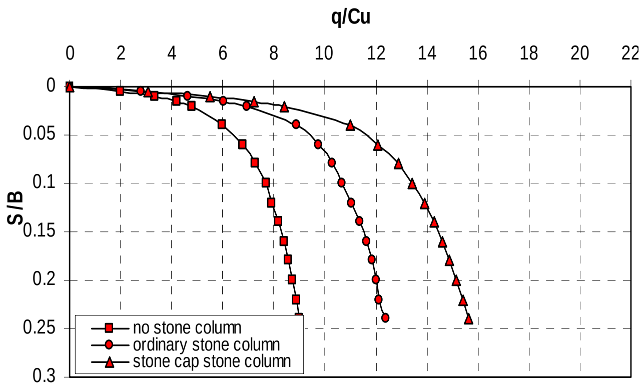

Figure 8: Relationship between the bearing ratio and settlement ratio of stone cap stone column, (Cu=20 kPa, L/d=4, a_s =0.25, stone thickness= 0.5 m, stone cap extension/footing diameter = 0.1).

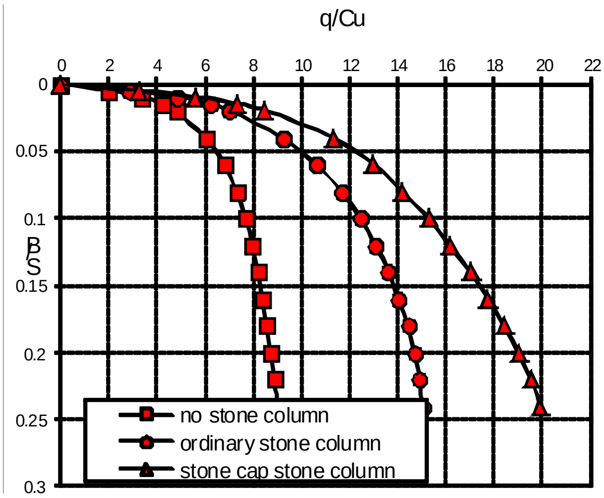

Figure 9: Relationship between the bearing ratio and settlement ratio of stone cap stone column, (Cu=20 kPa, L/d=8, a_s =0.25, stone thickness= 0.5 m, stone cap extension/footing diameter = 0.1).

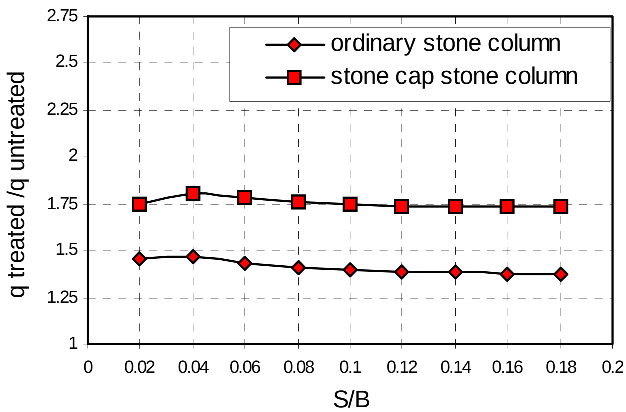

Figure 10: Relationship between the bearing improvement ratio and settlement ratio of stone cap stone column, (Cu=20 kPa, L/d=4, a_s =0.25, stone thickness= 0.5 m, stone cap extension/footing diameter = 0.1).

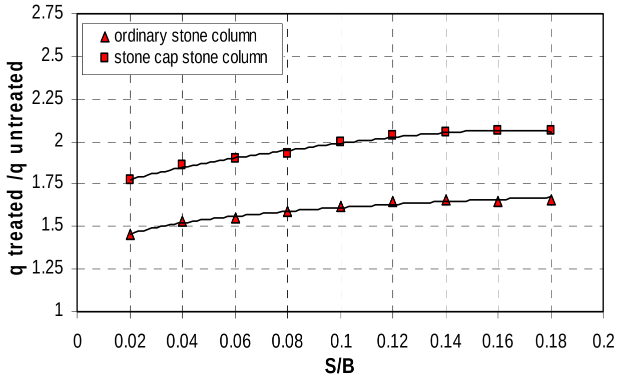

Figure 11: Relationship between the bearing improvement ratio and settlement ratio of stone cap stone column, (Cu=20 kPa, L/d=8, a_s =0.25, stone thickness= 0.5 m, stone cap extension/footing diameter = 0.1).

