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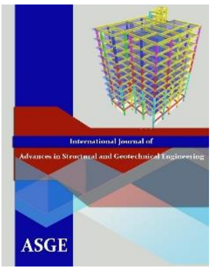

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A Numerical Study on the Factors Affecting the Capacity of Stone Column

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ABSTRACT

One of the recent techniques for soil improvement is unconnected stone columns embedded in soft/medium clay. Stone columns are excellent when compared with other ground improvement techniques, with respect to coast and durability. So, it is important to determine the parameters affecting the capacity of the unconnected stone columns which in turn strongly affect the total cost of foundation works. This study had two main objectives; the first one is to establish a numerical model to predict the optimum length, spacing and diameter of unconnected stone columns used to improve the clayey soil. Also, the second is to study the effects of different studied parameters on the stone columns capacity and settlement. The analysis was carried out using finite element analysis PLAXIS 3D.The model is capable to determine the bearing capacity and settlement for different parametric analyses. A parametric study was performed applying the established numerical model. The studied parameters included stone columns, other clayey soil parameters and also specific parameters of the cushion that may be found between the footings and clayey soil improved using stone columns. The stone columns diameter, length, material and spacing were considered in addition to the shear strength of the surrounding clayey soil. Regarding to the cushion, its thickness and material were taken into consideration in the parametric study.

Keywords: *Stone Columns, PLAXIS 3D, Bearing Capacity, Soft Clay, Recycled Concrete.*

INTRODUCTION

In last years, the increasing in population led to use all the land areas including soft problematic soils. These soils have low shear strength and high voids ratio, which results in excessive settlements even if subjected to low or moderate surface loads. There are many soil improvement techniques such as stone columns, preloading, compaction, deep mixing, densification, soil reinforcement, chemical treatments and drains to increase the bearing resistance of these soils. The choice of appropriate method depends on many factors like structural loads, type of structure, type of soil, availability of equipment and material, economic considerations, etc. Improving the soft clay by stone columns is one of the most popular techniques followed in the world [5]. It gains prominence by the ability to increase bearing capacity of the soil, reducing total and differential settlements and decreasing the time of consolidation. As well as, this during an earthquake stone columns work as a gravel drain column to release pore water pressure and the liquefaction potential of a ground can be reduced [6], [7], [8] . The stone columns are installed in many types of soils, beginning from loose sands to soft compressible clays. The stone column consists of drilling vertical holes in the ground which are thereafter filled with crushed stones or gravel or recycled concrete to install columns confined by the soil.
In this paper, numerical studies were carried out to evaluate the behavior of group of stone column by varying spacing to diameter ratio, lengths, number of columns, shear strength of

unimproved soft clay and stone columns filling material. In addition, cushion between the footing and stone columns was studied regarding to its thickness and material. Analysis is also carried out to simulate the behavior of clay without a stone column for the purpose of comparison. The numerical studies were carried out by using the well-known software package PLAXIS 3D, version 1.6.

THE NUMERICAL MODELING AND PARAMETERS

Finite element technique is a powerful tool for analyzing complex engineering problems. Plaxis 3D software is an efficient for capturing the complex behavior of groups of stone columns. The interface between the footing, stone column and soil were attached to the soil elements where the stone column touching with the soil. [2] reported that, the lateral boundaries of the computational domain should be positioned at a distance of 8B from the centre of the pad to avoid influencing the results due to it restrict radial movement. So, the soil mass take with dimensions 36mx36mx45m where the square footing side length (B=4.5m). The clay, stone and sand is modeled to behave as a conventional elastic- perfectly plastic model depended on Mohr-Coulomb failure criterion in PLAXIS 3D software while recycled concrete was modeled using the linear- elastic model. Also, drained condition was used for clay, stones, sand and recycled concrete. The Stone column was modeled as a massive cylindrical element .The footing was modeled as square element with 0.5 m thickness; side length was constant and equal to 4.5m and was loaded with uniform distributed stress. The mesh was refined near the footing edges where high stresses and strains were developed, as illustrated in figures (1a, 1b).Table (1) shows the input parameters and properties of the used materials, whereas the properties of footing are presented in table (2).

Table 1: The Parameters and Properties of the Used Materials in the Numerical Model

Type of soil		Soft clay	Recycled concrete	Stone	Dense sand
The used model		**MC**	**Linear-elastic**	**MC**	**MC**
Soil condition		**Undrained**	**Drained**	**Drained**	**Drained**
Unit weight	γ_d (KN\m^3)	15	13	18	18
	γ_{sat}(KN\m^3)	16.5	15	19	19
Shear strength	C_u , KPa	15 , 20 ,25	0	0	0
parameters	ϕ , 0	0	49	42	38
	φ , 0	0	19	12	8
Soil stiffness	E , KPa	1600	1.10E+07	100000	80000
parameters	⍰	0.45	0.25	0.35	0.3
	R_f	0.7	0.9	0.8	0.8

Table 2: The Material Properties of Rigid Footing in the Numerical Model

parameter	Value	Unit
Density, γ	2.50E+01	KN/m^3
Young's modulus, E_s	2.20E+07	KN/m^2
Poisson's ratio ,ν	0.2	--

As shown in figure (1a) :

H = The depth of soil layer. , L = The length of stone column.

d = The stone column diameter. , S = The spacing between stone columns, c.l to c.l.

