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A Comparative Three-Dimensional Numerical Study on Geosynthetic-Encased Stone Column Groups Under Varying Conditions

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Abstract. In the last 40 years, ordinary stone columns (OSCs) have gained popularity in improving soft cohesive soils, specifically in providing support to lightly and moderately loaded structures. However, such methods are not very useful for extremely soft soils. To overcome this limitation, geosynthetic-encased stone columns (GESCs) have been developed recently to enhance the performance in very soft soil. The present research paper deals with a comprehensive numerical analysis of full scale GESCs in soft clay installed in groups, performed in PLAXIS 3D software. The analysis investigates variable parameters of GESCs; column diameter (dc), geosynthetic stiffness, column length (Lc), encasement length (Le), undrained shear strength (cu) and angle of internal friction (ϕ) of the stone column material. The Mohr Coulomb model failure criterion was applied on clayey soil and stone columns. The performance of GESCs was evaluated in the terms of ultimate bearing capacity (UBC) and settlement reduction through load settlement plots. A geosynthetic encasement over ordinary stone columns has shown a notable increase in the ultimate bearing capacity. With reference to case floating GESCs, the gain in UBC was 67% and that for end-bearing GESCs was 164% when compared to the clay bed. The results indicate that increased column diameter reduced significant settlement by 40% in the case of OSCs.

1 Introduction

Traditional methods for modifying the engineering properties of soft clayey soil are usually time-consuming, expensive and not be effective in many situations [1-2]. The incorporation of geosynthetics encasement in stone columns, also known as Geosynthetic-Encased Stone Columns (GESC), has seen rapid growth in geotechnical engineering as a feasible means of reinforcing soft clay [3-4].

Ordinary stone columns (OSCs) provide very low enhancement because of lateral bulging when loaded but the application of geosynthetic encasements strengthens the confinement of the column, hence increasing its stability and load bearing capacity [5].

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Geosynthetic-reinforced stone columns represent an advanced ground improvement technique that has gained considerable attention over the past decade, particularly for construction on extremely soft soils. These systems are especially effective in deposits where the undrained shear strength is approximately 5 kPa or lower [6-7]. Under such weak ground conditions, conventional stone columns often experience excessive lateral deformation and bulging during installation and service loading, limiting their effectiveness. The inclusion of geosynthetic reinforcement enhances confinement, thereby improving the stability and load-carrying performance of the stone columns [8].

Various researchers carried out analytical, laboratory, field studies, and numerical analyses on GESCs using various approaches. Kelesoglu et al. [9] performed physical scale model studies with numerical computational to analyse modelling where column diameter, length and spacing were shown to affect load transfer and stability in soft clay soil. Various Authors [10] performed finite element analyses in the evaluation of the performance of geosynthetic reinforced stone columns and identified factors that are important in underlining the performance of numerical model when loads are applied, such as the stone column materials properties, geosynthetic properties, and the properties of the surrounding soil. The authors [11] used PLAXIS models to determine the characteristics of clayey soil with stone column encasement and soft compressible clay, also detailed that finite element analysis can reliably be used to simulate settlement and ultimate bearing capacity of stone columns. The earlier studies have supported an understanding of the laboratory behaviour of both single and grouped GESCs [12].

GESCs have great potential to enhance the performance of soft soils, but their group behavior under various loading conditions is not well understood. Critical gaps include optimal configurations based on insufficient studies, as well as the influence of geosynthetic materials, including column spacing and diameter. The present research paper provides a comprehensive numerical analysis of full-scale GESCs installed in soft clay using PLAXIS 3D. The study examines the effect of key variables, which include column diameter, geosynthetic stiffness, column and encasement lengths, undrained shear strength of soft clay, and the internal friction angle of the stone column material on GESC performance.

