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Numerical Analysis of Stone Columns in a Layered Soil System

Subhash Kumar Gupta[1], Soumen Naskar[2] and Awdhesh Kumar Choudhary[3]

[1]M.Tech Student, Department of Civil Engineering, National Institute of Technology, Jamshedpur-831014
subhashrouniyar@gmail.com
[2] Research Scholar, Department of Civil Engineering, National Institute of Technology, Jamshedpur-831014
snaskar737@gmail.com
[3]Assistant Professor, Department of Civil Engineering, National Institute of Technology, Jamshedpur-831014
awdhesh.ce@nitjsr.ac.in

Abstract. Stone columns are mainly used to improve the bearing capacity of soft soil. It reduces the settlement as well as imparts stability to different geotechnical structures constructed on it. When huge structures such as oil storage tanks, embankments and multi storey buildings are constructed on soft soils, the ordinary stone column alone will not be sufficient to bear the load coming on to it. Therefore, encased stone column is preferred over ordinary stone column during such construction.

In view of that numerical analysis has been carried out to investigate on the bearing capacity of ordinary stone column and encased stone column in layered clayey soils. The numerical model of ordinary stone column and encased stone column were simulated using finite element package PLAXIS^{3D}. Parametric study has been carried out and their response on the overall bearing capacity has been reported.

It is found that the bearing capacity of improved ground is mainly influenced by the presence of topmost layer up to a depth of 4 times the diameter of stone column in layered clayey soil.

Keywords: Encased Stone Column, Soft Clay, Layered Soil System, Bearing Capacity.

1 Introduction

Stone columns is considered to be one of the most efficient and cost-effective methods for improving the weak soil. It reduces the settlements and increases the strength of soft soil. Stone column is a dense aggregate column made of granular material that is embedded in weak soil strata. The granular column consists of compacted gravel or crushed stone which are arranged in the form of a column using a probe vibrator. It is one of the most common ground improvement techniques. Stone column improves the ultimate bearing capacity of the ground. It was earlier known as stone column as only stones were used for filling. Stone columns are mainly failed due to bulging (Hughes and Withers 1974; Hughes et al. 1976), general shear failure (Madhav and Vitkar 1978), and sliding (Aboshi et al. 1979). A long stone column having a length greater than its critical length (i.e., about 4 times the diameter of the column) fails by bulging irrespective of whether it is end bearing or floating. To overcome this situation encasing it in an appropriate geosynthetic material and then reinforcing it. Encasing the column and adding extra restraint both enhance the axial capacity in weak soils, which leads to a decrease in settlements, and also raise the stress concentration of the stone column, which results to a reduction in the load that is placed on the soil (Malarvizhi and Ilamparuthi 2008; Deb et al. 2007; Fattah et al. 2016). Encasement provides resistance to bulging by cylinder action. As columns bulge under loading, hoop stresses are developed in the encasement. These stresses are resisted by the tensile strength of the geosynthetic. This causes high ultimate load carrying capacity and less settlement of composite foundation. The pattern of installation of stone columns can be square or triangular. But densest packing can be achieved only through the equilateral triangular pattern (IS 15284, Part 1; 2003).

The above literature review shows that the experimental, analytical and numerical study on the settlement and bearing capacity of the stone column improved soil has been investigated considering surrounding soil to be homogeneous in nature. However, in reality, soils are layered with variable degree of stiffness of different layers. Very few studies have been conducted on the performance of stone column in layered soil (Shivashankar et al. 2011; Mohanty and Samanta 2015; Nayak et al. 2019). In view of this, effect of layering was investigated by performing 3-dimensional numerical analyses in PLAXIS^{3D}.Numerical study has been conducted to understand the behaviour of ordinary stone columns as well as encased stone columns in layered soil system.

In the present study behaviour of stone columns in soft soil have been investigated through a series of numerical analysis. The influence of undrained shear strength of clay bed on load carrying capacity of stone column has been analysed. The influence of layered soil system on the overall behaviour of OSC and ESC has been brought out. Parametric analysis in terms of friction angle of stone aggregates has been performed.

