Behaviour of Encased Stone Columns in Soft Clay

Mohamed A. Sakr[1], W. R. Azzam[1], Mona K. Mohamed[3]
[1]Prof. of Geotechnical Engineering, Faculty of Engineering, Tanta University, Egypt
E-mail: mamsakr@f-eng.tanta.edu.eg, azzamwaseim@f-eng.tanta.edu.eg,
[2]M. SC. Student, Faculty of Engineering, Tanta University
E-mail: mona_khairy@f-eng.tanta.edu.eg

Abstract- **Ground improvement techniques are commonly used in different construction sites where the existing soil conditions are very weak and can lead to unsatisfactory performance. Encased stone columns technique is employed to enhance the bearing capacity, shear strength, and stiffness of soil to reduce settlement, and accelerate the consolidation rate of soft soil. In this research, a series of (62) cases have been studied to investigate the behaviour of a single encased stone column in soft clay to figure out the encasement effect and its properties compared to that without encasement using a finite element model (FEM). PLAXIS 3D software package was used in this study stone columns with two diameters (D=0.4m and 0.6m) and the length of the stone column to the diameter (L/D) ratio is kept equal (10) in all cases. Two cases of stone columns were studied: without encasement which is an ordinary stone column (OSC) and with encasement as encased stone column (ESC) column which is surrounded by geotextile with different stiffness. At an internal friction angle of the stone column φ=45°, the increase in the BCR of the encased stone column over the case of untreated soil was found to be 227% and 200% for the two cases of column diameters (D=0.4m and 0.6m) respectively.**

Keywords- **Encased, Stone Column, Geotextile, PLAXIS 3D, Shear Strength, Soft Clay.**

I. INTRODUCTION

The encased stone column has an advance over the ordinary stone column as it reduces bulging due to that it provides a lateral confining to the column which gives it more stiffness to resist the surrounding conditions of the soil and the time rate of consolidation increases which reduces settlement. Encased stone column technique enhances the strength and decreases deformation**.** Based on the literature review, it has been found that the effect of using encasement around the stone column has been investigated experimentally and numerically with the majority by using 2D programs for a small model.

This paper sheds the light on the beneficial effects of such a technique on increasing the load capacity and reducing settlement, by investigating the effect of change in the internal friction angle of the stone column material either for an ordinary stone column or an encased stone column within the soft clay soil using a three-dimensional finite element program called PLAXIS 3D.

One of the best ways to increase the performance of stone columns is to wrap each one with the appropriate geosynthetic. Additionally, the encasement prevents stones from being laterally pushed into the clay soil around them and vice versa. Stone columns are tested by loading a single column and a group of stone columns, both with and without geotextile wrapping. Different geosynthetics were used in the tests. The obtained results of the load-settlement tests demonstrated that the encasement of the column significantly increased the load capacity of the stone columns. Murugesan and Rajagopal, (2010) [1]. The effects of many variables including the column diameter, the modulus of elasticity, and the friction angle of the column material on the general behaviour of the GEC group are investigated using a 3D numerical technique. According to the findings, encasing just the stone column group's exterior columns is adequate to provide an ideal design. Additionally, it was demonstrated that improving the encasement's stiffness improves the GEC group's behaviour. It was found that the internal friction angle of the column material has a relatively less impact on the performance of GECs and that, generally, the modulus of elasticity of the column material has a negligibly small impact on the group behaviour. According to the results, an increase in φs from 30° to 45° can produce a 20% reduction in both settlement and lateral deformation of the stone columns. Increasing the internal friction angle of the column material make the of increases the column strength and its ability for failure decreases. The results also suggest that, when settlements are taken into account, the effect of an increase in friction angle is more noticeable in the upper range of applied loads. Keykhosropur et al., (2012) [2].

It was found that the encasement critical length is a little less than the critical column length. The critical column length value is linked to the amount of the plastic deformation and that may be employed to define the column length in the design stage without the need for parametric studies. According to the studies the critical column length value is about 2D for ordinary and 2.5D for encased stone columns where (D) is the footing diameter. The 2D models were complemented with 3D analyses using PLAXIS 3D program. A square footing with the area as the 2D footing and with column internal friction angle φs changed from 35° up to 50° was used. The results appear as there is an increase in the internal friction angle of the column and a decrease in the settlement and this impact is more remarkable in the case of OSC as they are not confined laterally. Concerning the critical length of the column, it increases with the column friction angle in a similar approach for both OSC and ESC because, when the column strength is higher, it takes more load and transfers the load to a greater depth. Miranda et al., (2021) [3].