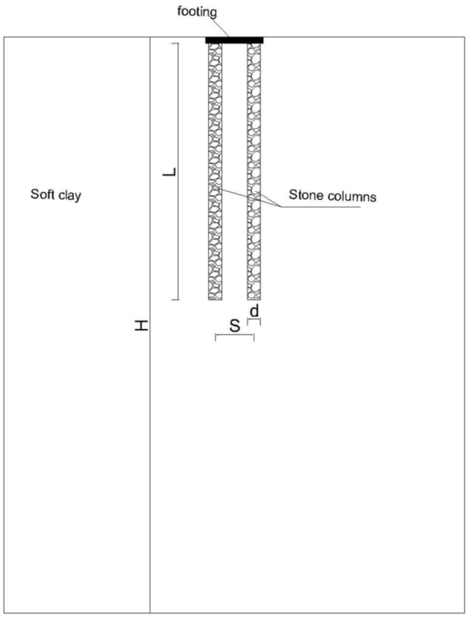

Fig. 1a: Model Geometry

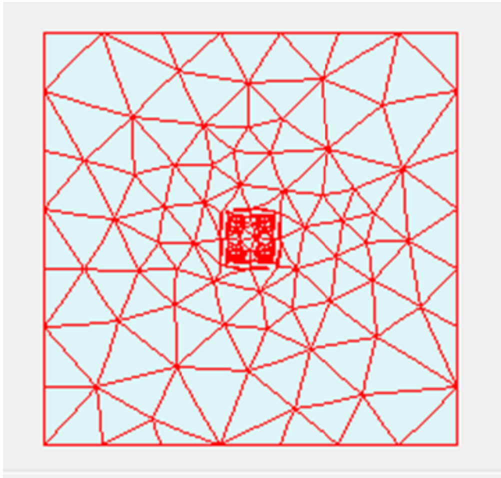

Fig. 1b: Meshing of the Material

Fig.1: Model Geometry and PLAXIS 3D model

THE VERIFICATION OF THE NUMERICAL MODEL

The purpose of verification of the numerical model is to ensure that the proposed elements, geometry and meshing refinement are appropriate to the intended analysis. A numerical analysis was carried out by using PLAXIS 3D software [3] to study the effect of stone column spacing on settlement improvement factor, β. The analysis is carried out on a group of four columns arranged with spacing 1m, 2m, and 2.5m and 3m. The clay layer was created with dimensions (36mx36mx10.5m) and the stone columns were of diameter 0.88m and length 10.5m and embedded in the clay layer. The improved clay layer was loaded with uniform vertical pressure P=100 KPa by means of rigid square footing of side length B=4.5m and rested on soil via interface elements. Ground water level was at the surface (γw =10 KN/m3). The clay soil and stone column followed Mohr-Coulomb model. Table (3) illustrated the properties of the clay and stones used in [3]. From figure (2), it is observed that the results obtained from the present numerical model well with the results reported by [3].

Table 3: The Properties of the Materials Used by Noura Nehab (2016) [3]

parameters	Soft clay	Stones	Unit
Dry density, γ_d	17	20	KN/m^3
Bulk density, γ_{sat}	18	21.5	KN/m^3
Young's modulus, E_s	2585	7.00E+05	KN/m^2
Poisson's ratio ,ν	0.33	0.15	--
Cohesion,C_u	25	0	KN/m^2
Friction Angle, ϕ	15	45	Degree
Dilatancy ,[illegible]	0	15	Degree