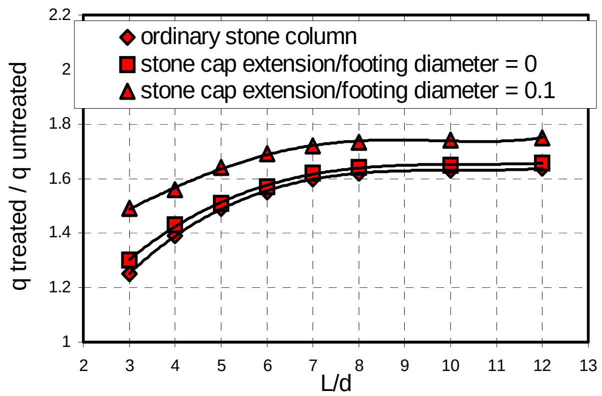

Figure 12: Relationship between the bearing improvement ratio and length to diameter ratio of stone cap stone column, (Cu=20 kPa, a_s = 0.25, stone cap thickness= 0.125 m).

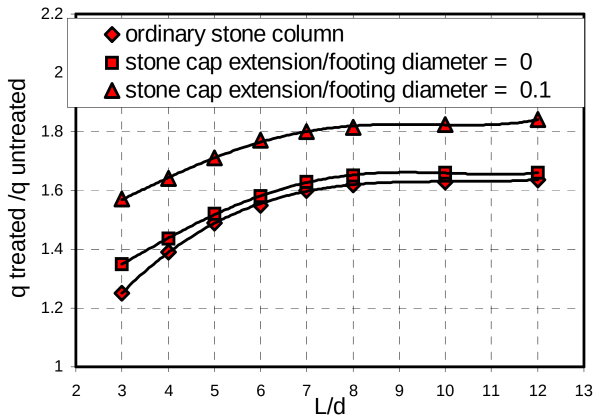

Figure 13: Relationship between the bearing improvement ratio and length to diameter ratio of stone cap stone column, (Cu=20 kPa, a_s =0.25, stone cap thickness= 0.25 m).

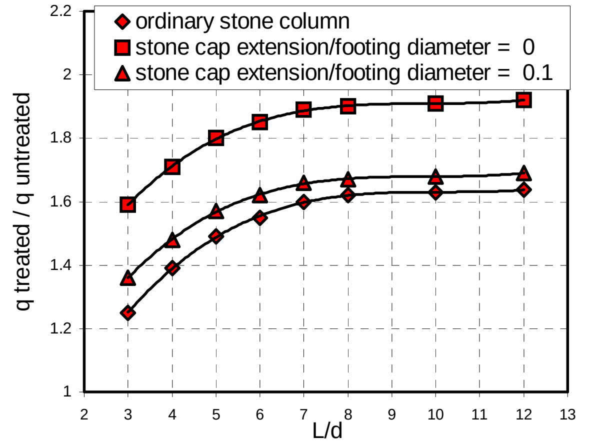

Figure 14: Relationship between the bearing improvement ratio and length to diameter ratio of stone cap stone column, (Cu=20 kPa, a_s = 0.25, stone cap thickness = 0.375 m).