The stone column can be improved using encasement with geosynthetic material. The encasing stone column enhances load transfer to deeper soil layers. Murugesan and Rajagopal, (2007) [4] Malarvizhi and Ilamparuthi, (2007) [5], Ghazavi and Afshar (2013) [6]. Stone columns are the most appropriate and cost-effective ground improvement technique for soft soil. Prasad and Satyanarayana, (2019) [7].

Unit cell modelling was used to make the design needed to assess the behaviour of the granular column in a single or a group of columns. Many researchers have adopted the unit cell concept in their studies. Hasan and Samadhiya (2017) [8], Ambily and Gandhi (2007) [9]. The unit cell concept has been adopted in this study.

Lateef and M. Shah (2020) [10] make studies where they investigated the impact of different internal friction angles of the stone column on the load settlement behaviour. In their investigation when they changed the angle of internal friction of the materials of the encased stone column for GESC of 0.5 m diameter with a value between 30°-50°, the enhancement is mild in the bearing capacity of GESCs which could be observed by increasing the angle of internal friction of the stone column. For prescribed displacement of 50 mm, 100 mm, and 150 mm, the improvement in the vertical load intensity by changing the friction angle from 30° to 50° increases by 76.32 % in 50 mm, 83.43 % in 100 mm, and 87.72 % in 150 mm.

Shaker Mahmood (2015) [11], the study used finite element analyses to assess the settlement of the reinforced soft clay with stone columns by using PLAXIS 2D. the study found that when using crushed stone columns with varying friction angles, the angle of 40° produces a significant reduction in the settlement of soft clay beneath embankments.

II. NUMERICAL MODELLING

A. Numerical Model

The Finite-Element-Method (FEM) has been utilized and has proven itself as a valuable tool for the study of complex engineering problems. In the last years, computer technology has led to the development of many computer programs for resolving several engineering difficulties. Mathematical modelling became an essential part of engineering analysis problems. PLAXIS 3D is a three-dimensional FE program that is specifically tailored for geotechnical applications. In this research, analysis was carried out by using the PLAXIS 3D program to examine the behaviour of a footing resting on soft clay soil with ordinary and with encased stone columns. Axial stress-settlement curves have been developed to evaluate the bearing capacity of the soft clay soil. The model used in this study is shown in Fig. 1. whereas the 3D mesh generation is generated for clay, ordinary, and encased stone columns in every case which is presented in the following Figures (2, 3, and 4.) respectively. The height of soft clay (H)=10m in all cases.

B. Materials Properties

Properties of soil materials used in the model (Tandel et al. 2013) [12], are presented in Table 1. Properties of geotextile materials used in the model are shown in Table 2. Model footing properties used are displayed in Table 3.

