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Research Article

Comparison of Encased Stone Column with Conventional Column for Varied Parameters through Experimental and Numerical Investigations

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Installation of stone columns is a widely used stabilization method in improving the characteristics of soft clays. In this study, laboratory tests were conducted to understand the influence of column number, spacing and encasement on the load-carrying capacity of the modified soil. Unit cell concept is adopted for column diameters of 25.4 and 31.75 mm, one and two numbers of columns and spacings of 50, 70, and 90 mm under the conditions of with and without encasement. In addition to the laboratory study, finite element analysis was also done for similar parameters to understand the modified soil's settlement characteristics and stress concentration ratio. Based on the analysis, it is understood that the load-carrying capacity increases with number of columns and spacing. Considering the influence of encasement, larger diameter columns showed a more significant increase in the load-carrying capacity when compared to the smaller diameter columns.

1. Introduction

Problematic soils are soils that have poor engineering characteristics which make them unsuitable and difficult to handle as an engineering material. The main problem of soils like expansive soil, black-cotton soil, marine clay, etc. is volume change. When the soil is fully saturated, the volume of the soil increases, which reduces with reduction in water content. But, the burgeoning of population has forced development of infrastructure and constructed facilities even on problematic soils. Such problematic soils can be stabilized by physical or chemical ground improvement techniques. Ground improvement increases the shear strength of the soil with reduction in settlement [1, 2].

Out of all the physical ground improvement techniques, installation of stone column(s) (SC) is a commonly preferred method for the improvement of soft problematic clays. This method came into practice in the middle of the 20th century [3]. The main purpose of this method is to improve the problematic soil's bearing capacity and to reduce the settlement [4–7]. The highlight of this technique is the increase in the soil's bearing capacity through drainage of pore water, as the column material dilates. The influence of fines in the stone column plays a vital role in settlement. The performance of SCs become insignificant, when the fines content is more than 20% [8]. Installation of SCs in soft soil embankments result in changes in the pore pressure and the total stress [7]. With increase in area replacement ratio, an increase in the undrained shear strength is noticed [9]. The use of stones in the column construction increases the strength of the soil by almost 40%, which is especially observed in construction of heavy structures. When the area ratio is less, there is a possibility of occurrence of bulging in single as well as group of stone columns [10, 11]. Field testing along with numerical simulation gives more confidence about the function of SC in a particular soil [12]. An envelope is required for the SC to reduce the problem of bleeding of stone chips into the soil and to provide more confinement; as the bulging happens in the top part of the column [13, 14].

To reduce this bulging effect, encasement is provided with suitable geosynthetic material to provide additional lateral confinement [15–19]. The introduction of geosynthetics in SCs reduces the settlement of the soil by 61% when used in stabilizing soft clays [19]. This also leads to an increase in the load-bearing capacity of the soil. Provision of encasement also gives additional passive resistance and confinement to the SC and increases the bearing capacity. When using the geosynthetic material, bulging of the column is taken care of and also the capacity increases with increase in diameter [20]. With an increase in diameter of the column, the developed stress in the column decreases [21]. The encased SC did not showcase a strain-softening behavior as exhibited by the conventional SC. In a set of columns, the maximum settlement is observed in the middle area between the columns [22] in lightly loaded structures.

By increasing the stiffness of the encasement material, the load bearing capacity of the SC is increased [23]. Reinforcing an embankment, addresses the arching effect and the load transfer mechanism of the geosynthetic columns. From a comparative study, it was concluded that the ideal encasement material was found to be geogrid for end-bearing column and geotextile for a floating column along with lateral geogrid reinforcement in the soil [24]. The encasement works well in an embankment of soft clayey soil; there is also a reduction in hoop tension [25–27]. By reinforcing the entire column, it improves the magnitude of load-carrying capacity of the column [28]; where the optimum length for encasement is four times the diameter of the column [29]. While considering the stress factor, it is observed that the resultant stress on the column top reduces by 65% when the diameter increases [30]. A laboratory study proved that the failure pattern of an encased SC is mainly punching failure [31]. All these studies showed encased SCs as a better alternative to improve the soil in less time and it also reduces the CO_2 footprint [3].

Major studies in SCs focus on either a single column or a simulated field model. Very limited number of studies are available in understanding the behavior of encased SCs with varied diameter (D) and spacing (S) in a group. In order to address this gap in literature, the present study was conceived wherein a laboratory study focusing on varying the diameter, spacing, and encasement of a group of SCs was conducted. A numerical evaluation was also done using a finite element tool (PLAXIS 2D) to understand the settlement and stress concentration values for the varied parameters.