2 Numerical Modeling

Numerical modelling was done with the help of finite element based software PLAXIS^{3D} to provide better understanding on the behavior of stone columns in a layered soil system under different test conditions. Initially, a homogeneous geometric soil model having dimension 1000 mm x 1000 mm x 1000 mm (length x width x height) was developed considering Mohr-Coulomb model as shown in the Fig. 1. Further, varying depth of two clay layered geometric soil model with same dimensions was prepared as shown in Fig.2. The model was fully fixed at the bottom (both horizontal and vertical movement was restricted) and partially fixed on the sides (horizontal movement was restricted). A circular shaped footing having diameter equal to 100 mm was placed at the centre of the group of stone columns which was arranged in triangular pattern having spacing equal to 3 times the diameter of stone column.

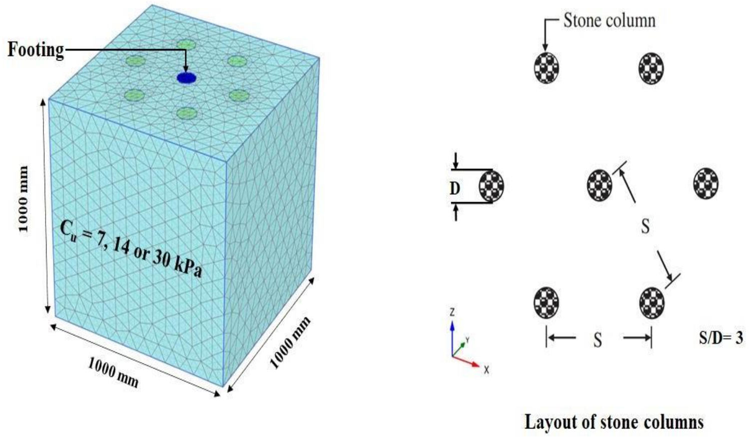

Fig. 1. Typical model geometry of stone columns in homogeneous soil

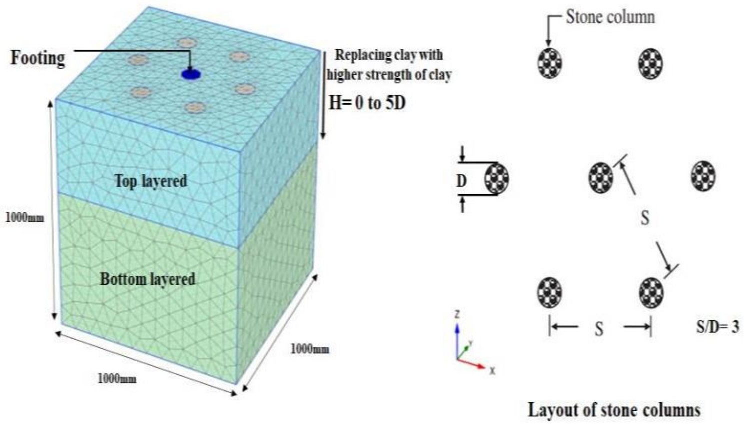

Fig. 2. Typical model geometry of stone columns in layered soil

Stone columns in layered clay have been used in this study. The material properties of clay and stone column were adopted from literature of Ambily and Gandhi (2007). The properties of clay and stone aggregates are presented in Table 1. For encasing the stone column, the properties of geogrid structure element have been adopted from literature of Debnath and Dey (2017) and are presented in Table 2.

Table 1. Input parameters for modeling stone columns in soft clay (Ambily and Gandhi 2007)

Material	C_u (kPa)	E (kPa)	μ	ϕ°	Ψ°	γ_{dry} (kN/m^3)	γ_{bulk} (kN/m^3)
Clay	30	5500	0.42	-	-	15.56	19.45
Clay	14	3100	0.45	-	-	14.60	18.98
Clay	07	2150	0.47	-	-	13.60	18.38
Stones	-	55000	0.30	43	10	16.62	-

Table 2. Properties of encasement materials used (Debnath and Dey 2017)

Material	Axial stiffness EA (kN/m)	Shear stiffness GA (kN/m)
Geogrid	210	80.77

The PLAXIS^{3D} software automatically generates a 3-dimensional model for this study. Medium meshing has been done in the stone columns in layered soil. The calculation phase was then performed and result of the numerical models has been analyzed.