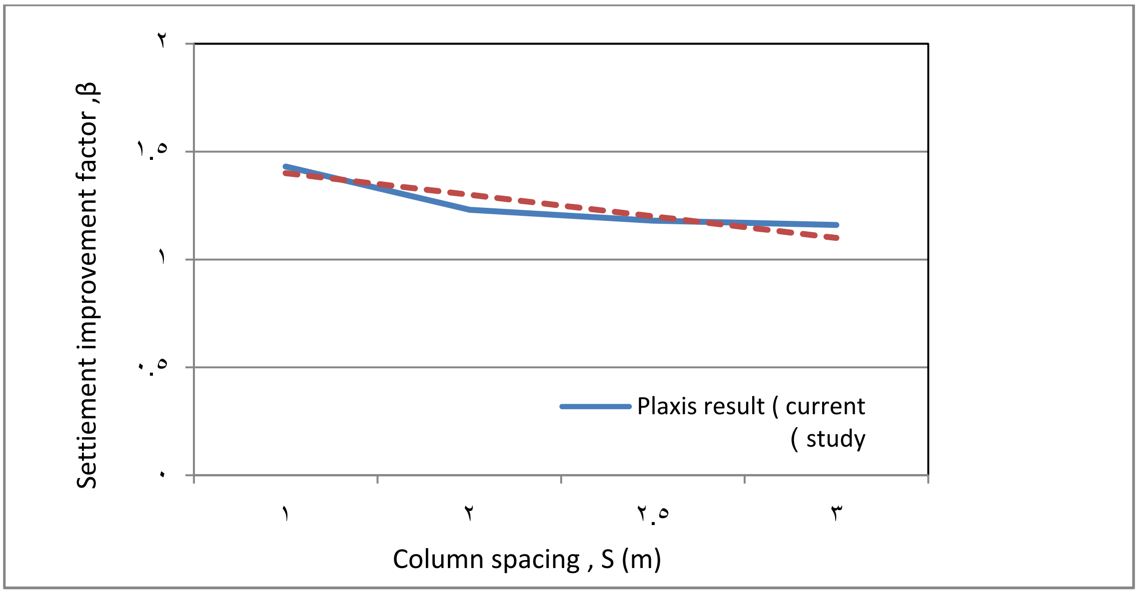

Fig.2: Comparison between Results of the Numerical Model and the Results of Noura Nehab (2016) [3]

THE NUMERICAL STUDY RESULTS AND DISCUSSIONS

Parametric study was carried out using the established numerical model. The studied parameters included spacing ratio (S/d) where (S) is the spacing of stone columns center line to center and (d) is its diameter, the ratio between the stone column length (L) and its diameter (d), the stone column material, shear strength of the unimproved soil (cu), and stone column material. Moreover, in case of using cushion beneath footings in addition to stone columns, the effect of cushion material, and the cushion thickness were studied. To evaluate the effect of different parameters, the improvement ratio (r) is proposed, r = [(allowable bearing capacity of improved soil) – (allowable bearing capacity of unimproved soil) / (allowable bearing capacity of unimproved soil)] X 100 % . The allowable bearing capacity was considered as the capacity corresponding to consolidation settlement equal to 25 mm.

The Effect of Stone Column Arrangement (S/d):

The spacing ratio (S/d) was used as a representative of the stone column arrangement. The improvement ratio (r) was determined for all studied cases with the variation of the stone column length (L) from 10 m. to 20 m., the shear strength of the unimproved soil (cu) from 15 kN/m^2 to 25 kN/m^2, and the spacing ratio (S/d) for different values of stone column diameter (d) between 0.7 m. and 1.0 m. Figures (3) and (4) illustrate the relationship between the ratio (r) and the spacing ratio (S/d) for a stone column diameter of 0.85 m. and soil shear strength (cu) = 15 kN/m2. It can be observed that the improvement ratio (r) is directly proportional to the spacing ratio (S/d) as well as the stone column length (L). Similar results were obtained for all the studied cases of this parameter, where the ratio (r) increased with a value ranging from 41.67% to 100%. The maximum obtained improvement ratio (r = 100 %) was corresponding to the ratio (S/d) = 3.0, stone column length (L) = 20 m., and diameter (d) = 1.0 m.

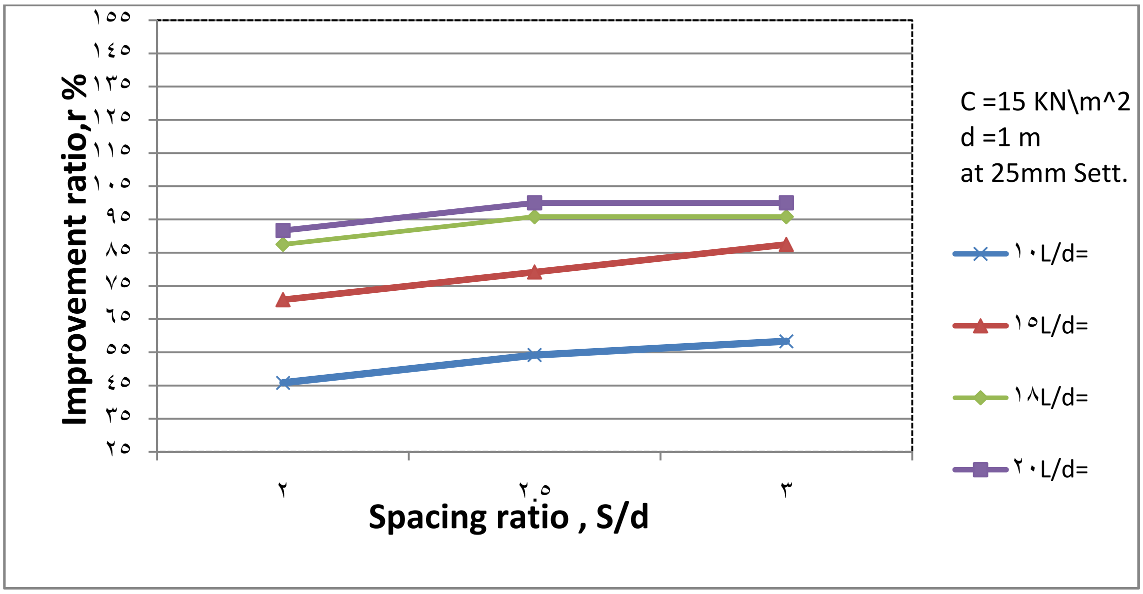

Fig. 3: The Relationship between the Improvement Ratio (r) and the Spacing ratio (S/d) and (d=1.0 m.)