2 Methodology

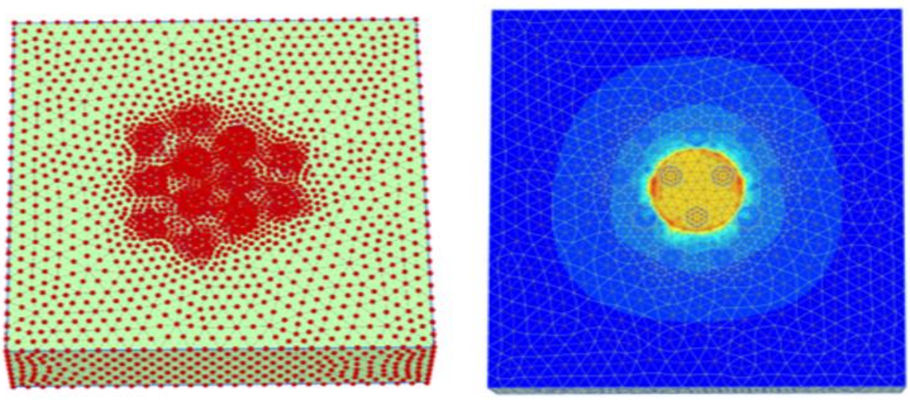
2.1 Model Validation

To validate the numerical model of PLAXIS 3D, the results of laboratory scale load tests on stone column reported by [12] were used. The authors [11] studied the group of stone columns under short term load application which is in line with the assumptions made in the present paper. The authors carried out laboratory model tests on stone columns of 60 mm diameter installed in a soft clay bed 300 mm deep, contained in a square tank of plan dimensions 1200 × 1200 mm. The numerical model was developed and examined using the Mohr-Coulomb failure criterion, in order to replicate the response of the constituent materials. Scaled models in geotechnical engineering have an immense role in understanding the way complex systems behave and verifying the numerical simulation of such a model. These include scale effects, simplified boundary conditions, and, most importantly, the inability to fully simulate real soil variability and loading scenarios; however, such models remain affordable means to infer material behavior as well as optimizing design parameters by allowing controlled experiments to separate isolated factors to aid in calibrating and validating numerical models like PLAXIS 3D. The material properties are presented in Table 1. The generated mesh as well as the output total displacements are shown in Figure 1.

Experimental and FEM analysis plots generated by PLAXIS 3D are shown in Figure 2, and a relatively good agreement is observable, thus verifying reliability of the numerical model in reproducing the physical performance.

Table1. Materials properties used for model validation

Properties	Model validation [13]		Present study	
	Clay	**Stone aggregates**	**Clay**	**Stone aggregates**
Young's Modulus, E (kPa)	600	40000	430	42000
Undrained shear strength, cu (kPa)	15	-	5	-
Dilatancy angle,ψ	-	10	-	10
Angle of internal friction, ϕ	0	46	0	42
Poisson's ratio, μ	0.47	0.3	0.48	0.3
Dry unit weight, γ (kN/m3)	16.8	16	13.85	14.51
Bulk unit weight, γb (kN/m3)	18.58	-	18.58	-



(a) (b)

Fig. 1. Generated Plaxis 3D model for validation, (a) mesh, (b) total displacements