2. Material Properties and Methodology

2.1. Properties of Materials. An inorganic, intermediately compressible clay was used for the test; it was taken from a locally available cohesive soil deposit from Chennai, India. The sample was dug from the shore of a lake to a maximum depth of 1 m; after excavating the soil sample, it was then transported to the laboratory and the visible organic remains of the soil was manually removed and air-dried. The properties of the soil are given in Table 1. The stone chips used in the experiment are of the average size of 5 mm, passing through Bureau of Indian standards (BIS) sieve of size 10 mm and retained in the BIS 4.75 mm sieve.

Table 1: Properties of soil.

Properties	Indian code	Values		
Specific gravity	[32]	2.57		
Particle size distribution: Gravel, Sand, Silt and clay	[33]	0.28	43.64	56.07
Liquid limit (%)	[34]	43.5		
Plastic limit (%)	[34]	29.37		
Plasticity index (%)	[34]	14.13		
Maximum dry density (kN/m^3)	[35]	16.3		
Optimum moisture content (%)	[35]	12.63		
Classification of soil	[36]	CI		

2.2. Methodology- Unit Cell. Unit cell concept was used to simulate the SC in cohesive soil [6]. The stone chips used for making the SC had an average particle size of 5 mm. In this study, two diameters of 25.4 mm (1 inch) and 31.75 mm (1.25 inch) were chosen to model a SC. Air-dried soil sample was mixed with water to achieve a water content of 40% and kept aside for 2 days to obtain a uniform consistency. The california bearing ratio (CBR) mold was considered as a unit cell; a sand layer was laid at the bottom of the mold to a minimum thickness to facilitate the drainage condition. Then poly vinyl chloride (PVC) pipes with internal diameters 25.4 mm (D1) and 31.75 mm (D2) were selected and kept in the desired location of the mold. The cohesive soil kept aside for 2 days was then filled in the CBR mold of 150 mm diameter and 125 mm height, layer by layer. Once the cohesive soil was filled in the mold, the stone chips of 5 mm size were filled in the PVC pipe and compacted while the pipe was slowly withdrawn. When the SC reached the height of 125 mm, the PVC pipe was removed. Another layer of sand was laid on the top as well (Figure 1) similar to the methodology adopted earlier [37].

To facilitate the encasement, a geotextile is tightly stitched to the PVC pipe and used to construct the SC using the same procedure as mentioned above. Once the column is made, the PVC pipe is removed leaving the SC inside the encasement.

2.3. Parametric Study. Considering the previous studies, the parameters varied were diameter, spacing, and encasement under same consistency of the cohesive soil (0.2). Table 2 shows the detailed parameters involved in this study with its notation.

3. Finite Element Analysis

A finite element modelling (FEM) tool PLAXIS 2D was chosen to model the SC with and without encasement [38]. The results obtained from the analysis is an elastoplastic solution of stress found in the SC and the soil based on axisymmetric analysis. To understand the behavior of multiple columns, the behavioral study involves both the SC in the analysis

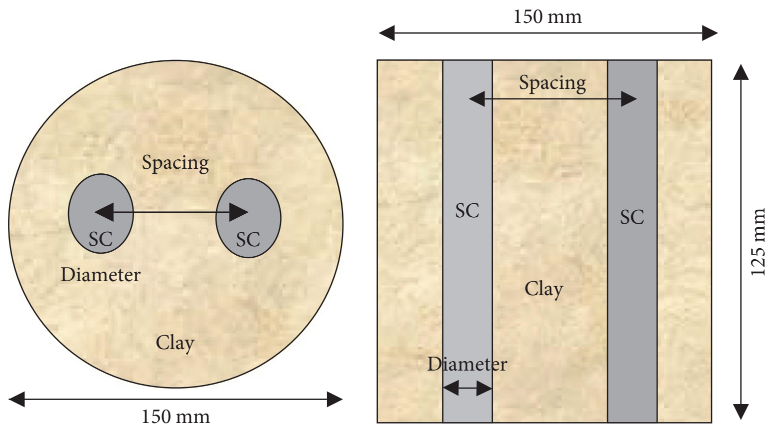


Figure 1: Schematic representation of SC.

Table 2: Parametric study.