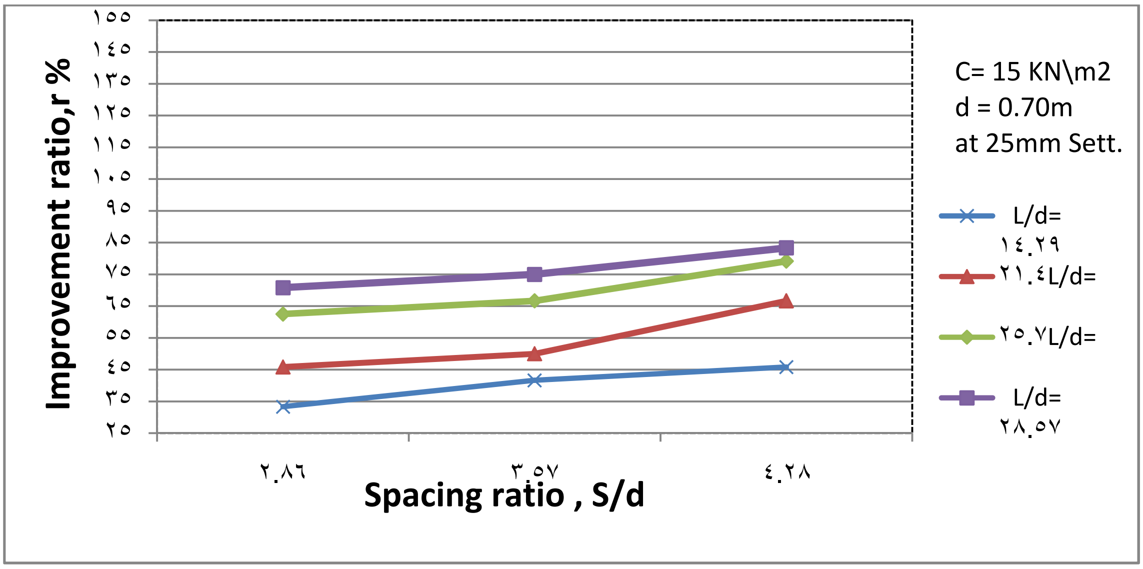

Fig. 4: The Relationship between the Improvement Ratio (r) and the Spacing ratio (S/d) and (d = 0.7 m.)

The Effects of Column Length Ratio (L/d):

Various column lengths were considered to study the effect of column length on the improvement ratio (r). The studied values of stone columns length were 10 m., 15 m., 18 m and 20 m. and diameters 0.70 m., 0.85 m. and 1.0 m. The stone column length was expressed in the form of length ratio (L/d) for different values of unimproved soil shear strength (cu) and spacing ratio (S/d). Figures (5) and (6) show the effect of the length ratio (L/d) on the improvement ratio (r) for different values of the spacing ratio (S/d). It can be noticed from the graphs that the ratio (r) is also directly proportional to the length ratio (L/d) for various values of (S/d) and the values of unimproved soil shear strength (cu). These results match with that reported by Kameshwar Rao [1]. The improvement ratio (r) ranged from 41.66 % at (L/d = 11.8) to 100 % at (L/d = 20).