3 Results and Discussion

In the present study, the bearing capacity of stone columns (ordinary as well as encased) in layered soil system, under circular footing has been analyzed. For this, numerical models have been developed in PLAXIS^{3D}. However, before detailed investigation and analysis, validation of the proposed models with the experimental studies of ordinary stone column (OSC) reported by Ambily and Gandhi (2007) and encased stone column (ESC) by Debnath and Dey (2017) have been carried out.The material properties of clay and stone column and dimension of stone column and footing used in the numerical model were adopted from experimental work performed by Ambily and Gandhi (2007). Subsequently, stiffness of encasement material was taken from experimental work performed by Debnath and Dey (2017).

The numerical simulation was done and accordingly influence of undrained cohesion of clay (C_u) on the performance of stone column in homogeneous soil has been investigated. The influence of layered clay on the load carrying capacity of stone column and the effect of friction angle of stone aggregates (ϕ_a) on the overall behaviour of stone column has been studied.

3.1 Validation of ordinary stone columns

At first, the numerical model was developed using finite element package PLAXIS^{3D} to analyze the load-settlement behaviour of ordinary stone column in clayey soil. The model dimensions and properties of soil and stone column were kept same as reported in the experimental model tests conducted by Ambily and Gandhi, 2007. The clay and stones are modeled using Mohr-Coulomb’s criterion and drained behaviour was considered for all the materials. The results obtained from numerical analysis are then compared with existing experimental results reported by Ambily and Gandhi (2007) as presented in Fig. 3. It can be seen that results from the numerical analysis are in good agreement with the experimental results for different C_u values ranging from 7 kPa to 30 kPa. Hence, it can be said that the present numerical model is capable enough to simulate the behavior of ordinary stone columns placed in clay beds.

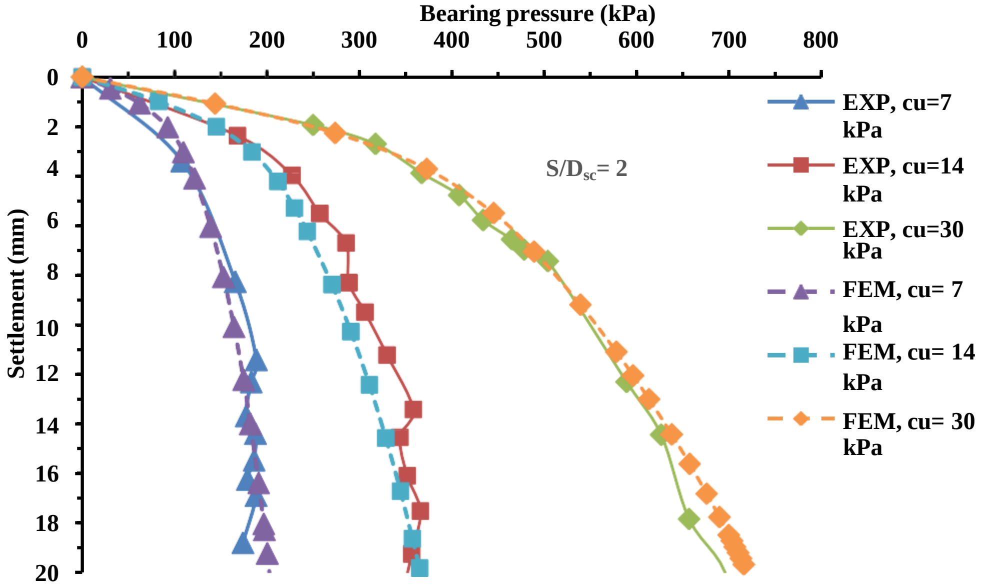

Fig. 3. Validation of OSC

3.2 Validation of encased stone columns

To provide better confinement and reduce bulging, ordinary stone columns are often encased with geosynthetics materials. Therefore, encased stone columns can be provided in place of ordinary stone columns. The numerical model comprising of encased stone column is validated with experimental work reported by Debnath and Dey (2017). The model dimensions, properties of soil and stone column were kept identical as reported in the experimental model tests by Debnath and Dey (2017). Further the axial stiffness and shear stiffness values of encasement material were 210 kN/m and 80.77 kN/m respectively. The comparison of numerical results with experimental one for ESC is shown in Fig. 4. It can be noticed that the numerical results are well comparable to the experimental results with marginal error. This error is probably due to inaccuracy in adopting the material properties of geosynthetic used as an encasement material during experimental work by Debnath and Dey (2017).