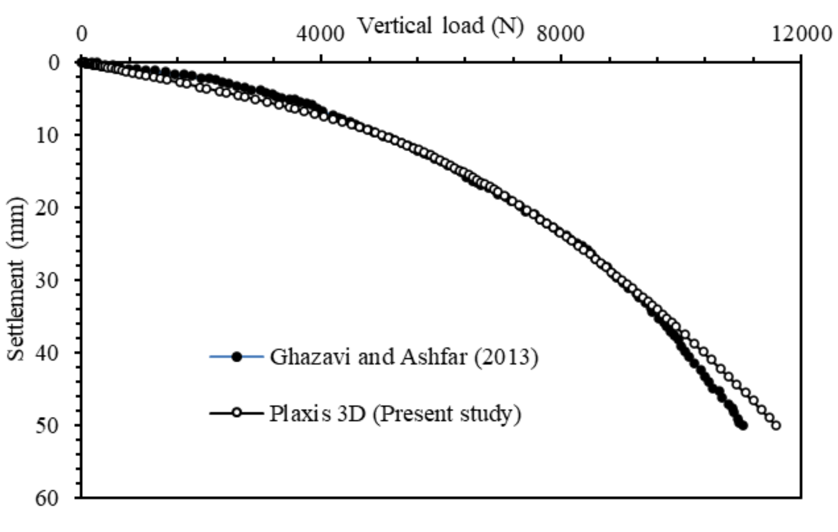


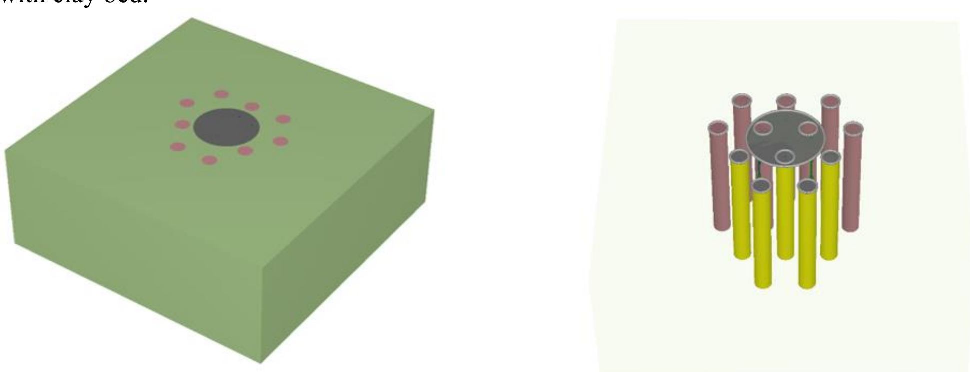
Fig.2. Experimental results and the results achieved by PLAXIS 3D

2.2 FEM Analysis

The present paper has been utilized the finite element software, PLAXIS 3D, for carrying out detailed numerical simulations. Widely used geotechnical engineering, PLAXIS 3D offers highly accurate computational techniques and robust three-dimensional modeling capabilities for simulating soil behaviour. The bottom boundary of the group of stone column model was fixed in all directions, while the lateral walls can only be translated vertically. Mohr-Coulomb model was used for modeling soft clay and stone columns. The geosynthetic material was modeled as an elastic material.

A bearing capacity and settlement analyses were conducted on full scale group of stone columns on beneath a simulated footing with diameter of 3.46 m, where prescribed displacements were applied as shown in Figure 3. Three column arrangements were considered with the triangular configuration having spacing, s = 2d, where s and dc are the spacing between columns and diameter of column respectively. The columns diameters were taken as 0.8 m with column length (Lc) was varied in order to keep the (Lc/Dc) ratio as 5 (floating columns) and 8d (end bearing columns). The material properties used in the numerical model are presented in Table 1 as reported by Hasan and Samadhiya [13]. Finite element analysis (FEA) was performed by adjusting parameters such as column height, geosynthetic, geosynthetic stiffness, shear strength of clay and internal friction angle of stone column materials.

Bearing pressure-settlement plots was carried out on untreated soil, soil reinforced by ordinary stone columns (OSC) and soil reinforced by geosynthetic encased stone columns (GESC). The UBC and settlement analysis of GESC treated soil were studied and compared with clay bed.



(a) (b)

Fig. 3. Plaxis 3D model, (a) Geometry, and (b) Footing simulation

In consideration of the analysis results, total displacement and deformed mesh of full scale GESCs groups (d = 0.8m) are shown Figure 4. It has been observed that the displacement profile of the area surrounding the stone columns has high displacement zone close to the column and a low displacement zone with increase in length of columns.

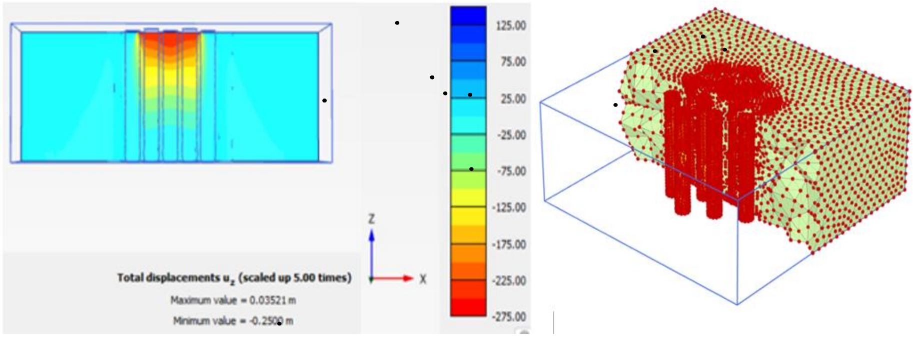


Fig. 4. Total displacement and deformed mesh of GESCs

3 Results and Discussions

Bearing pressure and settlement plots were generated to study the performance of soft clayey soil treated with full scale ordinary stone columns (OSCs) and geosynthetic encased stone columns (GESCs). Using full scale simulations, the influence of several parameters was investigated on the behaviour of the GESC group. These parameters were column length, shear strength of the soil, angle of internal friction, encasement effect, encasement length, and stiffness of the geosynthetic. This paper reports a quantitative analysis of the ultimate bearing capacity (UBC) of the stone column treated soil. Table 2 summarizes the key findings, highlighting the variations in the tested parameters and their effects on the UBC and settlement reduction.