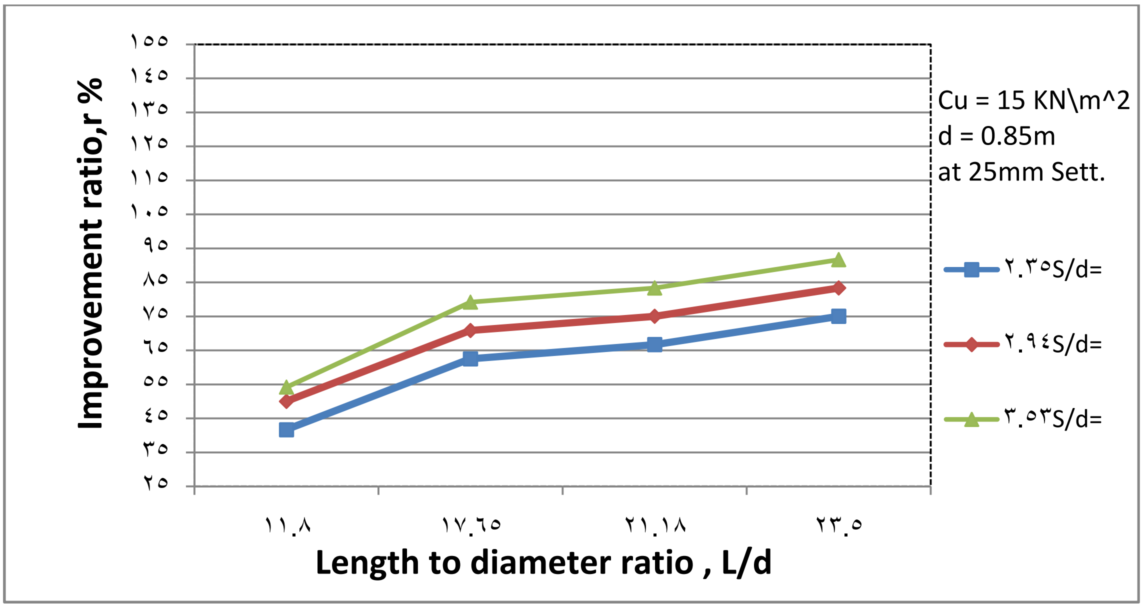

Fig. 5: The Relationship between the Improvement Ratio (r) and the Length ratio (L/d) and (d = 0.85 m.)

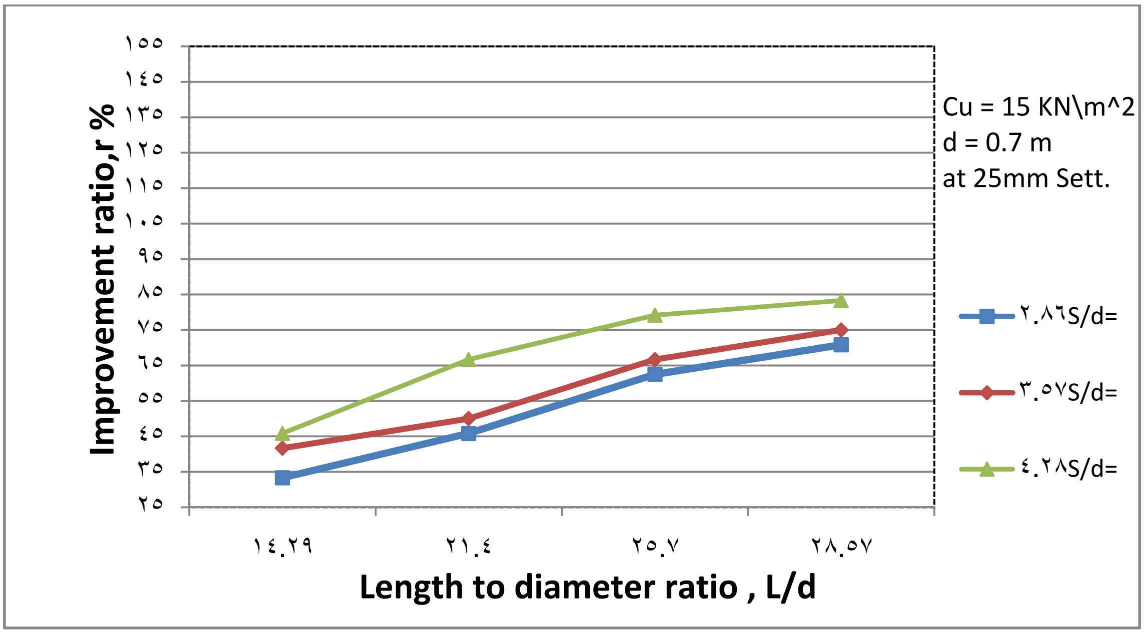

Fig.6: The Relationship between the Improvement Ratio (r) and the Length ratio (L/d) and (d = 0.70 m.)

The Effects of Shear Strength of Unimproved Soil (cu):

The variation of the value of improvement ratio (r) with the shear strength of unimproved soil shear strength (cu), for different values of length ratio (L/d), is presented in figure (7). The figure shows that as the soil shear strength (cu) and stone column length ratio (L/d) increase, the improvement ratio (r) increases. For all studied cases, the same trend was observed. In addition, it is noticed that the increase of the ratio (r) is clear in the soil of low shear strength, but it increased slightly in higher values of (cu). The improvement ratio was ranging from 45.83 % to 108.7 % for the studied cases.