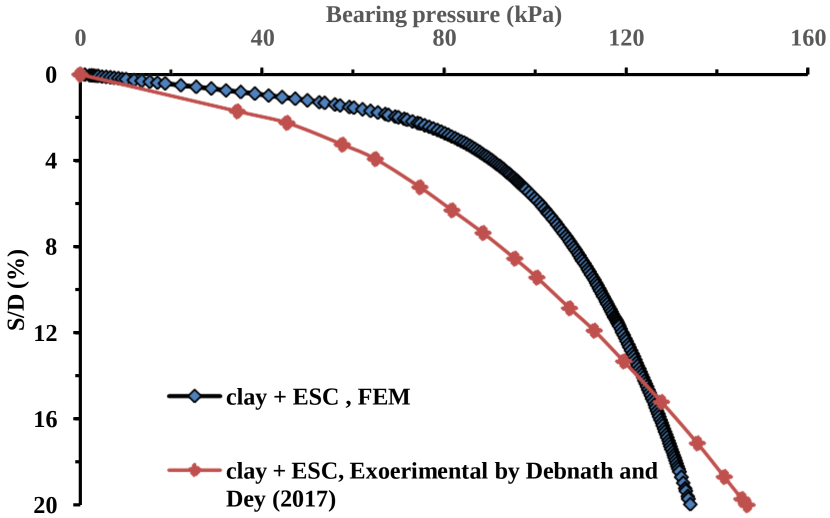

Fig. 4. Validation of ESC

3.3 Behaviour of stone columns in homogeneous clay

The response of footing placed above unreinforced, ordinary stone column reinforced and encased stone column reinforced clay bed has been investigated in this section. In view of this, soil model having dimension 1000mm×1000mm×1000mm has been created as shown in Fig. 1. Group of stone columns were placed in triangular pattern with spacing being equal to 3 times the diameter of stone column i.e., 100 mm and a circular footing having diameter equal to the diameter of stone column is placed at the centre of group of stone columns (Ambily and Gandhi, 2007). The value of undrained cohesion of clay i.e., C_u = 7kPa has been kept the same in all the cases. The bearing pressure vs. settlement curve for unreinforced clay bed, clay bed consisting of OSC and ESC has been presented in Fig. 5. It can be observed that with the provision of OSC in unreinforced clay bed, the footing is able to bear greater loads under same value of settlement. Further when OSC was replaced by ESC, the load carrying capacity of the composite system gets significantly increased. It is because of the fact the OSC in soil provides lateral confinement to upcoming load and encasement of OSC provides higher resistance to radial bulging of the same.