Diameter (mm)	Number	Spacing (cm)	Encasement	Notation
25.4	2	5	Yes	DS15Y
25.4	2	5	No	DS15N
25.4	2	7	Yes	DS17Y
25.4	2	7	No	DS17N
25.4	2	9	Yes	DS19Y
25.4	2	9	No	DS19N
31.75	2	5	Yes	DS25Y
31.75	2	5	No	DS25N
31.75	2	7	Yes	DS27Y
31.75	2	7	No	DS27N
31.75	2	9	Yes	DS29Y
31.75	2	9	No	DS29N

(Figures 2(a) and 2(b)); however, the results obtained from the analysis belong to the bisected model.

The soil was modeled as a Mohr-Coulomb material, with a modulus of 4,500 kPa for clay and 45,000 kPa for the SC, with the shear strength of the clay as 25 kPa, angle of internal friction of the SC as 38° and poisson's ratio (μ) as 0.33. The geotextile is modeled as an elastoplastic material and an interface element of $R_{int} = 1$ was used.

After the model was framed, fine mesh was generated with no water table and initial stress was simulated. In the calculation phase, under plastic analysis, initially, the load was not activated. The load was applied over the SC under uniform distribution similar to the experimental work.

4. Results and Discussion

The ultimate load was calculated from the load–settlement curve by drawing tangents to it (Figure 3). Tests were carried out for two diameters, 25.4 mm and 31.75 mm, with and without encasement for single and double columns. It is observed that when the diameter increases from 25.4 mm to 31.75 mm, the load-carrying capacity of the single column increases by 1.5 times. With the provision of encasement, the capacity of the single SC increases by 4.6 times for 25.4 mm SC and 3.6 times for 31.75 mm SC.

In practice, the SC is placed in a group in the weak soil to enhance the permeability and shear characteristics of the soil. To simulate it, laboratory tests were also done with varied spacing for a pair of columns. The ultimate load carried by DS15N, DS15Y, DS17N, DS17Y, DS19N, and DS19Y are 2.25, 3.01, 3.10, 3.54, 3.28, and 3.63 kN, respectively. Similarly for DS25N, DS25Y, DS27N, DS27Y, DS29N, and DS29Y are 2.51, 7.43, 3.15, 8.18, 3.72, and 8.32 kN, respectively (Figure 4). It is observed that the load increment with an increase in spacing between the SCs is minimum. It ranges between 1.18 and 1.48 times for the spacings of 7 and 9 cm, respectively, when compared with the spacing of 5 cm, for both the diameters. With an increase in spacing, the increase in load is not significant and it is linear. For an increase in diameter, the ultimate capacity has a linear increase under no encasement condition.

The presence of encasement increases the ultimate load. The increase in load capacity is by almost 2.21–3.63 times for D1 with 5, 7, and 9 cm spacing, when compared to SCs without encasement. Similarly, for D2 with 5, 7, and 9 cm spacing, the load capacity increases by 2.51–8.32 times that of SCs without casing for the same diameter. The presence of geotextile as encasement increases the modulus of the column. When the modulus increases, the stiffness of the soil composite increases; which as a consequence, increases the bearing capacity of the weak soil. This makes the soil more suitable for further loading without much settlement. The additional advantage of having geotextile is to have better filtration characteristics of the modified soil with SCs. However, the filtration characteristics were not studied in this work.

From Figure 5(a), it is observed that the occurrence of failure is immediate for the conventional SC; whereas with the presence of encasement, the load-bearing capacity increases from the beginning and it shows, it can withstand more axial stress and the failure happens much later, i.e., it happens beyond 2.5 times of the load capacity of conventional SC. For varied spacing, the SC with encasement indicates that the modified soil is able to take more load, however, the test is terminated much earlier. This helps in understanding that the modified soil takes more load because of the increment in its stiffness which includes the stiffness of the cohesive soil and the