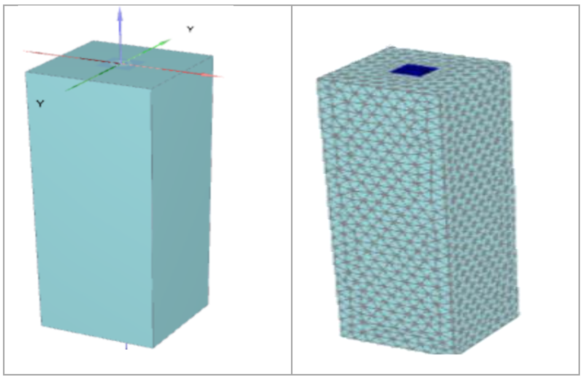

Figure 1. 3D Model geometry

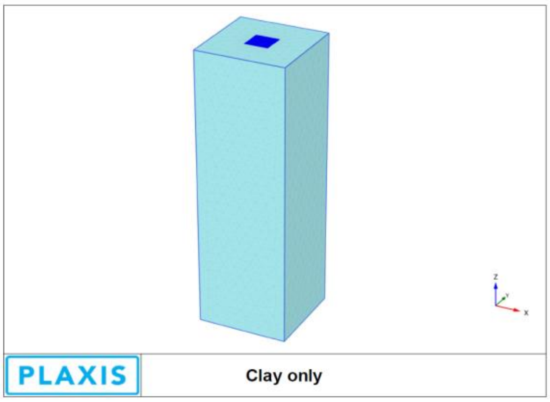

Figure 2. 3D mesh generation clay only

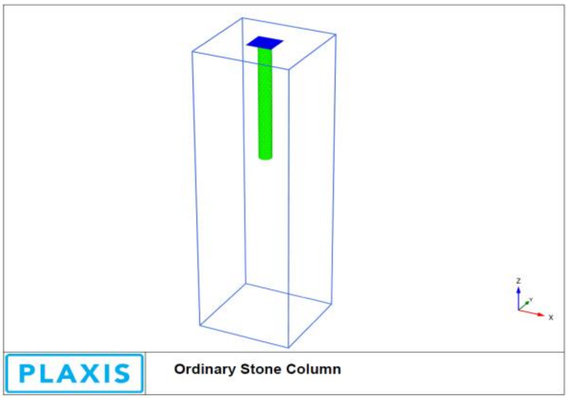

Figure 3. 3D mesh generation ordinary stone column

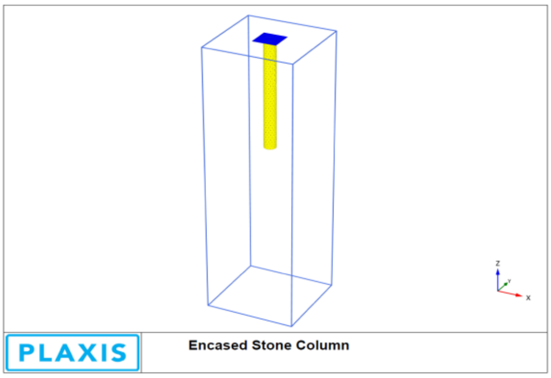

Figure 4. 3D mesh generation fully encased stone column

Table 1. Soil Properties used in PLAXIS 3D (Tandel et al. 2013)

Soil Parameter	Soft Clay Soil	Stone column
Model Type	Mohr Coulomb	Mohr Coulomb
Drainage type	Undrained	Drained
Saturated density, γ_{sat} (kN/m^3)	17	18
Young's modulus, E_s (kN/m^2)	3000 4000 5000	66000 55000 36000
Poisson's ratio, ν	0.4	0.3
Undrained shear strength, c_u (kN/m^2)	15 20 25	----
Friction angle, φ °	---	45° 40° 32°
Angle of Dilatancy, **Ψ** °	---	15° 10° 2°

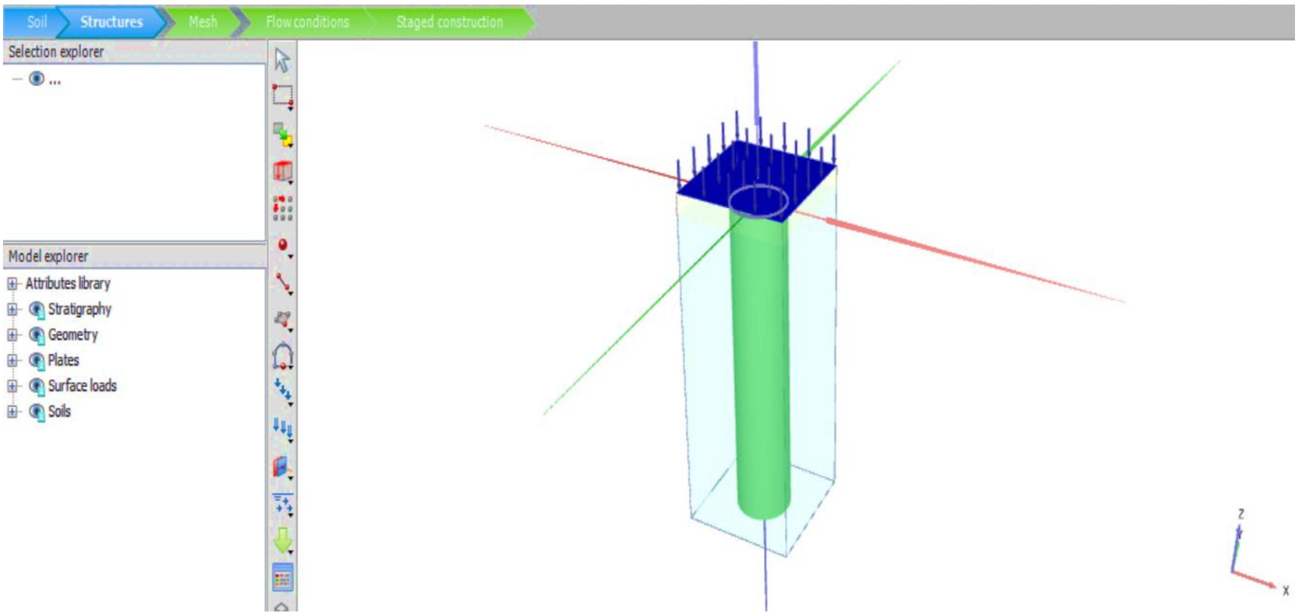

Figure 5. Model for the case of the entire area loaded by PLAXIS 3D.