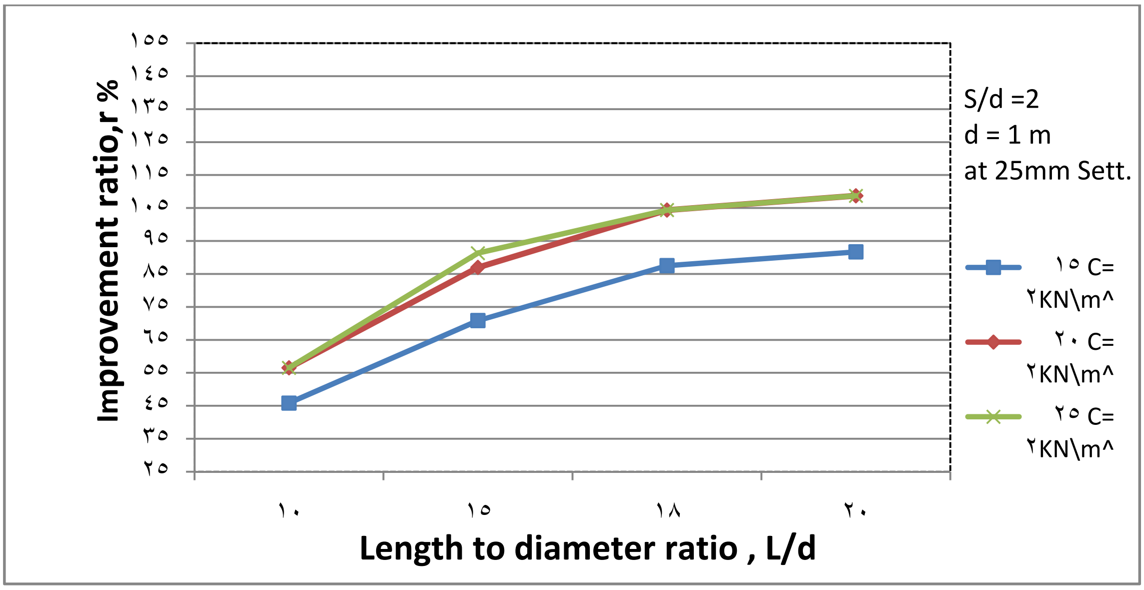

Fig.(7): The Improvement Ratio (r) Versus Shear Strength of Soil for Different Values of Stone Column Length at (S/d=2).

The Effect of Stone Column Material:

Three types of stone column material were considered to investigate their effect on the improvement ratio (r). These materials were recycled concrete, stones and sand. As illustrated in figure (8) stone column of recycled concrete material clearly showed a considerable value of improvement ratio at any specified value of length ratio (L/d). Whereas, there was no significant difference of the ratio (r) in case of sand column and crushed stone column.

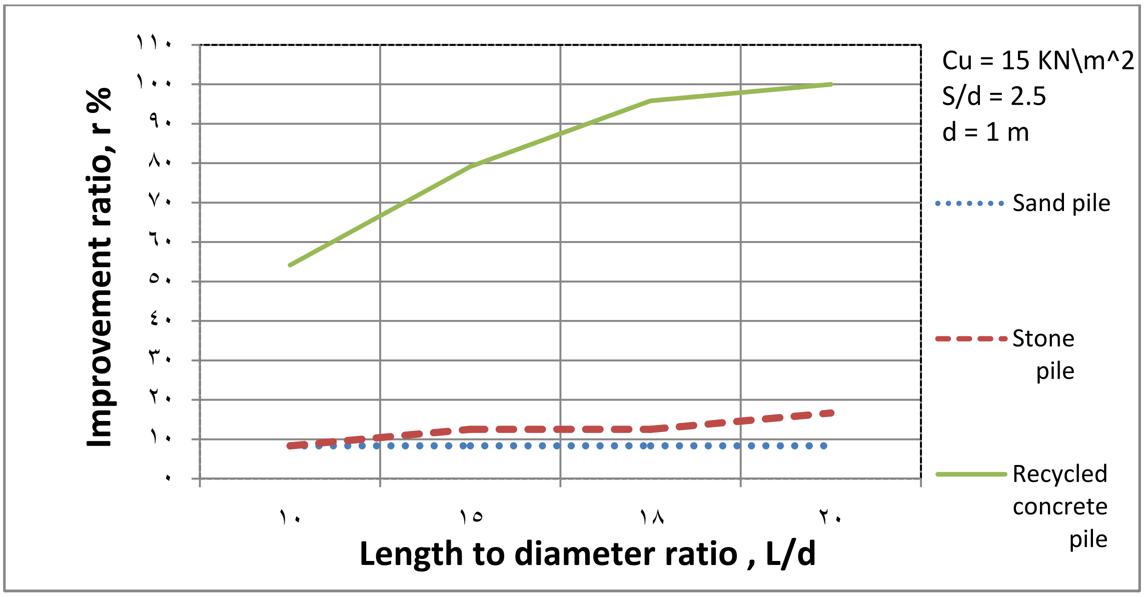

Fig.(8): The Improvement Ratio (r) against the Stone Column Length for Different Materials of Stone Column

The effect of properties of the cushion material:

The current study aimed also to investigate the effect of the existence of cushion resting on the soft clay improved by stone columns. The cushion material may be formed from different material under rigid shallow footings. Three cushion materials were taken into account; recycled concrete, stones, and sand. For all studied cases, it was assumed that the material of cushion is the same as the stone column. The results of studying this parameter insured that the allowable bearing capacity of the soil improved with cushion and stone columns increases the capacity of soil improved by stone column only. In addition, the study showed that using the recycled concrete in forming the cushion increases the soil capacity more than using crushed stone or sand. The reason may be the higher value of modulus of elasticity (E) and the angle of internal friction (ф) of the recycled concrete more than other studied materials. Figures (9) and (10) present the relationship between the improvement ratio (r) and stone column length ratio (L/d) for different cushion material. The shown trend was also obtained for all studied cases. Where the ratio (r) ranged from 54.16% and 100% in case of using stone columns without cushion whereas the corresponding ratio (r) became 91.67% to 162.5% when using stone columns with cushion. It is obvious from the attached graphs that for any specified length ratio, the ratio (r) resulting from using recycled concrete for both cushion and stone columns had the larger value more than other studied materials.