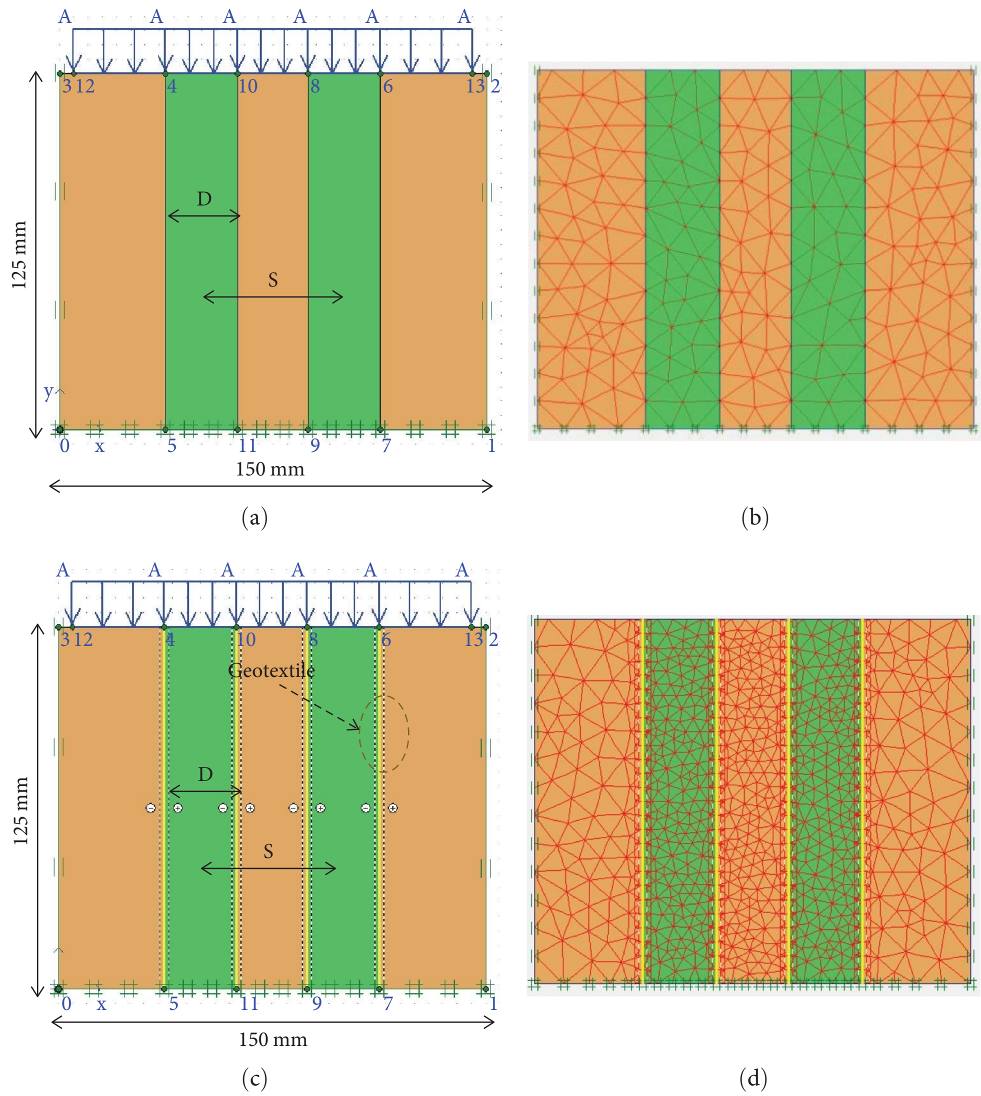


Figure 2: Generated model: (a) model of DS15N, (b) generated mesh of DS15N, (c) model of DS15Y, and (d) generated mesh of DS15Y.

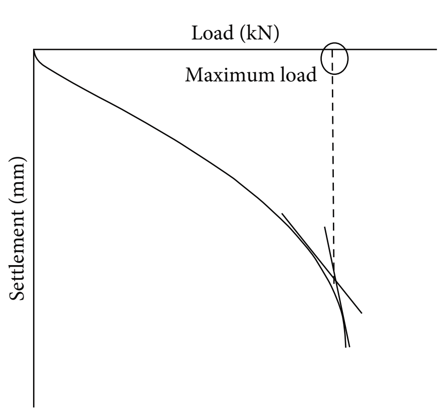


Figure 3: Ultimate load calculation.

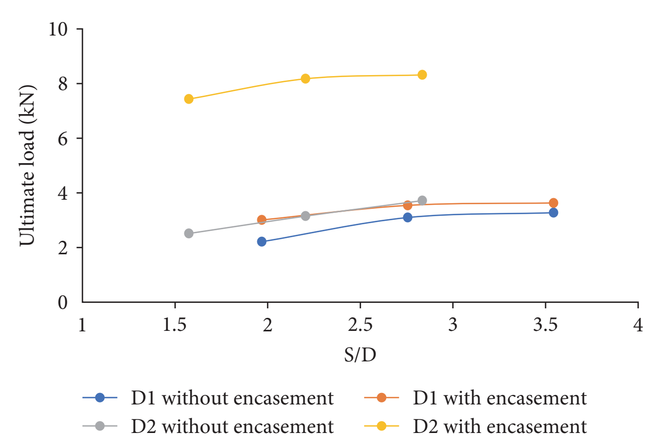


Figure 4: Ultimate load obtained.

geotextile. When a column is introduced in the soil to increase its capacity, the water in the soil is drained leading to a decrease in void ratio, in turn increasing the density. With an increase in density, the shear strength of the modified soil also increases. The larger spaced SCs with encasement carry more load for any given settlement criteria (Figure 5(b)). Overall comparison of axial stresses indicates that encasement plays a major role compared to diameter and spacing (Figure 6).