Table 2. Summary of key findings from the present study

Parameter	Variation	% Increase in UBC	% Decrease in Settlement
Clay bed		0%	0%
Column diameter OSC	dc = 800 mm	57%	70%
	dc = 1000 mm	71%	70%
Column diameter GSC	dc = 800 mm	164%	81%
	dc = 1000 mm	149%	79%
Undrained Shear Strength	Cu = 5 kPa	57%	70%
	Cu = 10 kPa	129%	76%
	Cu = 15 kPa	163%	76%
Angle of internal friction for column aggregates	$\phi = 38°$	46%	67%
	$\phi = 42°$	57%	70%
	$\phi = 46°$	73%	76%
Geosynthetic stiffness	J = 600 kN/m	164%	81%
	J = 1000 kN/m	210%	85%
	J = 1500 kN/m	264%	85%
Encasement length	Le = 25%	96%	70%

	Le = 50%	136%	80%
	Le = 75%	162%	81%
	Le = 100%	164%	81%
Column length Lc	5d = 4 m (Floating)	48%	64%
	8d = 6.4 m (End bearing)	57%	70%

3.1 Effect of column length

The 0.8 m diameter OSCs were modelled having length of 5d (floating columns) and 8d (end bearing columns) to study the effect of column length on UBC. Bearing pressure – settlements plots for stone column in both floating and end bearing with respect to the clay bed are shown in Figure 5. Since it was no clear failure of the stone column up to 250 mm settlement, it has been considered bearing pressure corresponding 20% strain relative to column diameter (160 mm) as ultimate bearing capacity as reported by Ng & Tan [12]. Due to the variation of length for OSC, it has been noted that, there is a substantial increment of UBC for floating 49% (39.8 kPa) and end bearing 57% (42 kPa) with respect to the Clay bed (26.9 kPa). The further increase in the end bearing of the OSC is attributed to the column resting on a firm supporting base.

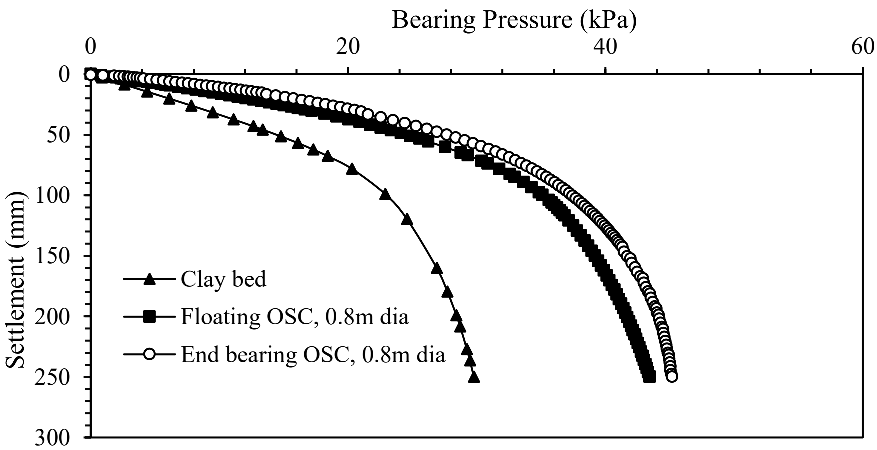


Fig. 5. Effect of column length on bearing pressure -settlement plots

3.2 Effect of geosynthetics

In order to analyze the influence of Geosynthetics on the Ultimate Bearing Capacity, GESCs of 0.8 m diameter were conceptualized having lengths of 5d (for floating columns) and 8d (for end bearing columns). The bearing pressure – settlements curves for stone column in both floating and end bearing with respect to clay bed are represented in Figure 6. With the application of geosynthetics over the OSC, a further increase in UBC of 67% (45 kPa) and 164% (71 kPa) was observed for the floating and end bearing columns, respectively, relative to the clay bed (26.9 kPa). This increase is attributed to the confinement of the stone columns by the geosynthetics and has also been reported by other researchers [7, 13].