The effect of cushion thickness:

Finally, the effect of cushion thickness in case of improving the soft clay soil with cushion and stone columns. So, various values of cushion thickness (0.25m, 0.5m, 1m, 1.5m and 2m) were taken into consideration to investigate the influence of cushion thickness on the improvement ratio (r). Figure (11) shows the relationship between the improvement ratio (r) and stone column length ratio for different values of cushion thickness at cu=15KPa, S/d=2.5 and recycled concrete material used in cushion and stone column. Similar relationships were resulted for all studied cases. The ratio (r) is directly proportional to the cushion thickness (t). But it was noticed that the effect of changing the cushion thickness on the improvement ratio (r) is more less than changing the cushion material.

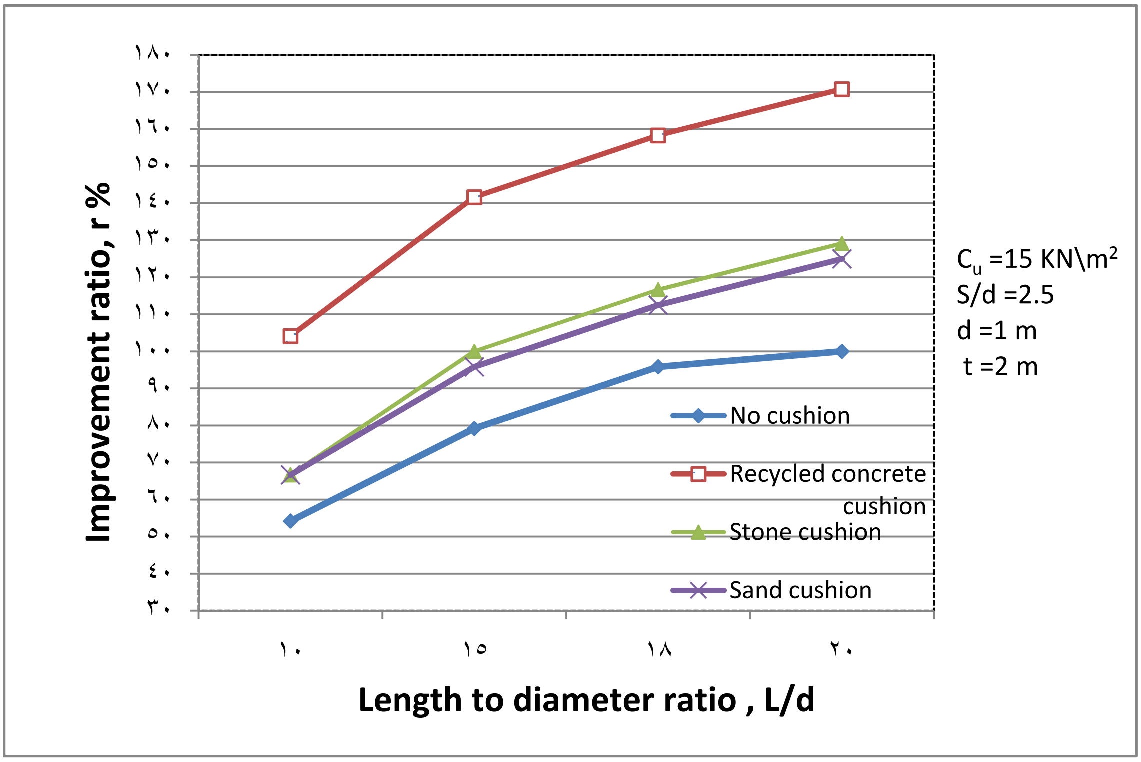

Fig.(9): The Improvement Ratio (r) against the Ratio (L/d) for Different Materials of Cushion (Cushion Thickness t = 2.0 m.)

