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Pressure settlement behaviour of ring footing resting on geotextile encased stone column

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ABSTRACT

The present paper discusses the performance of clay bed reinforced with ordinary stone columns and geotextile encase stone columns using PLAXIS-3D. A surface ring footing having external diameter 200 mm and internal diameter 80 mm was used in the numerical modelling. In addition, vertical concentric loading was applied in the surface ring footing to produce its pressure-settlement behaviour. Moreover, a parametric study was carried out by varying the number (0, 4, 5 and 9), length (200 mm, 300 mm and 400 mm), diameter (32 mm and 50 mm) and geotextile encasement length (150 mm and 300 mm) of stone columns. From the numerical modelling it was observed that the inclusion of ordinary stone column in clay bed improved its load-carrying capacity significantly, i.e., up to 3 times, and to increase it even further, geotextile encasement is very useful.

Keywords: *Clay bed, Circular footing, Stone column, Geotextile, Numerical analysis.*

Notations:

FEM:	Finite Element Method	Nc:	Number of Stone columns
OSC:	Ordinary Stone Column	Lr:	Length of stone column
RSC:	Reinforced Stone Column	Dc:	Diameter of stone column
E:	Elastic Modulus	Dof	Diameter of Ring footing
M:	Poisson's ratio	Lgc	Length of Encasement
BCR:	Bearing Capacity Ratio	Φ:	Angle of internal friction of soil

1. Introduction

Shallow foundations resting on soft soil can have detrimental effects such as excessive settlement, differential settlement and upheaval etc. which can seriously damage the superstructure. Moreover, providing deep foundations in such a case is highly uneconomical hence, not recommended. Therefore, the alternative solution is either to replace the existing soil with a more suitable soil or improve the in-situ properties of soil. Former option being uneconomical and tedious, the latter option is much more suitable. Improving the in-situ soil properties is termed as ground improvement techniques. These techniques have four major categories: mechanical, hydraulic, blending and reinforcement methods.

Ground improvement using stone column is a novel technique which not only improves the load carrying capacity of soft soil but reduces the settlement also. The stone column was initially used for ground improvement in 18th century. The pile-sized hole was filled with crushed aggregates. It was first utilized as military foundations in Bayonne, France, which were supported by 0.2 m diameter and 2 m column. Bouazza et al. [1] reported that a partial envelope length on the steel column, increasing the embedded length reduces vertical strain for both a single and a group of stone columns. A full encasement length increases column stiffness and reduces strain. Chenari et al. [2] examined the stifling and bearing capacity of stone columns experimentally and quantitatively. Experiments showed that the upgraded system's bearing capacity ratio increases with the number of columns. Stone column increased loose sand carrying capacity by 2.75 times. McCabe et al. [3] stated that 40% plasticity index (PI) soil is ideal for stone column installation. Sometimes soil with a plasticity index of 40% helped vibro stone columns work better. When installing stone columns, recent clay fills might enhance the ground. Stone columns will settle quicker, but total settling will compensate. Hughes et al. [4] reported that the usage of stone columns reduces settlement and improves bearing capacity. Stone columns were more environmentally friendly when they utilize dry feed instead of wet feed and recycled aggregates instead of primary aggregates due to their residual strength. When stone columns were subject to static loads, increasing load-bearing capacity and lowering soil compression rate were observed by Ashour et al. [5]. However, cyclic loading behaviour has received less attention, especially in transport sectors like railroads. The stone columns under cyclic load on clay soil lowered threshold stress and pore water pressure by draining.

Performance enhancement of soft soil using stone column technique was initiated by few researchers in the mid-1970s [4, 6-8]. Hughes and Withers [4, 8] described the use of stone columns for improving the

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strength and consolidation characteristics of soft clays with the aim of studying the behaviour of soil and columns separately. For this, radiographic techniques were used and then patterns of vertical and radial deformations were observed. From their study, it was found that the load carrying capacity of isolated column, if loaded on its top, depends on the surrounding soil. Moreover, it was concluded that the stone columns are more suitable for lighter loads than very heavy loads due to its deep load transference limitation. Hughes et al., [4] conducted a field trial on the performance of stone columns installed in soft clay. It was found that the ultimate load carrying capacity of isolated stone column depends on the friction angle of material used to form stone column, size of stone column and the lateral resistance to deformation offered by the surrounding soil. It was found that the column substantially improved the load carrying capacity of clay bed. Engelhardt and Golding [6] proposed a solution in the form of stone columns for the construction of sewage treatment plant over a seismic vulnerable area containing deep, soft cohesive soil. To do so, large scale field tests were conducted. From the test results an improvement in the shear strength properties of the soil was observed.