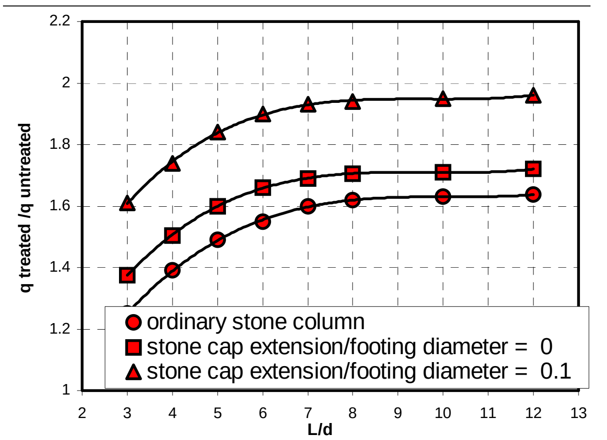

Figure 15: Relationship between the bearing improvement ratio and length to diameter ratio of stone cap stone column, (Cu=20 kPa, a_s =0.25, stone cap thickness= 0.5 m).

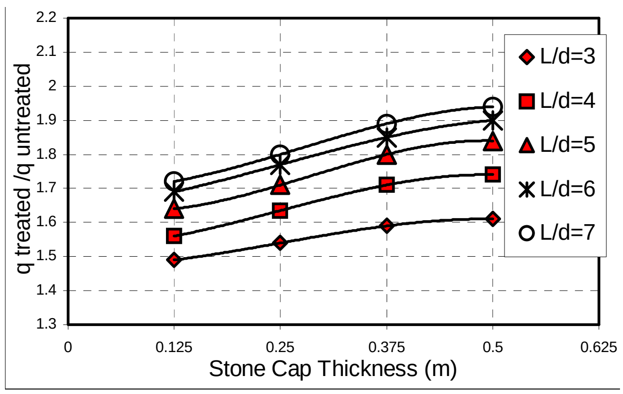

Figure 16: Relationship between the bearing improvement ratio and stone cap thickness of stone cap stone column, (Cu=20 kPa, a_s = 0.25, stone cap thickness = 0.5 m, stone cap extension/footing diameter = 0.1).

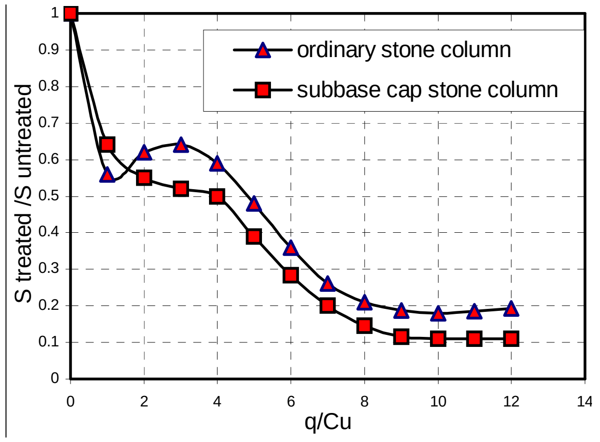

Figure 17: Relationship between the settlement reduction ratio and the bearing ratio of stone cap stone column, (L/d=4, Cu=20 kPa, a_s=0.25, stone cap thickness= 0.5 m, stone cap extension/footing diameter = 0.1).

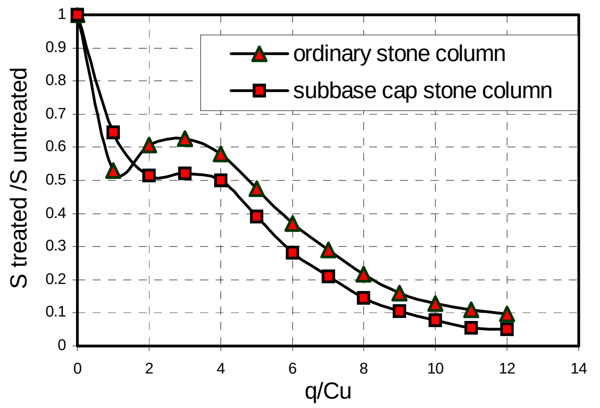

Figure 18: Relationship between the settlement ratio and the bearing ratio of stone cap stone column, (L/d=8, Cu=20 kPa, a_s = 0.25, stone cap thickness= 0.5 m, stone cap extension/footing diameter = 0.1).