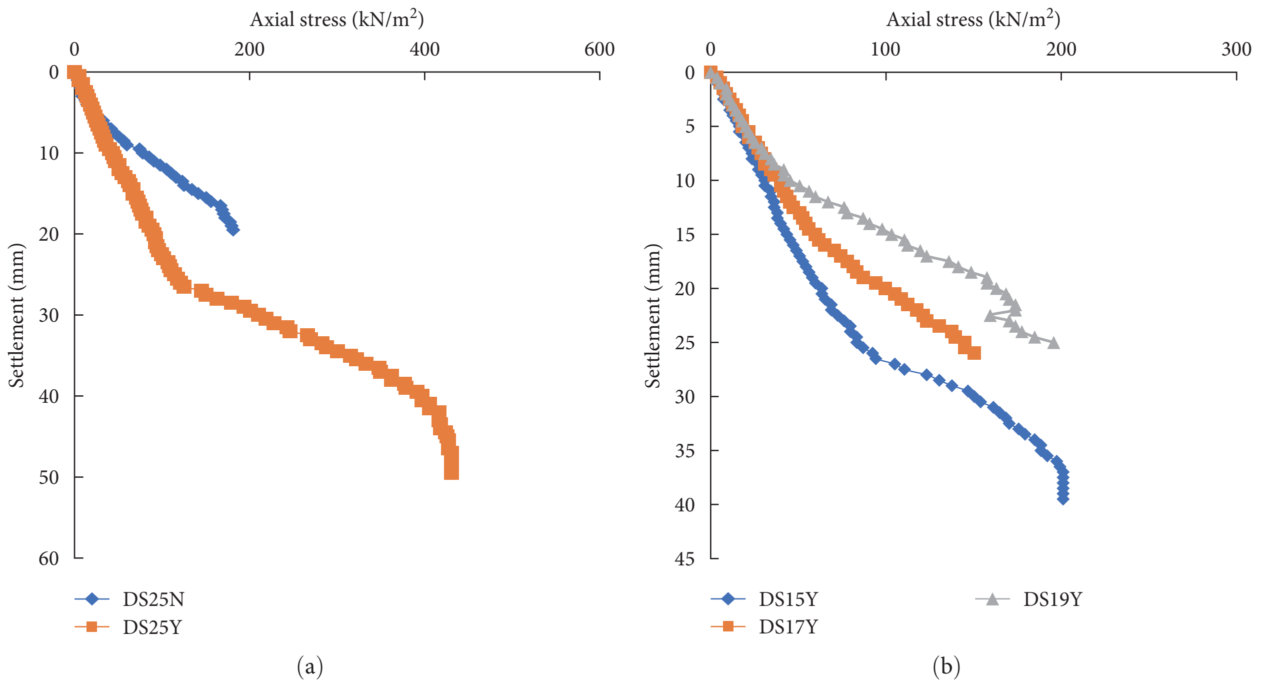


Figure 5: Variation of axial stress for varied condition: (a) comparison of load intensity with encasement and (b) comparison of load intensity with spacing.

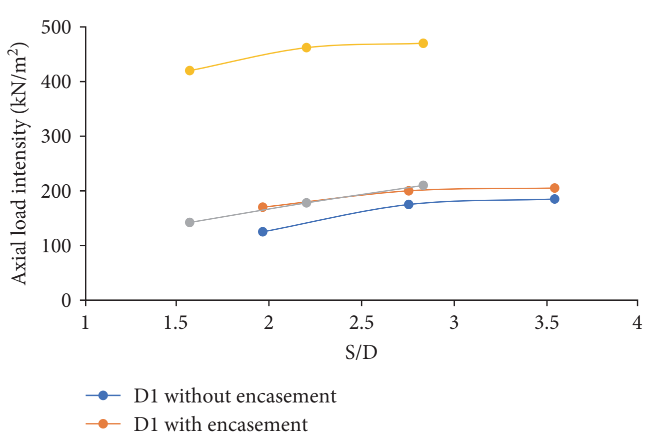


Figure 6: Axial stress variation.