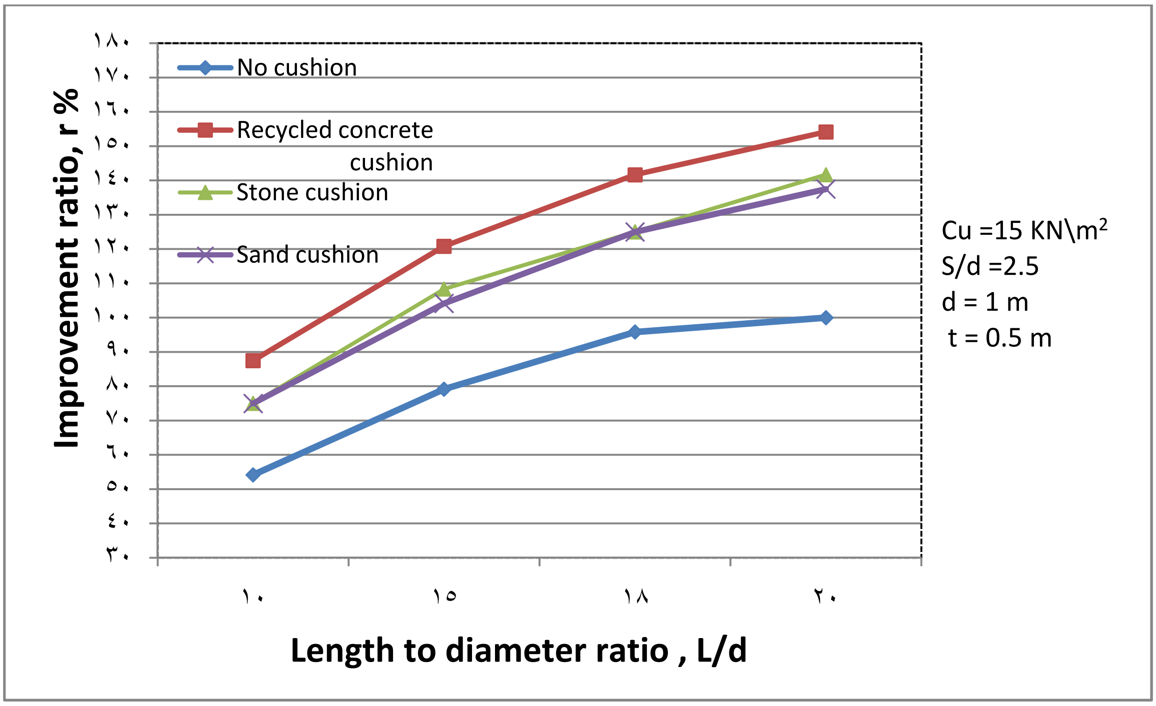

Fig.(10): The Improvement Ratio (r) against the Ratio (L/d) for Different Materials of Cushion (Cushion Thickness t = 0.5 m.)

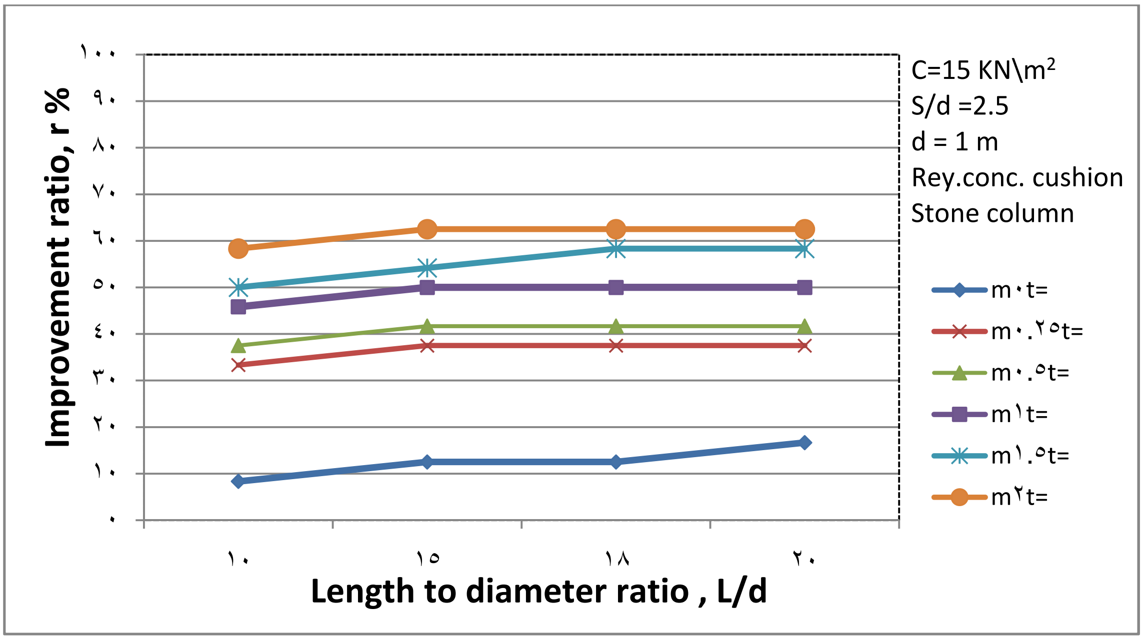

Fig.(11): The Improvement Ratio (r) against the Ratio (L/d) for Different Thickness of Cushion

CONCLUSIONS

These conclusions that may be drawn from the present study are:

1. The soil improvement ratio (r) is directly proportional to the spacing ratio (S/d), length ratio (L/d), shear strength of unimproved clayey soil (c_u), and cushion thickness (t).
2. Using a cushion beneath the shallow footings in addition to stone columns to improve the soft clay soil is highly more effective than improving the soft clay with stone columns only.
3. The use of recycled concrete material in both of cushion and stone columns is better than stones or sand.
4. It is recommended to use the cushion material the same as the stone column material.
5. The cushion thickness affects slightly on the value of the soil improvement ratio (r).

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