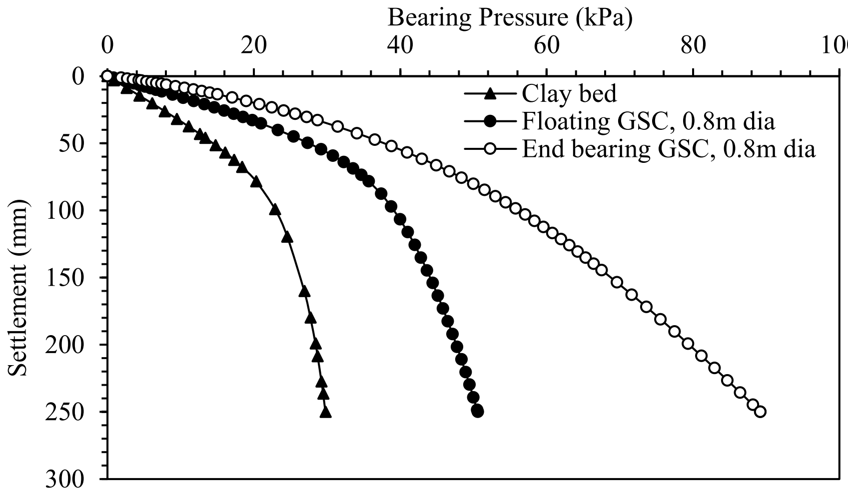


Fig. 6. Effect of geosynthetic on bearing pressure -settlement plots

3.3 Influence of geosynthetic stiffness

Bearing pressure – settlements plots for GESCs groups with varying stiffness are shown in Figure 7. Changing the column stiffness between *J*=600 kN/m and *J*=1500 kN/m, significantly improved UBC of GESCs. Subsequent increases in the stiffness values as *J*=600 kN/m, *J*=1000 kN/m, and *J*=1500 kN/m produced uniform improvements in UBC as 164% (71 kPa), 210% (83.5 kPa), and 264% (98 kPa), respectively, relative to the untreated clay bed. This improvement may be due to the lateral confinement stresses that are mobilized within the column [11].

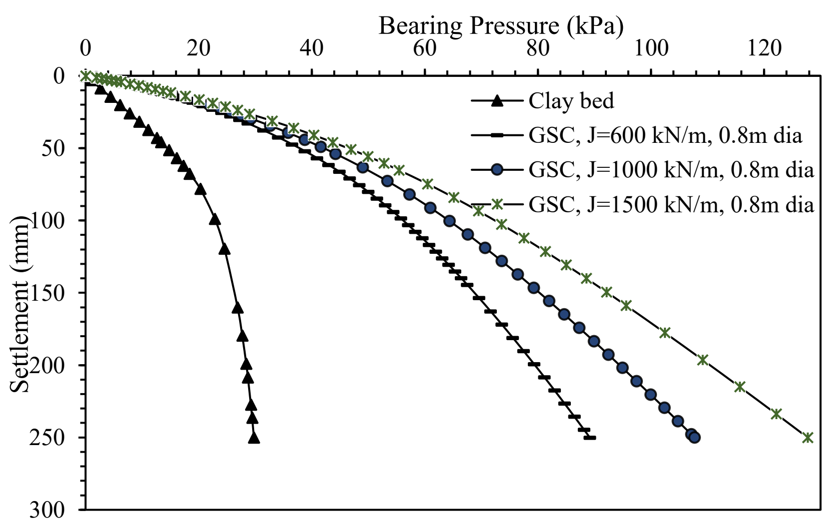


Fig. 7. Effect of geosynthetic stiffness on bearing pressure -settlement plots

3.4 Effect of unconfined shearing strength

The unconfined shearing strength to the stone column 0.8 m diameter were determined for 8d (end bearing columns) to study the effect of unconfined shearing strength on UBC. Bearing pressure – settlements plots for stone column with respect to the clay bed with varying unconfined shearing strength shown in Figure 8. The variation of stiffness from Cu = 5 kPa to Cu = 15 kPa has revealed that, there is a noteworthy improvement of UBC for Cu change with respect to the Clay bed. The increment for UBC in a variation of Cu = 5 kPa, 10 kPa and 15 kPa provides an improvement of ultimate bearing capacity of 57% (42.3 kPa), 129% (61.6 kPa) and 163% (70.7 kPa) respectively compared to the clay bed. This increment is due to the improvement of lateral resistance (prevent bulging) to the stone column and minimizing settlement as it was reported by authors [11&13].