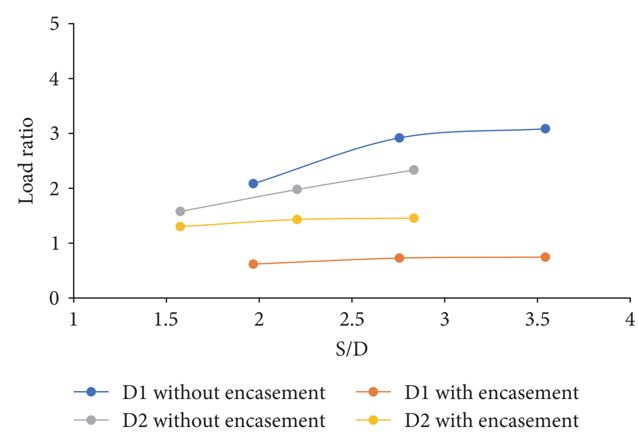


Figure 7: Load ratio.

Load ratio (LR) is the ratio of the ultimate load of a group of SCs with a single SC for the same condition. When the LR is more than 1, it indicates that there is an improvement in the load-carrying capacity of the SC compared to the conventional column. Similar to the ultimate load criteria, the LR is within the range of 1.6–3.1 times without encasement, which then increases to 2.8–5.2 times for an encased column of the same condition. Figure 7 gives insight and can act as a reference chart for varying diameter and spacing with and without encasement to find the axial stress. For a lower diameter of 25.4 mm SC, the LR is less for encasement conditions compared to the conventional SC. The same trend is observed for a larger diameter of 31.75 mm, but the LR range gap is less and it falls between lower diameter encasement and conventional condition.

The study is further extended by doing the FEM analysis. To ensure the genuineness of the tool, a comparison is made between the single SC's load settlement with the work published by Rao and Prasad [39], who studied the influence of SCs in increasing the bearing capacity of the soil for the same conditions. The load-settlement behavior for the experimental and numerical analysis followed the same pattern till its yield; with an increase in load, the experimental data shows more resistance than the numerical analysis (Figure 8). There is a variation of 19.24% between the experimental and numerical data; the same was observed in a study carried out by Sivapriya and James [40].

Axisymmetric analysis was done for 15 nodes with Mohr–Coulomb failure theory for the semi-infinite column. A fine mesh was developed and uniform loading was

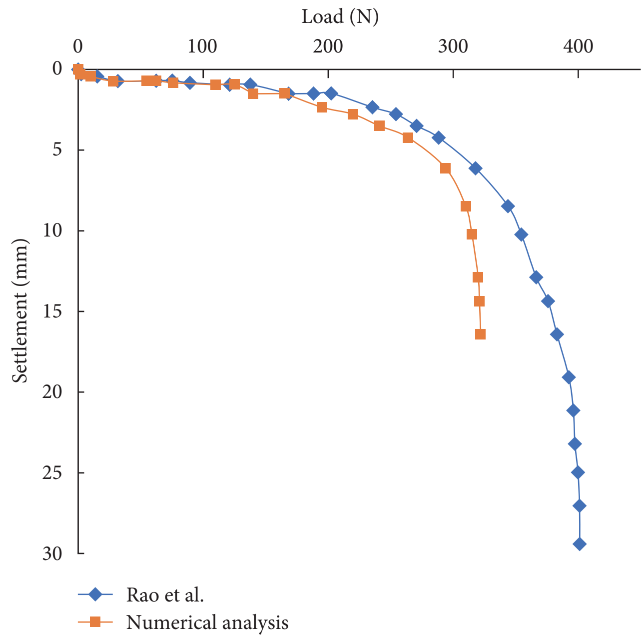
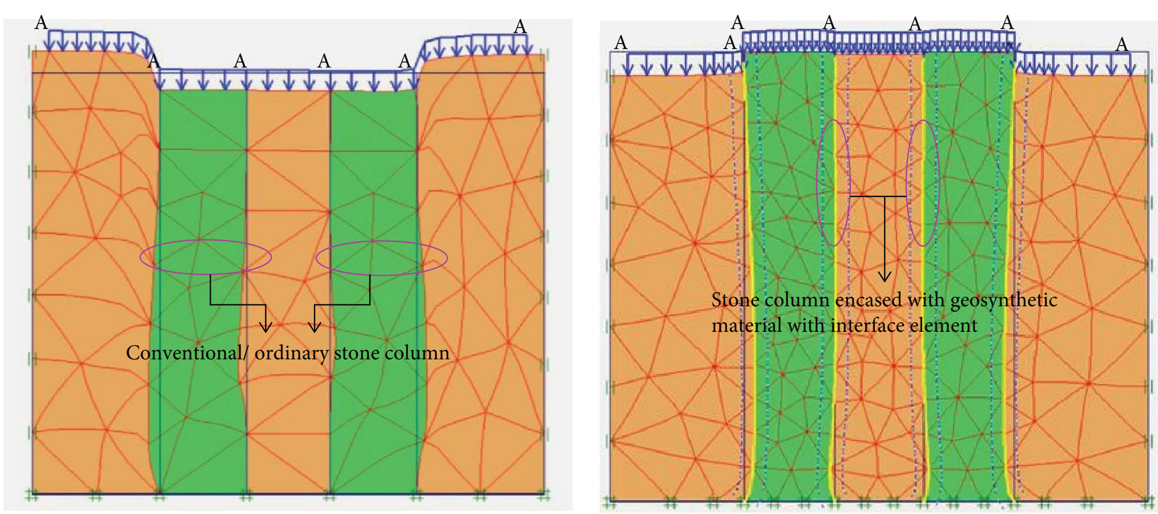