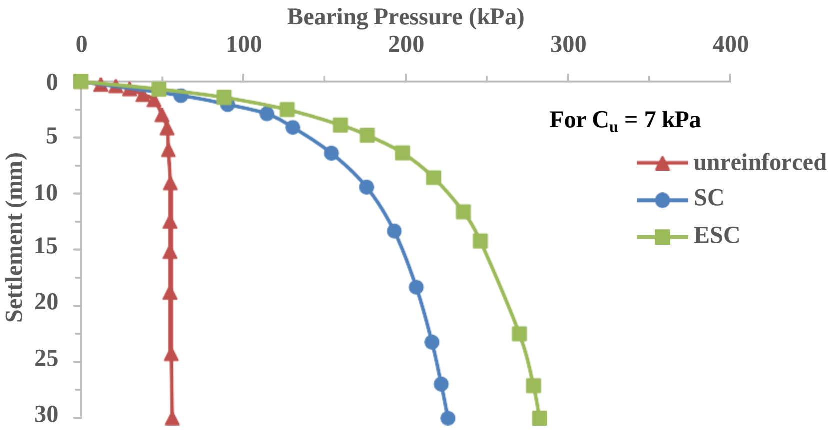

Fig. 5. Bearing Pressure-settlement response of stone columns in homogenous clay

3.4 Behaviour of stone columns in layered clay

The behaviour of stone columns in layered clay has been investigated by changing single layer soil system (homogeneous clay) into a two layered soil system. In view of this soft clay up to depth equal to 'H' is being replaced by clay having higher undrained shear strength as shown in Fig. 2. The model geometry has been kept the same as in section 3.3. In this layered system, undrained shear strength of clay, C_u of the top layer is always kept greater than that of the bottom layer.

Fig.6. and Fig.7. show the bearing pressure vs. settlement curve in homogenous and layered clay for OSC and ESC respectively. It can be seen that the bearing capacity of OSC and ESC in layered clay increases with an increase in the depth of top layer. However, beyond depth of top layer equal to 4D, the further rate of increment in bearing capacity is found to be negligible for both OSC and ESC. The performance improvement is represented in terms of improvement factor ratio (IFR) which is equal to the ratio of bearing pressure at 30mm settlement of OSC (or ESC) in layered system to the bearing pressure at 30mm settlement of homogenous soft clay. The increase in IFR with increase in depth of top layer in case of both OSC and ESC is presented in Table 3 and 4 respectively. It was found that the bearing capacity of the composite system comprising of OSC increases with an increase in the depth of top layer (H). However, the performance improvement is found to be negligible beyond the depth of top layer equal to 4D as indicated by rate of increase in IFR values. Similar behaviour has been observed in case of ESC as well. However, the performance improvement is found to increase at a marginal rate as can be seen from the Table 4. Hence, it can be said that the optimum depth of upper clay layer to achieve maximum increase in bearing pressure is 4D. The vertical displacement contours of OSC and ESC in layered clay is shown in Fig. 8 and 9. It can be observed that the displacement contours are longer in layered soil system as compared to homogeneous clay system. However, beyond the depth of 4D in layered soil system, the displacement contours are nearly same as that of homogeneous clay. Similar behaviour has been observed in

case of ESC as well. But displacement contours were found to be spread more along the column in case of ESC as compared to that of OSC.