As one of the limitation of stone column is its inability to carry heavy loads, researchers, now-a-days, are reinforcing these columns with encasement using geosynthetics [2, 9-18] . Murugesan and Rajagopal [9] used a numerical technique to model stone columns and the encasement. Form the test simulation it was observed that the encasement of stone columns increases their load-carrying capacity significantly. Castro and Sagaseta [10] used and analytical technique to study the deformation and consolidation around encased stone columns. An interesting yet important point was mentioned that the loading on stone column should be restricted equal to or less than the tensile strength of the material used as encasing. Miranda et al. [11] had his research focused on finding out the critical length of encased stone column for its optimum performance. To achieve this, two- and three-dimensional finite element analyses were carried out. From the investigation it was found that the critical length of encasement is slightly less than the critical length of stone columns. In addition, there exist a relationship between the critical column length and the extent of plastic deformation of soil, which can become useful input while designing the encased stone column system. Chen et al. [12] conducted a series of centrifuge model tests were conducted to study the performance of geosynthetic encased stone columns-supported embankment resting over soft clay. From the testing it was observed that the encasement of stone column has multiple advantages: settlement reduction, acceleration in pore water pressure reduction and improvement in load-carrying capacity. Very recently, Xie et al., [13] tested the performance of encased stone columns using different encasing materials: stainless-steel wire mesh, geogrid and geotextiles. No doubt, the encasement improved the load carrying capacity and also reduced the settlement, surprisingly, the results of geotextiles as an encasement gave much better response than the other two types of encasing materials.

The performance of stone columns in soft soils can be improved by wrapping a geosynthetic column. Geotextile covers give complete side containment and rigidity and strengthen the columns of stone. Furthermore, if the stone columns are coated with geosynthetic systems, the vertical drainage function of a stone column is supported. This is another crucial geotextile function, to prevent particles from being combined with stone components. Mecabe, et al. [3] examined the performance of stone columns with stiff footings. They analysed this study using a finite element approach and soil hardening model. Stone columns distant from the centre perform better with shorter lengths (l/d<10) compared to those in the centre. Column stiffness depends on the number of supporting columns. Stone columns had performed better beyond l/d=10. Marto et al. [19] examined the effects of encasing soft clay-based stone columns using finite element method. The results of regular and enclosed stone columns were compared. They also observed that larger stone columns may handle more weight than smaller ones. Encasing the stone column reduces lateral bulging by confining it and improving its load capacity and stiffness due to geogrid's elastic modulus. Moayed et al. [20] validated computational finite element models to compare two small-scale settlement-controlled loading experiments on stone columns. The geotextile encasement increases bearing capacity by 40%. After numerical modelling, complete models of single and group stone columns were evaluated for static progressive displacement. Results showed a lateral maximum deviation from the stone column top at D=0.3L. Due of low upper confining pressure, the stone column cannot receive adequate lateral pressure. Ali et al. [21] tested kaolin soil and built a 0.3-m-diameter, 0.6-m-deep cylindrical tank. The bearing capacity of geosynthetic-encased stone columns has improved significantly. Smaller stone columns were more effective. Geosynthetics may be used in the upper zone (nearer to zero depth) when stone columns are bulging. FEM was used to compare laboratory testing on steel and geosynthetic-encased columns [22]. For clay stone columns, use a 300-mm-wide sand pad. Sand layer evenly deducts foundation load. Stone columns on soft soil generally collapse. This difficulty is best solved using geosynthetic materials.

Ibrahim et al. [23] stabilized the soft clay with stone piles below the ring footing. The stone piles with ring footing showed a significant increase in bearing capacity below 1.5B. According to Engelhardt et al. [6] the critical column length is the smallest column that can support the maximum charge without improvement in load capacity. However, additional stone columns may be needed for settlement management. Hughes and Withers [4] found that geometric effect is especially visible in determining the stone column's failed mode, thus if the diameter ratio is smaller than four, the stone column would fail by end bearing rather than bulging.

Although the behavior of circular footings on stone columns is extensively recorded, there is a significant deficiency of research examining the performance of ring footings, which can provide material efficiencies and comparable performance at certain diameter ratios. Surprisingly, ring footings can perform equally well as that of circular footing and many researchers had confirmed it from their research findings, if the ratio of internal diameter/radius to the external, radius ratio, is 0.4 [24, 25]. Therefore, with this in view, the aim of this present paper is to study the load-settlement behaviour of ring footing resting on ordinary stone column (OSC) and encased stone columns (ESC) reinforced clay bed using PLAXIS-3D. The variable parameters are the number of stone columns, length of the stone column, diameter of stone column and length of encasement of stone column.

2. Problem definition and model parameters

In the present work, the pressure-settlement behaviour of a ring footing resting on clay bed reinforced with ordinary stone column and geotextile encased stone column subjected to a vertical concentric load was examined numerically using Plaxis 3D. Kaolin clay bearing Specific gravity, cohesion, modulus of elasticity, Poisson's ratio, dry unit weight and bulk unit weight of 2.66, 30 kPa, 5,500 kPa, 0.42, 15.56 kN/m^3, and 19.45 kN/m^3 was used, respectively [22]. The ratio of stone-column diameter to the grain size of fill material should lie in the range of 12-40 [4]. Considering this in view, the crushed stone aggregates of size ranging between 2-10 mm were used to prepare the stone column.