Table 2. Geotextile Properties used in PLAXIS 3D (Tandel et al. 2013)

Parameter	Geotextile
Model Type	Linear Elastic
Axial stiffness, J (kN/m)	$J_1 = 500$ $J_2 = 1000$ $J_3 = 1500$ $J_4 = 2000$ $J_5 = 2000$ $J_6 = 3000$ $J_7 = 4000$ $J_8 = 5000$
Poisson's ratio, ν	0.3

Table 3. Footing Properties used in PLAXIS 3D (Tandel et al. 2013)

Parameter	Geotextile
Model Type	Linear Elastic
Young's modulus, E_s (kN/m^2)	2.1×10^8
Poisson's ratio, ν	0.2

III. NUMERICAL MODEL VERIFICATION

A. Verification using Ambily and Gandhi, 2007

A finite-element model was utilized in this research using Software Program PLAXIS 3D. The model was validated by modelling an experimental study that was performed by Ambily and Gandhi (2007) [9]. Fig. 5 shows the model of the soil with a single stone column of 100 mm diameter. In Fig .6-a and Fig. 6-b, mesh is generated. The tests are done with the entire area loaded and the column only loaded. From Fig. 7, there was a very good matching between the results conducted by Ambily and Gandhi (2007) [9].

IV. STUDIED SERIES AND PARAMETERS

A series of many cases were carried out to investigate the effect of different parameters such as the angle of internal friction of the stone column on the bearing capacity of the soft clay soil. All the cases have been done on soft clay soil, ordinary stone column (OSC), and encased stone column (ESC).

The following parameters are taken into consideration:

1- Soft Clay Soil Height, H (= 10m).
2- Stone Column Length, L (4.0 m and 6.0 m).
3- Stone Column Diameter, D (0.40 m and 0.60 m).
4- Column Length to Diameter ratio, L/D (=10).

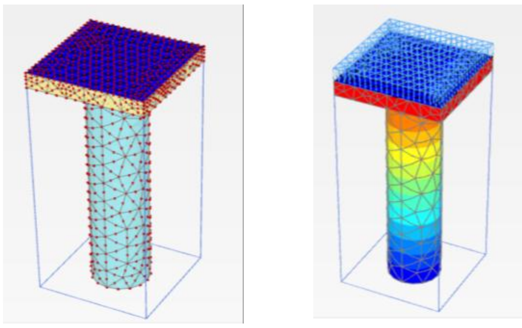

Fig.6-a: The mesh generated Fig.6-b: The deformed mesh

Figure 6. Mesh and deformed mesh for the case of the entire area loaded

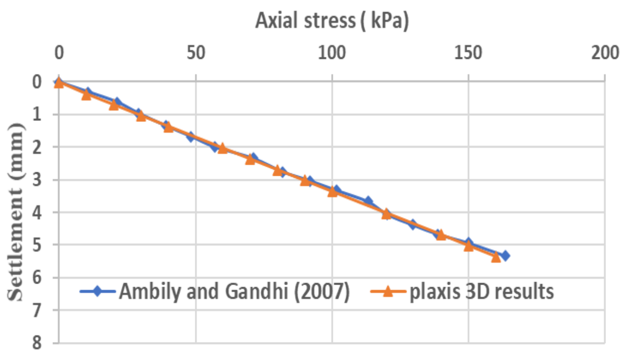

Figure 7. Validation of the results of the PLAXIS 3D program and the load-settlement curve in case of the entire loaded area for Ambily and Gandhi, 2007

Table 4. Different Angle of Internal Friction (φ).