Figure 8: Validation of the tool.



(a)

(b)

Figure 9: Deformed mesh: (a) conventional SC and (b) encased SC.

simulated similar to that of the laboratory study. The number of elements generated under fine meshing is 527, the number of nodes is 4,335, and the generated element size is 0.004 m. The load is applied in increments and the sides of the boundary have roller supports with the fixed bottom. The load is applied at the surface such that load is not distributed to the walls of the mold. The top layer is free to have displacement for the applied load. *In situ* stresses were first generated before the calculation. The initial state of calculation includes the *plastic analysis* followed by "*phi-c*" reduction. *phi-c* analysis is done after activating the load and also it ensures the stability of the analysis.

With good compatibility of the tool, the analysis is carried out for observing the stress acting on the SCs and the surrounding soil. The tool also helps in understanding the displacement along with the depth of the SC for the applied load. For a conventional SC, it is observed that the settlement of the column happens simultaneously avoiding arching. It is seen that when an encasement is provided the settlement of the soil is more than the column (Figures 9(a) and 9(b)). And the settlement of the soil present in-between the encased column is less than the surrounding soil. The column deformed outward for normal SC, whereas for encased conditions the deformation is inward. The encasement provides more rigidity to the column compared to the conventional type, hence the settlement of the soil is less in-between the columns and more in the soil around the column.

The settlement of the column under both conditions (with and without encasement) for the same diameter and

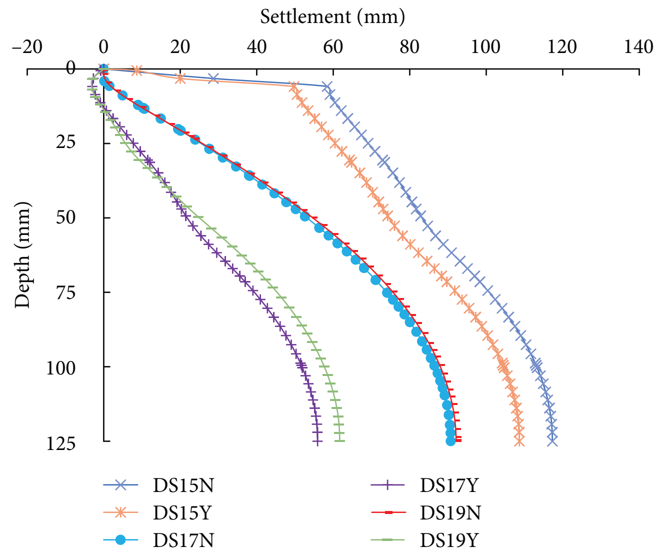


FIGURE 10: Vertical displacement along the length of the column (depth).