Maximum dry unit weight, minimum dry unit weight, specific gravity, coefficient of uniformity (Cu), coefficient of curvature (Cc) of stone aggregates, modulus of elasticity of aggregate were 16.95 kN/m^3, 14.35 kN/m^3, 2.7, 2.25, 1.62, and 55000 kPa, respectively [22]. Based on the gradation characteristics, the material used to make stone column was classified as poorly graded gravel (GP) according to USCS (Unified Soil Classification System). For encasing the stone column, nonwoven polypropylene geotextile of thickness, secant stiffness at ultimate strain, and ultimate tensile strength equal to 1.4 mm, 15 kN/m, and 10 kN/m, respectively was used. The ring footing of 10 mm thickness and of two diameters 80 mm (internal) and 200 mm (external) were used as shown in Figure 1. For modelling, the Poisson's ratio of footing was taken as 0.2. In this study diameter of stone column was taken as 32 mm and 50 mm. The length of stone column was varied from 200 mm, 300 mm and 400 mm. The number of stone column was taken as 0, 4, 5, and 9. The stone Column was encased up to half length and full length. The detailed of parameter varied in this study is summarised in Table 1. The numbers of stone column (4, 5, and 9) were taken to represent a small group, a common pentagonal pattern, and a denser group to study group efficiency effects. Length-to-Diameter Ratio (Ls/Dof) of 1, 1.5, and 2 were taken to analyze the transition from floating to end-bearing column behavior and to identify a critical length for this specific configuration. Diameter Ratio (Ds/Dof) of 32 mm and 50 mm were selected to give Ds/Dof ratios of 0.16 and 0.25, which are typical for stone column design and allow for the investigation of area replacement ratio effects. Figure 2 shows arrangement of 5 ordinary stone columns of 50 mm diameter and 300 mm length with ring footing. Figure 3 reveals ring footing with Ordinary stone column (OSC), half encased stone column (ESC) (Lr/B = 0.75) and fully encased stone column.

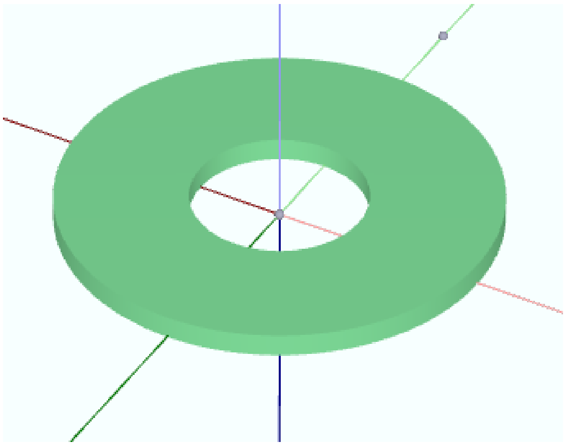

Figure 1. Dimension of ring footing modelled.

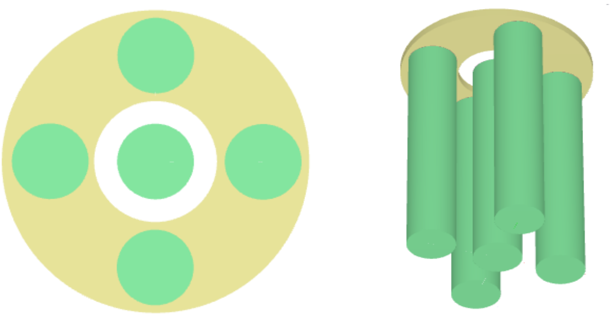

Figure 2. Stone columns of 50 mm with Ring footing at L/B=1.5.

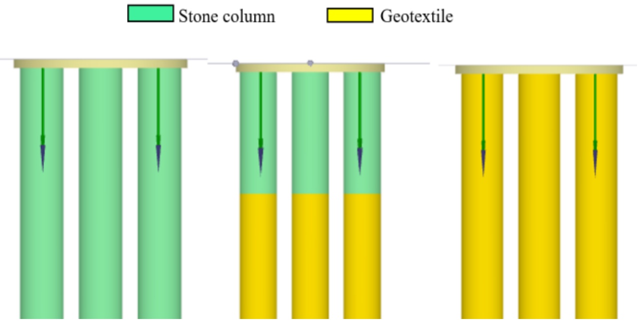

Figure 3. Ring footing with (a) Ordinary stone column (b) half encased stone column (Lr/B = 0.75) and (c) fully encased stone column.

3. Finite element meshing and boundary condition's

The clay bed model of dimensions 5B from the edge of footing in both X and Y direction was created. Keeping the minimum stresses at the boundaries in view, the boundaries of the model were selected. At the boundaries of the model, general fixities condition was imposed. The meshing in Plaxis software consists of different types of schemes such as very coarse, coarse, medium, fine and very fine. For the analysis, medium meshing of 15-noded triangular element was used. The Mohr-Coulomb model was adopted to model the soil behaviour. As per guideline of IS 15284, the dimensions of footing should be twice that of column diameter. For this study, the diameters of the footing and stone column were kept constant. The interface strength factor between stone column and clay bed was not considered. The exclusion of interface features between the stone column and the clay is recognized as a simplification that might impact the precision of the anticipated bulging behavior and load transmission mechanism. The numerical model was validated against the centrifuge test results of Chen et al. [12] for a single encased column, showing a close match in load-settlement response observed in this work.

4. Results and discussion

In this paper, the results are discussed in the form of bearing capacity ratio (BCR), Equation 1.

$$BCR = \frac{P_{OSC} \text{ or } P_{ESC}}{P_{ur}} \qquad (1)$$

where,

P_{osc} = pressure corresponding to a particular settlement level for OSC or ESC reinforced clay

P_{Esc} = pressure corresponding to the same settlement level for unreinforced clay

This ratio, Equation1, is useful in quantifying the performance improvement in load-carrying capacity of clay bed on reinforcing it with OSC or ESC. Moreover, simply multiplying PR with 100 will give us percent improvement in the load-carrying capacity of the clay bed.