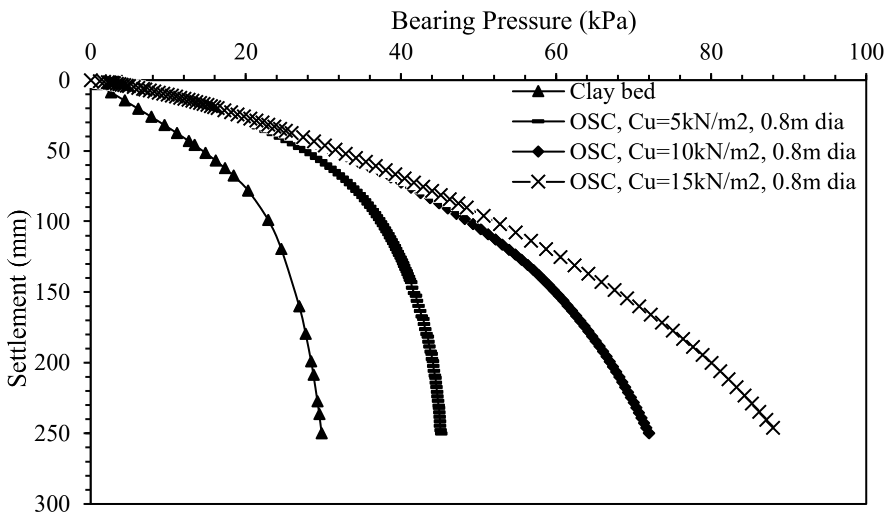


Fig. 8. Effect of shear strength on bearing pressure -settlement plots

3.5 Effect of angle of internal friction

Bearing pressure – settlements plots for GESCs with varying angle of internal friction are shown in Figure 9. It was noticed that increasing the friction angle from $\phi = 38°$ to $\phi = 46°$ considerably increases the ultimate bearing capacity (UBC) of GESCs. By changing the friction angle to $\phi = 38°$, $\phi = 42°$ and $\phi = 46°$, the ultimate bearing capacity is improved by about 46% (39.4 kPa), 57% (42.3 kPa) and 73% (46.5 kPa), as related to the untreated clay bed. This enhancement is attributed to the frictional resistance forces developed in the column's aggregate materials.

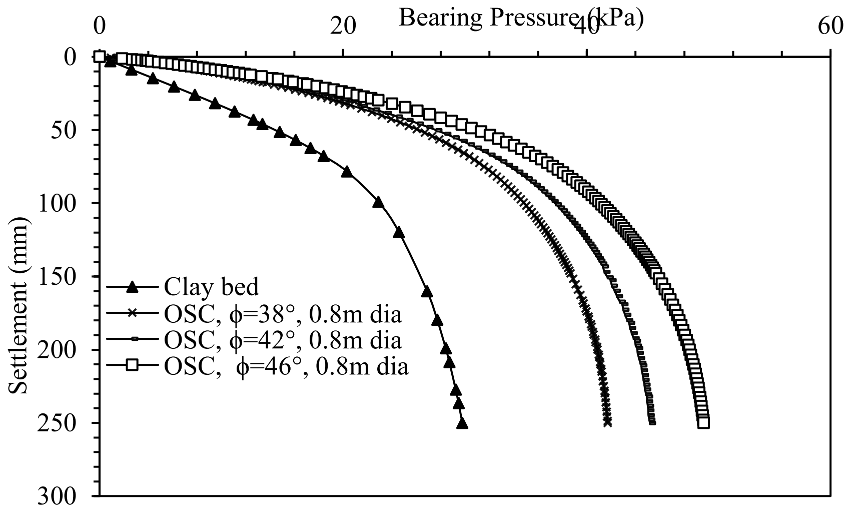


Fig. 9. Effect of angle of internal friction on bearing pressure -settlement plots

4 Conclusions

Bearing pressure-settlements plots were generated to study the performance of full scale OSCs and GESCs treated soft clayey soil. The UBC of OSCs and GESCs were investigated and following conclusions may be drawn:

1. In end-bearing configurations, the Ultimate Bearing Capacity (UBC) of end bearing OSC was enhanced by 57%, reaching 42 kPa.
2. The use of Geosynthetic encasement (GE) improved UBC values by 164% owing to the advantages of strong lateral confinement.
3. Use of Stiffer Geosynthetic of stiffness 1500 kN/m resulted in 264% increase in UBC, proving relatively increase in load transfer purposes.
4. Shear Strength values (c_u) are controlled at higher values resulting in 163% increased UBC justifying the improvement of soil strength.
5. The determinants of the internal friction angle to the increase in UBC are 73% subsequently underscoring the role of friction in carrying loads.

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