Case	H (m)	L (m)	D (m)	L_{enc} (m)	L/H	L/D	L_{enc}/L	L_{enc}/D	φ (°)
Clay only	10	-	-	-	-	-	-	-	-
OSC	10	4.0	0.4	-	0.4	10	-	-	32°
									40°
									45°
	10	6.0	0.6	-	0.6	10	-	-	32°
									40°
									45°
ESC	10	4.0	0.4	2.0	0.4	10	0.5	5.0	32°
									40°
									45°
	10	6.0	0.6	3.0	0.6	10	0.5	5.0	32°
									40°
									45°

OSC: Ordinary stone column, ESC: Encased stone column

Table 5. BCR for different (φ) values (D=0.40 m and 0.60 m), c_u = 20 kN/m², J =2000 kN/m

		φ	q_u (kPa)	BCR	BCR increase
D=0.40m	Clay		150		
	OSC	32°	200	1.33	33%
		40°	240	1.60	60%
		45°	280	1.87	87%
	ESC	32°	412	2.75	175%
		40°	460	3.07	207%
		45°	490	3.27	227%
D=0.60m	Clay		150		
	OSC	32°	174	1.16	16%
		40°	200	1.33	33%
		45°	230	1.53	53%
	ESC	32°	376	2.51	151%
		40°	426	2.84	184%
		45°	450	3.00	200%

5- Encasement Length, L_{enc} / L = 0.5.
6- Undrained shear strength of soft clay soil, c_u (20 kN/m²).
7- Angle of Internal Friction of Stone Column Material, φ° (32°, 40°, and 45°).
8- Axial Stiffness of Geotextile Encasement, J (2000 kN/m)

An investigation has been done on column diameters 0.40 m and 0.60 m to study the effect of the angle of internal friction (φ). Table 4 shows the results at different angle of internal friction.

V.RESULTS AND ANALYSIS

The results of the numerical analysis of the axial stress to settlement curve have been accomplished.

A. Effect of Angle of Internal Friction of Stone Column Material (φ°) on Settlement and Bearing Capacity

It was detected that the improvement of the bearing capacity of the stone column due to a change in the parameter of the value of the internal friction angle of the column material has less effect than other parameters and this agreed with Keykhosropur et al. (2012) [2].

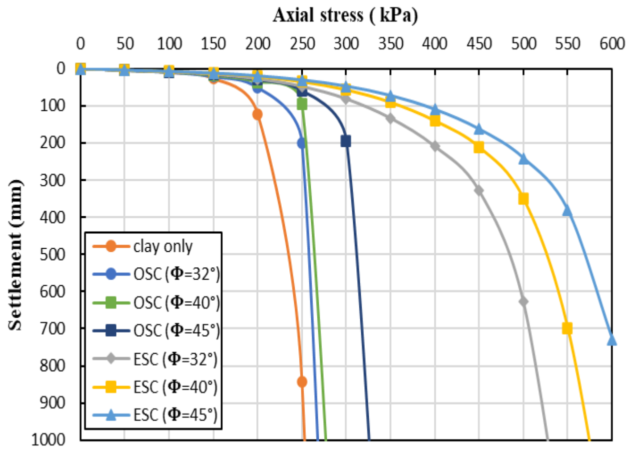

Figure 8. Axial stress – settlement curves for different (φ°) (D =0.40 m, c_u = 20 kN/m², L_{enc}/D=5, J =2000 kN/m)

Based on the result shown in Table. 5. for a stone column of a diameter (D= 0.40 m) It was realized that a column which not encasement by geotextile (OSC) has an improvement in the bearing ratio over the untreated soil by 1.33, 1.60 times, and 1.87 times for the angle of internal friction are (φ =32°, φ =40° and φ =45°) respectively. Where the increase in the percent of the ratio of the BCR is 33%, 60%, and 87% for the angle of internal friction (φ =32°, φ =40°, and φ =45°) respectively. For column which encasement by geotextile (ESC) was most effective in improving the bearing ratio of reinforced soil by approximately 2.75, 3.07 times, and 3.27 times for angle of internal friction are (φ =32°, φ =40°, and φ =45°) respectively. As can be seen in Figure. 8. and from Table 5. For (D=0.40 m) with encased stone column (ESC) the improvement over the untreated soil increased for the angle of internal friction (φ =32°, φ =40°, and φ =45°) by 175%, 207%, and 227% respectively.

For diameter D=0.40 m, the BCR increase in OSC for the column is found to be reached its maximum value at 87 % with the angle of internal friction (φ= 45°) and 53 % for diameter D=0.60 m for the same angle of internal friction from (φ =45°). The BCR increase in ESC for a column that has a diameter D= 0.40 m reaches its maximum value at 227 % with the angle of internal friction (φ=45°) and 200 % increase for diameter D=0.60 m at internal friction angle (φ =45°).