4.1. Effect of number of Stone columns

From the Figure 4, it can be clearly seen that with the increase in number of columns, the load-carrying capacity increases. For Nc = 4 of ordinary stone columns of 32 mm diameter, 38.24% increase in load-carrying capacity was observed. Similarly, the load-carrying capacity of group of stone columns increased by 56.37% and 63.18%, respectively for 5 and 9 number of stone columns. Impressive improvement in the load carrying capacity for Nc=5 can be seen in Figure 4 with the addition of encasement to the stone columns as compared to the ordinary stone columns. Sivakumar, et.al (2004) also reported an increase in the load-carrying capacity of encased stone-column compared to the ordinary stone columns. For 50 mm diameter stone columns, there was 46.55% increase in bearing capacity for Nc=4, and for Nc=5, the increment was 62.06%. Similarly, for 9 stone columns the increase in bearing capacity was 68.96%. An exception has been noticed from the Figure 4 (a) and Figure 4(b) i.e. the load-carrying capacity of the ordinary stone column at Nc=9 is greater than that of geosynthetic encased stone column at Nc=4. It is obvious that increasing the number of columns leads to an increase in the bearing capacity in the region below the footing. The horizontal displacement of the column lowers with increased number of columns, and this drop in horizontal displacement rises significantly when the column is packed with geotextile material. For unreinforced clay, the load-carrying capacity is quite low, but an improvement is observed when 4 stone columns were installed. This behaviour can be attributed due to the provision of confinement and improve shear strength. Further raising ESC number to 5, the carrying capacity compared with unreinforced clay increases.

Table 1. Parameter of ordinary stone column and encased stone column varied.

Stone column	Number of columns (Nc)	Diameter of stone Column	Length of stone column	Encasement	
				Full length	Half length
Unreinforced clay	-	-	-	-	-
Ordinary stone column	4, 5, 9	32, 50	200, 300, 400	-	-
Encased stone Column	4, 5, 9	32,50	200, 300, 400	200, 300, 400	100, 150, 200

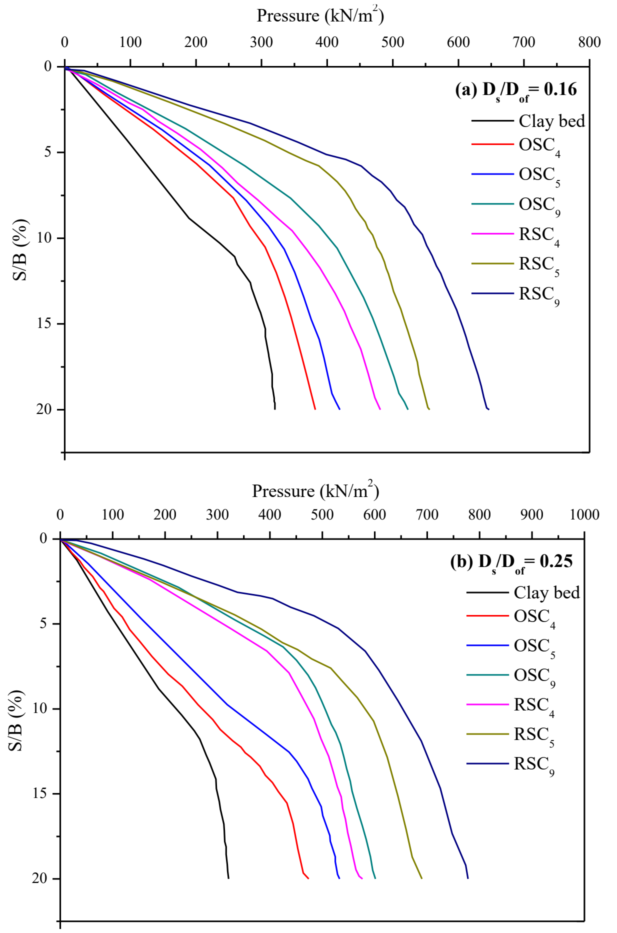

Figure 4. Pressure – settlement behaviour of ring footing resting on OSC and RSC at L_s/D_{of} =1.5 (a) D_s/D_{of} = 0.16 (b) D_s/D_{of} =0.25.

Figure 5 illustrates the BCR values corresponding to 5%, 10%, 15%, 20% of S/B ratio at L_s/D_{of} = 1.5. As a result, the rise in the number of columns demonstrates a considerable rise in BCR value and a rise in the settlement BCR value. RSCs lessen lateral bulging as compared to OSCs because geosynthetic materials provide better lateral confinement. By encasing a full-height OSC with geotextile (RSC), the enhancement of BCR obtained is 4.2 times of untreated clay for 5% settlement ratio. But the value of BCR is decreasing as we move from 5% to 20% of S/B ratio. There is a huge margin in the bearing capacities of the clay bed and OSC, this means installation of stone columns has high impact on the load bearing capacity. At lower depths RSCs had somewhat more lateral expansion. That might have happened as a result of the engraving effects of the applied surface load deeper into the column. Ultimate bearing capacity obtained at full geotextile encasement was 2.7 times the ordinary stone column. It is obvious that in the column the lateral strain is larger than that in clay with no strengthening and half enclosed columns compared to the comparable lateral stress.