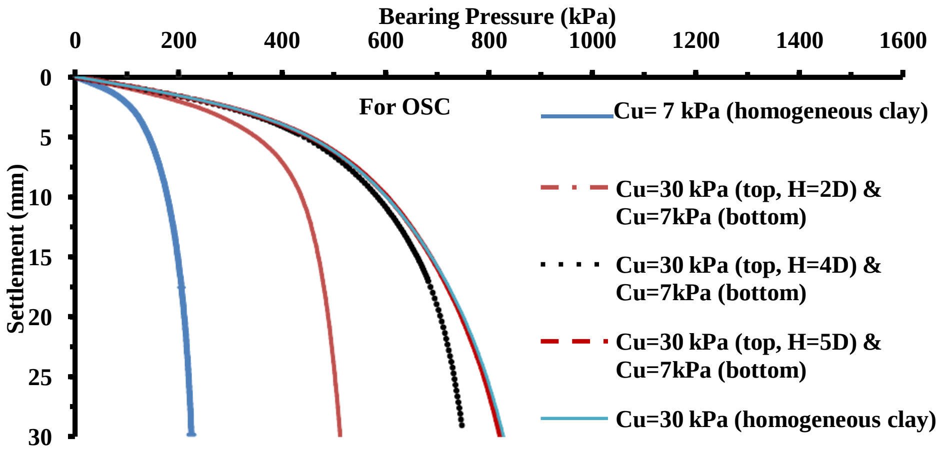

Fig. 6. Bearing pressure-settlement response of OSC in layered clay

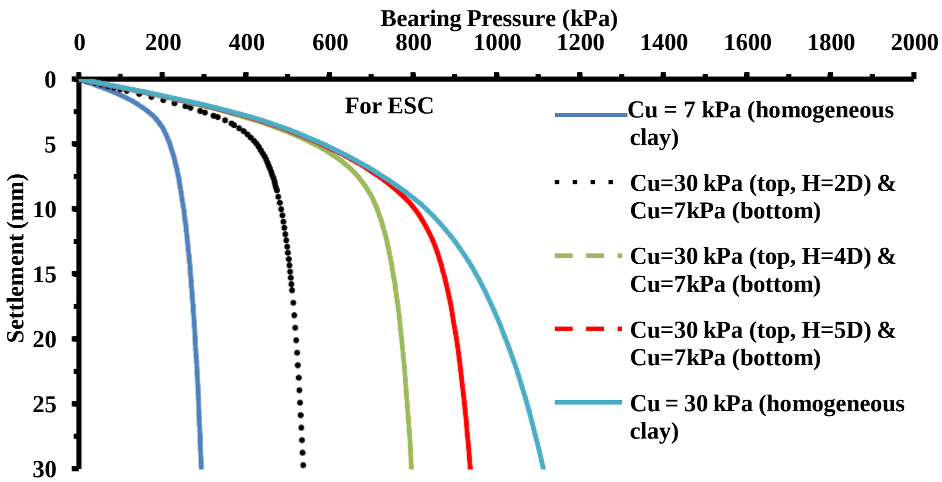

Fig. 7. Bearing pressure-settlement response of ESC in layered clay

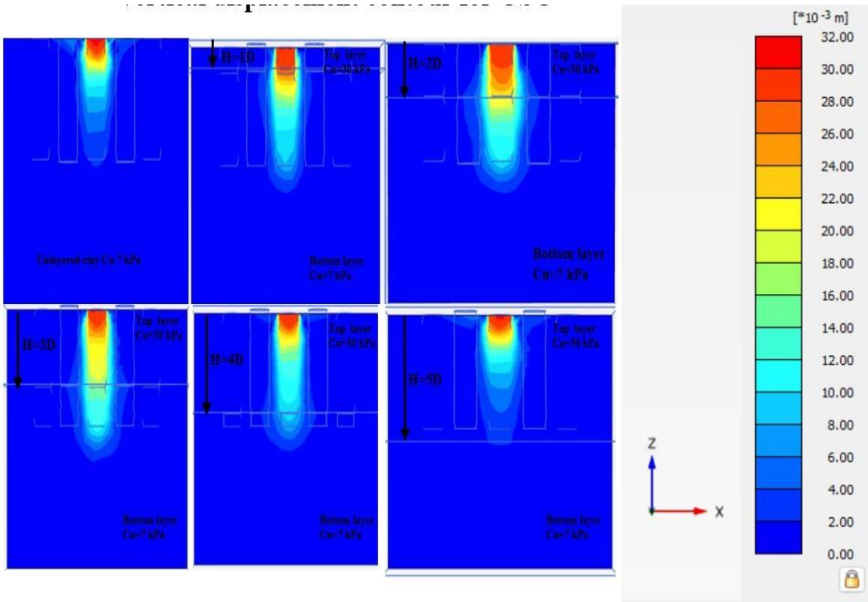

Fig. 8. Vertical displacement contours of OSC in layered clay

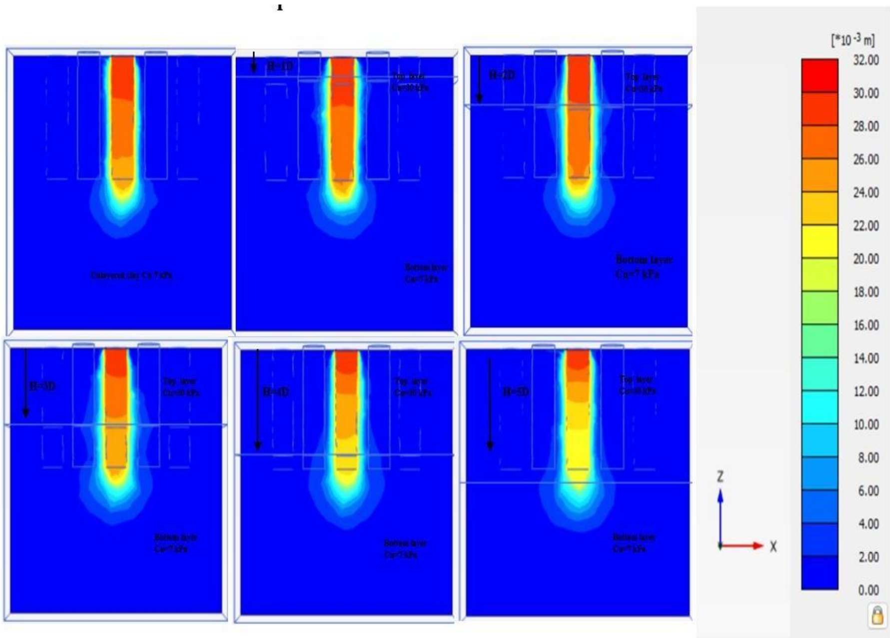

Fig. 9. Vertical displacement contours of ESC in layered clay

Table 3. Rate of increment of IFR with increase in top soil layer depth (H) in OSC

Sl. No.	H/D	Bearing Capacity (kN/m^2)	Improvement Factor Ratio (IFR)	Rate of increment (%)
1.	0	225	1.00	-
2.	1	362	1.61	61.0
3.	2	511	2.27	41.0
4.	3	655	2.91	28.0
5.	4	749	3.33	14.4
6.	5	825	3.66	10.0
7.	10	831	3.70	01.0

Table 4. Rate of increment of IFR with increase in top soil layer depth (H) in ESC

Sl. No.	H/D	Bearing Capacity (kN/m^2)	Improvement Factor Ratio (IFR)	Rate of increment (%)
1.	0	293	1.00	-
2.	1	408	1.39	39.00
3.	2	538	1.84	32.4
4.	3	681	2.33	26.6
5.	4	796	2.72	16.7
6.	5	937	3.20	10.3
7.	10	1115	3.80	18.7

3.5 Influence of friction angle of stone aggregates