Ordinary stone columns (OSC) with a diameter of D=0.60 m have an improvement in the bearing ratios over the untreated soil by 1.16 times, 1.33 times, and 1.53 times, for the internal friction angles of 32°, 40°, and 45° respectively. the increase in improvement of (φ=32°, φ=40°, and φ=45°) can produce an increase in the BCR ratio over untreated soil by 16%, 33%, and 53% respectively.

Encased stone column (ESC) was much higher in improving the bearing ratio of reinforced soil ratios over the untreated soil by approximately 2.51 times, 2.84 times, and 3.00 times for the angles of the internal friction of (φ =32°, φ =40°, and φ =45°) respectively. While for the encased stone column (ESC) the improvement of the BCR ratio increased over the untreated soil for (φ=32°, φ=40°, and φ=45°) up to 151%, 184%, and 200% respectively.

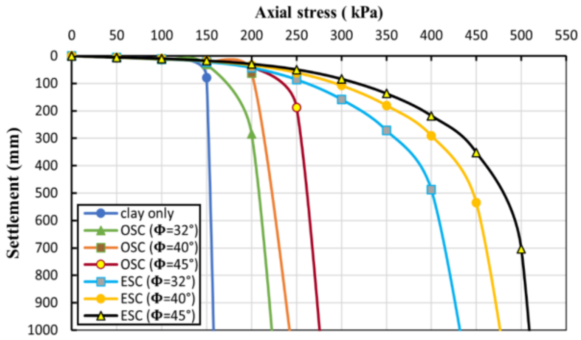

Figure 9. Axial stress – settlement behaviour for different (φ°) (D =0.60 m, c_u = 20 kN/m², L_{enc}/D=5, J =2000 kN/m)

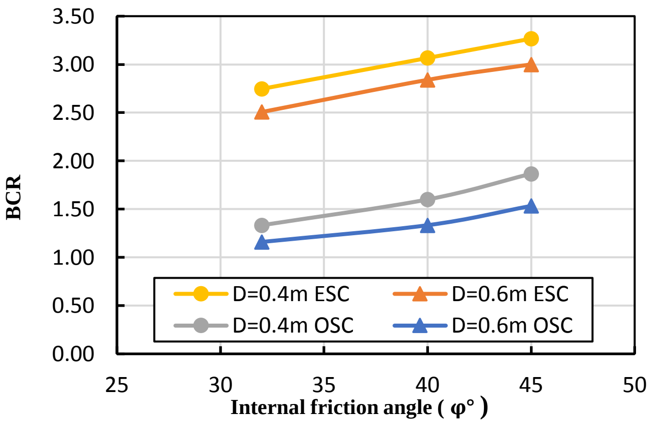

Figure 10. BCR for different (φ°), (D=0.40 m and D= 0.60 m of OSC and ESC)

VI. CONCLUSION

In the present study, the effect of different parameters on the behaviour of ordinary stone columns (OSC) and encased stone columns (ESC) on soft clay soil has been investigated. Such as the angle of internal friction. Several conclusions have been represented and can be summarized as follows:

1. For (OSC) and (ESC) the ultimate bearing capacity increased, and the settlement decreased with the increase in the value of angle of internal friction for ordinary stone column (OSC) of (φ= 32°, φ= 40°, and φ= 45°).
2. For diameter D=0.40 m the BCR enhancement in ordinary stone column (OSC) increased at (φ=32°) up to 33% over the clay only soil.
3. Over clay only soil the column of diameter D=0.60 m it was found that the BCR improvement in ordinary stone column (OSC) increased at (φ=32°) up to 16% over the clay only soil (untreated soil).
4. The BCR increase in OSC for column diameter D= 0.40 m is found to be reached its maximum value at 87 % with angle of internal friction (φ= 45°)
5. The BCR increase in OSC for column diameter D= 0.60 m is found to be reached its maximum value at 53 % for diameter D=0.60 m for angle of internal friction at (φ =45°).
6. The BCR increase in the ESC for column diameter of D= 0.40 m reaches its maximum value at 227 % at the internal friction angle (φ =45°).
7. The BCR increase in ESC for column diameter D= 0.60 m reaches its maximum value at 200 % at the internal friction angle (φ =45°).

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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