Further, the impact of geosynthetic encased on the stone columns was quantified by reinforcement ratio. It is defined as the ratio of bearing capacity of geosynthetic encased or reinforced Stone column to the bearing capacity of unreinforced (ordinary) stone column. Its significance shows the impact of providing reinforcement or encased on the stone column.

It can be expressed as:

$$R.\ R= \ = \frac{Qesc}{Qur}$$

where R.R = Reinforcement Ratio

Qesc =Bearing capacity of reinforced/ encased stone column

Qur = Bearing capacity of unreinforced stone column.

Three types of models considered i.e. Nc=4, 5 and 9. Where each reinforced model of stone columns is compared with its own unreinforced stone. Table 2 reveals the effect of encasement on the reinforcement ratio with respect to the number of stone columns. The peak value of reinforcement ratio is obtained at 2.188 for Nc=9 at 5% of S/B ratio. But improvement in reinforcement ratio from Nc =4 to Nc=5 is far better than that from Nc=5 to Nc=9 in case of encased stone columns.

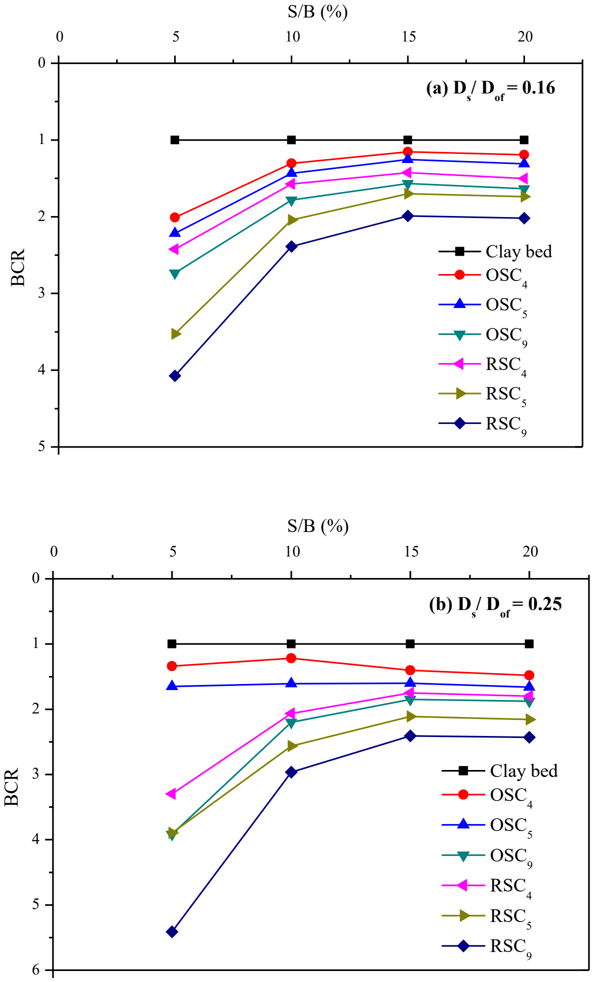

Figure 5. BCR v/s Settlement ratio of ring footing resting on OSC and RSC at L_s/D_{of} =1.5 (a) D_s/D_{of} = 0.16 (b) D_s/D_{of} =0.25.

Table 2. Reinforcement ratio of ring footing resting on OSC and RSC at L_s/D_{of} =1.5

D_s/D_{of}	N_c	S/B (%)			
		5	10	15	20
0.16	4	1.20	1.20	1.23	1.25
	5	1.59	1.42	1.35	1.32
	9	1.49	1.33	1.26	1.23
0.25	4	2.46	1.69	1.24	1.21
	5	2.36	1.59	1.31	1.29
	9	1.38	1.34	1.30	1.29

4.2. Effect of length of stone columns

To assess the effect of length of stone columns, pressure – settlement behaviour corresponding to 5 number of stone columns were taken as shown in Figure 6. An increase in bearing capacity was observed with increase in L_s/D_{of} ratio. At D_s/D_{of} = 0.16, for OSC, increase in bearing capacity is 12.96% for L_s/D_{of} =1 and 20.68% for L_s/D_{of} =1.5 and 38.71% for L_s/D_{of} = 2. Similarly for RSC, increase in bearing capacity is 48.27% for L_s/D_{of} =1 and 56.37% for L_s/D_{of} =1.5 and 75.86% for L_s/D_{of} =2, respectively.