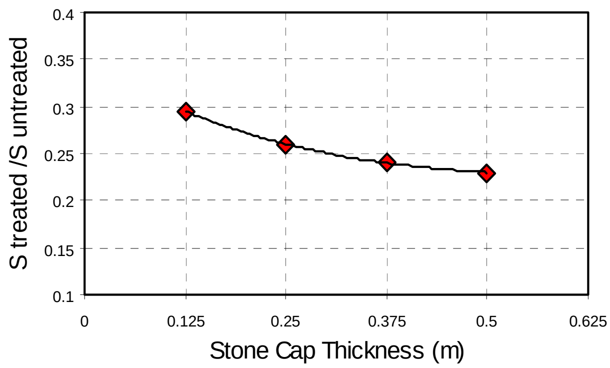

Figure 19: Relationship between the settlement reduction ratio with the bearing ratio of stone cap stone column, (L/d=8, Cu=20 kPa, a_s = 0.25, stone cap thickness= 0.5 m, stone cap extension/footing diameter = 0.1).

[8] Fattah, M. Y., Shlash, K. T., Al-Waily, M. J. M., (2010), "Stress Concentration Ratio of Model Stone Columns in Soft Clays", Geotechnical Testing Journal, Vol. 34, No. 1, Paper ID GTJ103060, ASTM, Nov 29 14:27:16 EST 2010.

[9] Kempfert, H., and Gebreselassi, B., (2006), "Excavations and Foundations in Soft Soils", Springer-verlay Germany Berlin.

[10] Majeed, Q. G., (2008), "Assessment of Load Capacity of Reinforced Stone Column Embedded in Soft Clay", M.Sc. thesis, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq.

[11] Mitchell, J.K., (1981), "Soil Improvement (State of the Art Report)", General Report Session 12, Proceedings, 10th International Conference on Soil Mechanics and Foundation Engineering, Vol. 4, Stockholm, Sweden, pp. 509-565.

[12] Rasheed, A.H., (1992), "Efficiency of Stone Column in Improving the Behaviour of Footing Resting on Soft Soils", M.Sc. thesis, Building and Construction Engineering Department, University of Technology, Iraq.

[13] Shenzhen Ktyu Insulation CO., Ltd., www.geogrid.biz.

[14] Schweiger, H. F., and Pande, G. N., (1986), "Numerical Analysis of Stone Column Supported Foundations", Computers and Geotechnics, No. 2, pp. 347 – 372.

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.

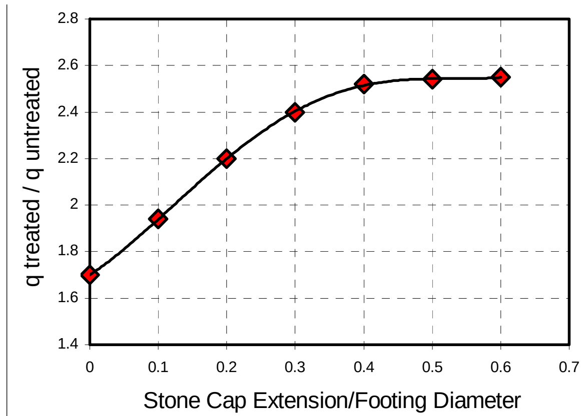

Figure 20: Relationship between the bearing improvement ratio with the stone cap extension/footing diameter of stone cap stone column, (L/d=8, Cu=20 kPa, a_s =0.25, stone cap thickness= 0.5 m).

International Journal of GEOMATE , Sept., 2012, Vol. 3, No. 1 (Sl. No. 5), pp. 343-350
MS No. 1262 received May 11 2011, and reviewed under GEOMATE publication policies.

Corresponding Author: Mohammed Y. Fattah