The influence of variation in friction angle of stone aggregates for both OSC and ESC in layered soil system having top layer C_u = 30 kPa with depth of 4D and bottom layer having C_u = 14 kPa is presented in Fig. 10 and Fig. 11. From Fig. 10, it can be observed that the bearing capacity of OSC in layered soil system increases with increase in friction angle of stone aggregates. The increment observed is from 663 to 820 kPa when friction angle of stone aggregates is changed from 37° to 46°. This is because of the fact that more frictional resistance has been mobilized to counter the upcoming load as the friction angle of stone aggregates is getting increased. Similar behaviour has been observed in case of ESC but percentage increment is less as compared to OSC case. Even for lesser value of friction angle of stone aggregates, encasement provides more lateral confinement to the column which leads to an increased performance of the composite system.

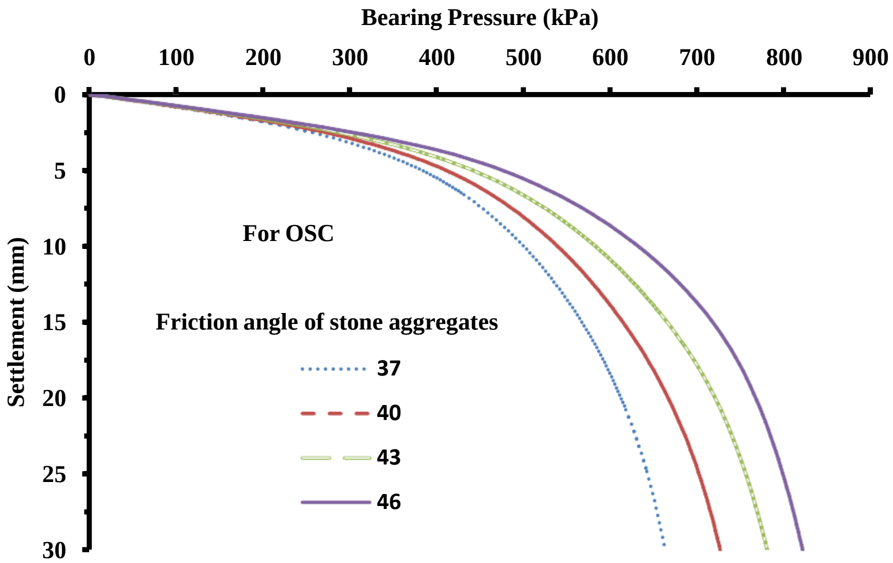

Fig. 10. Bearing pressure-settlement response of OSC for varying friction angle of stone aggregates