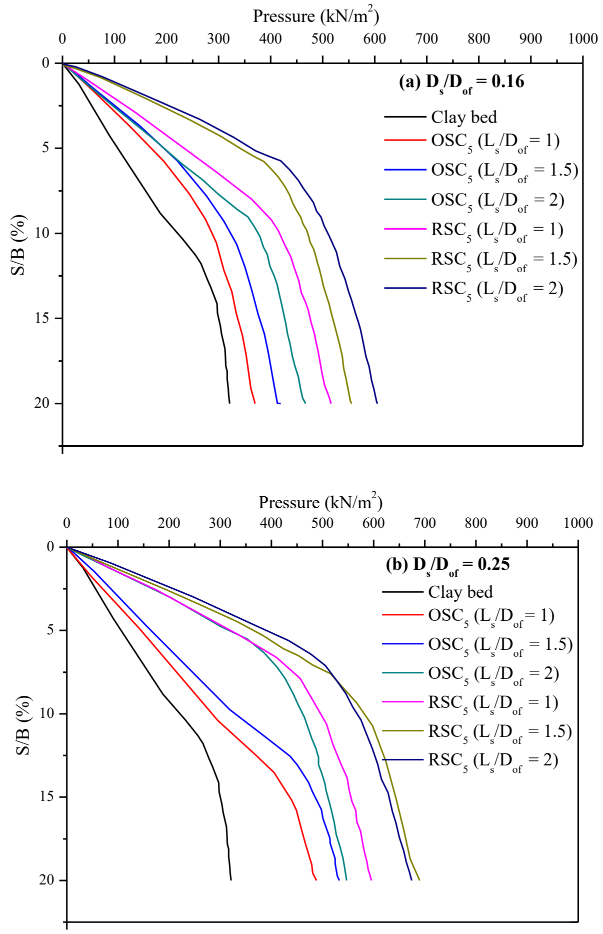

Figure 6. Pressure – settlement behaviour of ring footing resting on OSC and RSC at Nc = 5 (a) D_s/D_{of} = 0.16 (b) D_s/D_{of} =0.25.

Similar trend was seen for D_s/D_{of} = 0.25. The percentage increase in the bearing capacity with respect to the clay bed is slightly higher that the stone column of 32 mm diameter. For OSC, increase in bearing capacity is 27.86% for L_s/D_{of} =1 and % for L_s/D_{of} =1.5 and 33.71% for L_s/D_{of} =2. Similarly for RSC, increase in bearing capacity is 48.27% for L_s/D_{of} =1 and 62.06% for L_s/D_{of} =1.5 and 75.86% for L_s/D_{of} =2, respectively. But on considering the values of ordinary stone columns at L_s/D_{of} =2 and geosynthetic encased stone column at L_s/D_{of} =1 shows similar almost similar results at the initial loading stage.

The influence of the column length on the bearing capacity ratio (BCR) for S/B ratio of 5%, 10%, 15%, 25% is presented in Figure 7 for 5 columns were installed on the ring footing for D_s/D_{of} = 0.16 and D_s/D_{of} = 0.25. The effect of raising the length of RSC is seen in Figure 7. Here, 5 stone columns with each of 50 mm diameter were installed on ring footing. The results demonstrate that the length of L_s/D_{of} = 1 is 2.4 times that of unreinforced clay, L_s/D_{of} =1.5 is 3 times that for untreated clay, and the length that increases to L_s/D_{of} = 2 the length is 3.4 times that of untreated clay. With the increase of the column length, the skin friction generates a bigger fraction of its total ability and may be mobilised at significantly lower settlements. Optimum improvement is attained in the loading capacity of L_s/D_{of} =1.5, therefore the column length is L_s/D_{of} =1.5 more effective than the unreinforced clay than L_s/D_{of} =1 and L_s/D_{of} =2. Overall, the optimal improvement in BCR is achieved at L_s/D_{of} = 1.5.

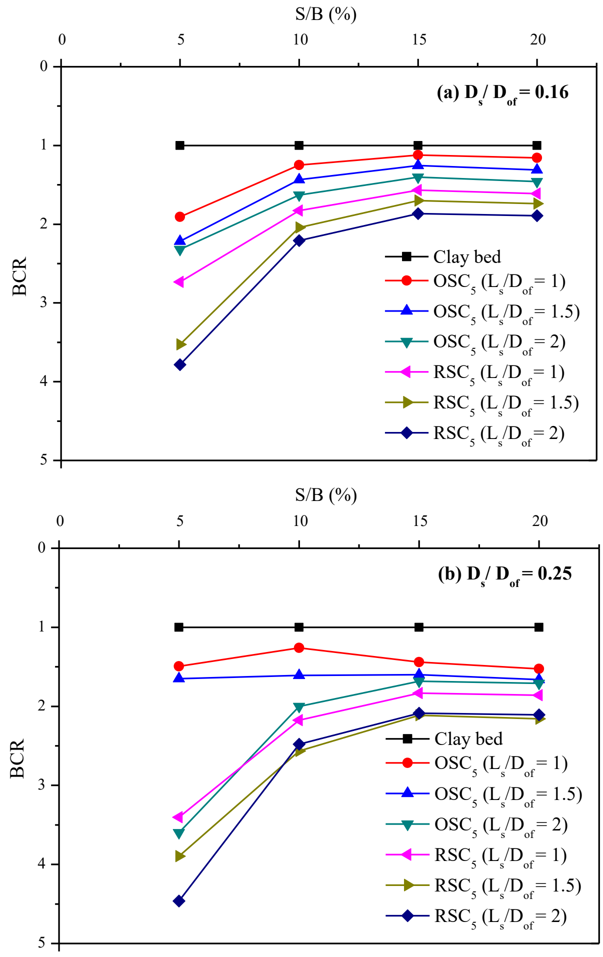

Figure 7. BCR v/s Settlement ratio of ring footing resting on OSC and RSC at Nc = 5 (a) D_s/D_{of} = 0.16 (b) D_s/D_{of} = 0.25.

The effect of change of length of column on the reinforcement ratio is shown in In Table 3. The peak value of reinforcement ratio is achieved in case of L_s/D_{of} =1.5 at 5% of settlement ratio and then followed by L_s/D_{of} = 2 and then L_s/D_{of} =1. The peaked value obtained was 2.32. But reinforcement ratio in case of L_s/D_{of} = 1.5, decreases drastically and attain last position even lower than L_s/D_{of} =1.

4.3. Effect of change in diameter

Figure 8 (a) reveals the effect of change of diameter on the pressure – settlement behaviour at N_c = 5 and L_s/D_{of} = 1.5 for D_s/D_{of} = 0.16 and

0.25. It was observed that on increasing the diameter of the stone column the bearing capacity also increases. A 43% increment in load carrying capacity was observed for $D_s/D_{of} = 0.25$. Figure 8(b) shows variation of BCR with S/B ratio at $N_c = 5$ and $L_s/D_{of} = 1.5$. Table 4 shows the reinforcement ratio at $N_c = 5$ and $L_s/D_{of} = 1.5$.

Table 3. Reinforcement ratio of ring footing resting on OSC and RSC at Nc = 5

D_s/ D_{of}	L_s/ D_{of}	S/B (%)			
		5	10	15	20
0.16	1	1.43	1.46	1.39	1.39
	1.5	1.59	1.42	1.35	1.32
	2	1.63	1.35	1.32	1.29
0.25	1	2.27	1.72	1.27	1.21
	1.5	2.36	1.59	1.31	1.29
	2	1.24	1.23	1.23	1.23

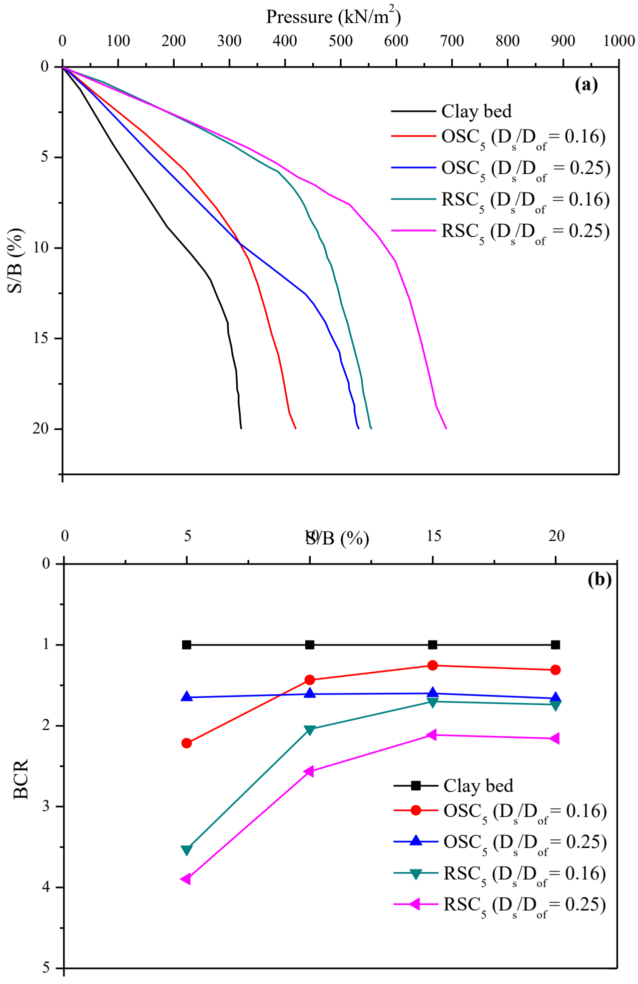

Figure 8. At Nc = 5 and Ls/Dof = 1.5 (a) Pressure – settlement behaviour (b) BCR v/s Settlement of ring footing resting on OSC and RSC.

Table 4. Reinforcement ratio of ring footing resting on OSC and RSC at $N_c = 5$ and $L_s/D_{of} = 1.5$

D_s/ D_{of}	S/B (%)			
	5	10	15	20
0.16	1.59	1.42	1.35	1.33
0.25	2.36	1.59	1.32	1.29

4.4. Effect of encasement

Figure 9 (a) reveals the effect of encasement on the pressure – settlement behaviour at $N_c = 5$ and Lge/ D_{of} = 1.5 for $D_s/D_{of} = 0.25$. Providing a layer of geotextile (Polyester) around the stone column definitely increase the load bearing capacity of stone column and also helps in reduction in the settlement. Encasement was provided as 0%, 50% and 100% i.e. one OSC and RSC (Lge/ D_{of} =0.75) and RSC (Lge/ D_{of} =1.5). These constraints were tested while the Lge/ D_{of} ratio is kept constant at 1.5 and 5 number of stone columns were installed. And these three cases were compared with the unreinforced clay bed. The lateral expansion in case of RSC near the ground has been substantially smaller than that of OSCs. Figure 9(b) shows variation of BCR with S/B ratio at $N_c = 5$ and Lge /D_{of} = 1.5 for $D_s/D_{of} = 0.25$. Table 5 shows the reinforcement ratio at $N_c = 5$, $L_s/D_{of} = 1.5$, and $D_s/D_{of} = 0.25$.