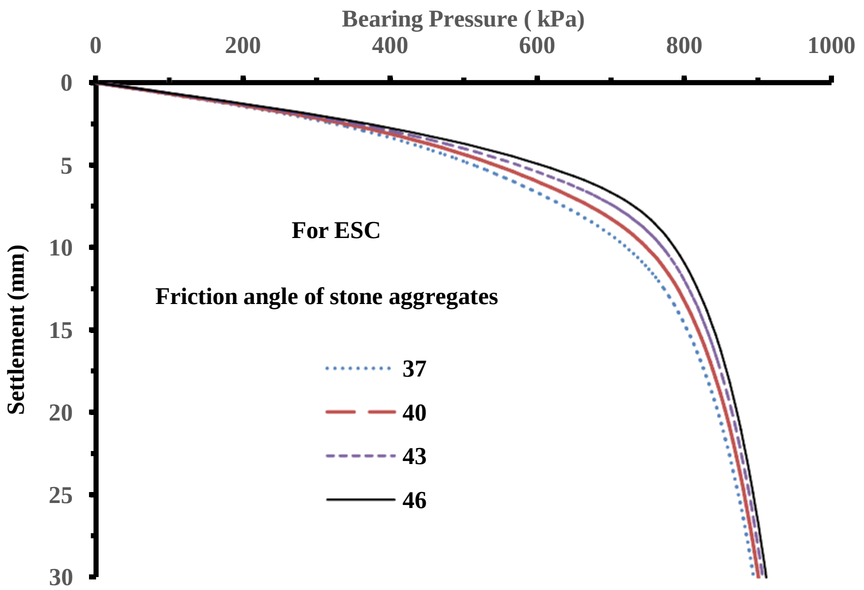

Fig. 11. Bearing pressure-settlement response of ESC for varying friction angle of stone aggregates

4 Conclusion

Numerical simulation of ordinary and encased stone columns have been done using PLAXIS^{3D} to analyze the influence of undrained shear strength of clay and friction angle of stone aggregates in a layered soil system. Based on the various results and analysis the following conclusions have been brought out.

1. It has been observed that the bearing capacity keep on increasing in all the three cases, namely, unreinforced clay, OSC reinforced clay and ESC reinforced clay. It is because of the fact the OSC in soil provides lateral confinement to upcoming load and encasement of OSC provides higher resistance to radial bulging of the same.
2. In OSC and ESC layered clay system, improvement was observed when the stiffer clay layer was above the weak clay layer. Further, best performance was observed when soft clay is replaced by clay having highest undrained shear strength (C_u = 30 kPa here).
3. For OSC in layered clay system, the bearing capacity increases with increase in the depth of top layer of clay (having higher C_u value than bottom one). Beyond a depth of 4D, the increase in bearing capacity was observed to be negligible. Therefore, it can be said that for optimum performance, a depth equal to 4D can be replaced with stiffer clay.
4. For ESC in layered clay system, the bearing capacity increases with increase in the depth of top layer of clay. Beyond a depth of 4D, the increase in bearing capacity was observed to be significant, but the rate of increment is very less. Therefore, the recommended top layer depth in ESC reinforced layered soil is 4D.
5. In layered clay system, the effect of friction angle of stone aggregates was observed to be significant in OSC, i.e., the bearing capacity increases with increase in friction angle. However, in case of ESC, the effect of friction angle of stone aggregates on bearing capacity of system is very marginal, i.e., very little increase was observed in bearing capacity with increase in friction angle.

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