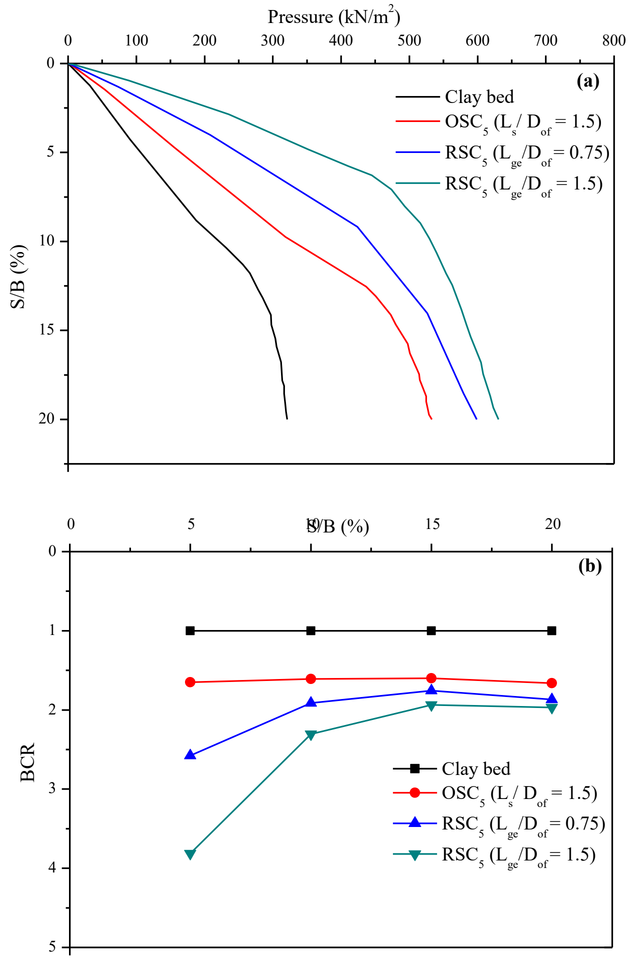

Figure 9. At $N_c = 5$, $L_s/D_{of} = 1.5$, and $D_s/D_{of} = 0.25$ **(a)** pressure – settlement behaviour **(b)** BCR v/s Settlement ratio of ring footing resting on OSC and RSC.

Table 5. Reinforcement ratio of ring footing resting on OSC and RSC at $N_c = 5$, $L_s/D_{of} = 1.5$, and $D_s/D_{of} = 0.25$.

L_{ge}/ D_{of}	S/B (%)			
	5	10	15	20
0.75	1.56	1.19	1.09	1.12
1.5	2.31	1.43	1.21	1.18

4.5. Comparison with literature

Table 6 shows comparison of BCR values obtained in the present study with existing literature. Ambily & Gandhi [22] focused

Table 6. Comparison of BCR Values from Literature.

Study	Type of column	BCR range	Key parameters
Ambily & Gandhi [22]	OSC	1.5 – 3.0 (approx.)	$s/d = 2-3, c_u = 7–30$ kPa
Murugesan & Rajagopal [9]	ESC	2.0 – 4.0 +	$J = 250–10{,}000$ kN/m, $d = 0.6–1.0$ m
Present Study	OSC	1.38 – 1.69	$N_c = 4–9, L_s/D_{of} = 1.5, D_s/D_{of} = 0.16–0.25$
	ESC	2.31 – 2.46	$N_c = 5, L_s/D_{of} = 1.5, D_s/D_{of} = 0.25$, full encasement

On stiffness improvement and stress concentration, which indirectly suggest BCR values between 1.5 and 3.0 for OSCs. Murugesan & Rajagopal [9] showed that encasement stiffness is a major factor in enhancing BCR, with values often exceeding 4.0 for high-stiffness geosynthetics. The present study BCR values for both OSC and ESC under a ring footing, shows OSC and ESC in range of 1.4–1.7 and 2.3–2.5, respectively. Reinforcement Ratio (RR) reached up to 2.46 for ESC. It reflects that the present study is align well with prior studies, confirming that encasement significantly improves performance, especially under ring footings.

5. Conclusions

This study discusses performance of clay bed reinforced with ordinary stone columns and geotextile encase stone columns using a numerical package PLAXIS-3D. The effect of number of stone columns, diameter of stone column, length to diameter ratio of stone column, external reinforcement by wrapping the stone column with vertical encasement of geotextile on the load carrying capacity was examined. The following conclusions are drawn from the results:

- By wrapping the stone column around the ordinary stone column with a geotextile without using any interface will increase the bearing capacity by 3 times.
- The encased stone column achieved an optimal performance at 5 number of columns, which enhances the bearing capacity for untreated clay by 3 times on comparing with untreated soil. With increase in number of stone columns there will be increase in the bearing capacity up to 9 columns.
- The rise in the L_s/ D_{of} ratio will cause the bearing capacity to improve. In all cases, however, at L_s/ D_{of} =1.5 stone columns had the highest efficiency in comparison to untreated soils. L_s/ D_{of} =1.5 i.e. 300 mm.
- Ultimately, the bearing capacity rises with the increase in column diameter, when stone column diameter changes from 0.16 B to 0.25 B.
- On the aspect of BCR ratio, it is noticed that BCR value is many times high at the first 5% of S/B ratio for both constraints i.e. number of column and effect of L_s/ D_{of} ratio. But in both the cases the BCR gradually decreases till 20% of Settlement ratio.
- Reinforcement ratio in case of RSC Lge/ D_{of} = 1.5 shows higher values at initial settlement ratio than Lge/ D_{of} =1 and 2. And afterwards at 15% Settlement ratio, the value of Lge/ D_{of} = 1 and 2 overtakes that.

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