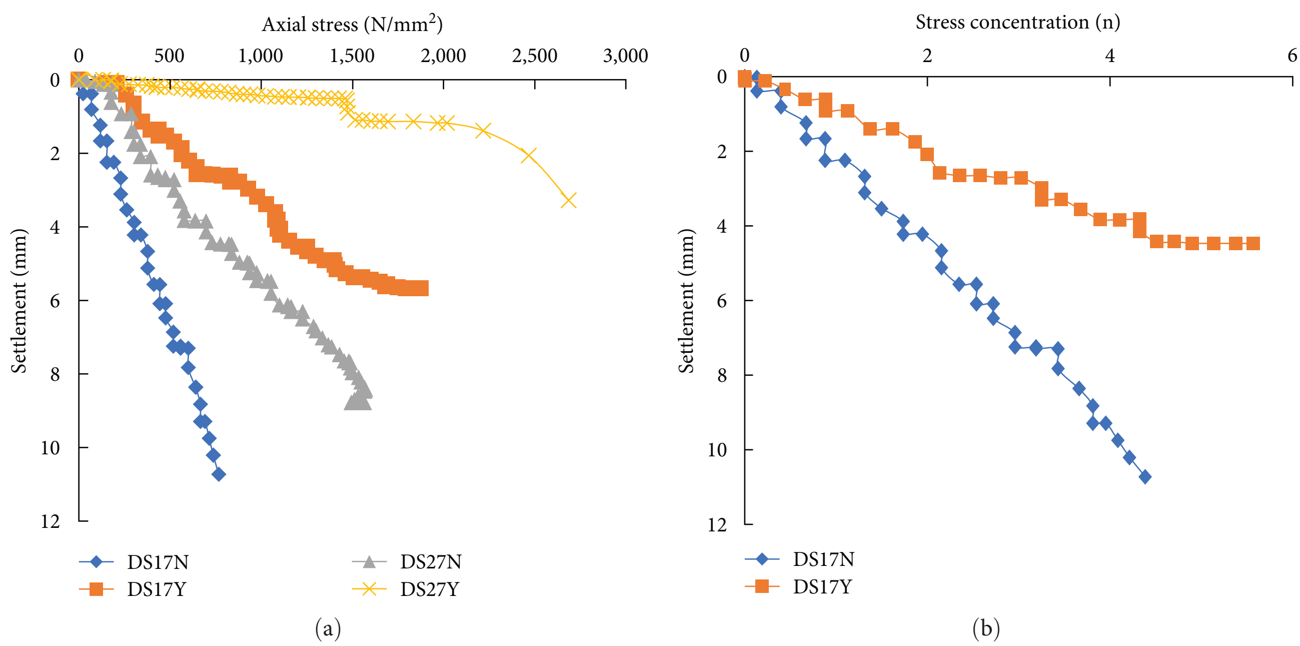


FIGURE 11: Stress concentration ratio: (a) stress concentration variation with diameter and (b) stress concentration variation with encasement.

spacing is also observed. The maximum settlement is observed in the top surface for both conditions. With an increase in depth, the settlement reduces. The presence of encasement increases the strength of the soil composite, which reduces the settlement. The maximum settlement value for the conditions DS15N, DS15Y, DS17N, DS17Y, DS19N, and DS19Y are 117.28, 108.65, 90.78, 55.92, 92.12, and 61.67 mm, respectively (Figure 10).

The stress concentration ratio (n) is the ratio of axial stress of the SC to the surrounding soil. The stress concentration increases with an increase in the axial stress and it is more for encased columns and larger spacing (Figures 11(a) and 11(b)). The increase in 'n' value indicates that the increased surface area of the column leads to an increase in the shear strength of the soil. With encasement, the 'n' value is high because of the increase in its stiffness and confinement [25] (Figure 12).

5. Conclusion

A structure built on problematic soil will undergo a large settlement. To make the soil more suitable for structures, soil can be stabilized by the physical or chemical improvement techniques. Modification of soft soil with a SC is a promising physical ground improvement technique; it improves bearing capacity and reduces the settlement characteristics of the soil. Laboratory

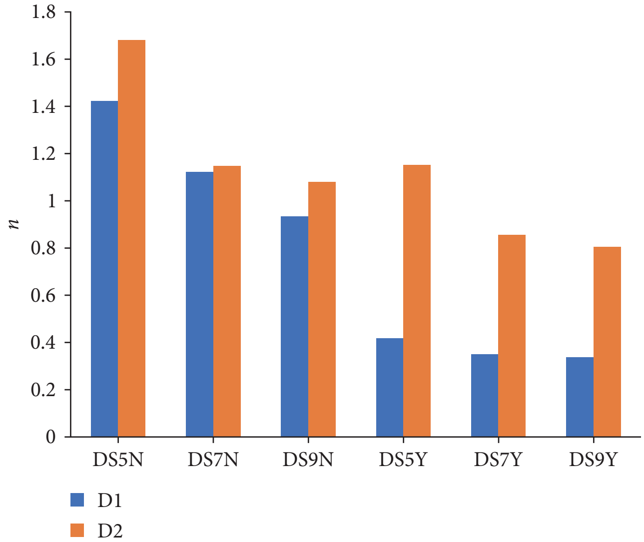


Figure 12: Variation of stress concentration ratio.

tests were conducted in understanding the importance of an increase in diameter (25.4 mm and 31.75 mm) and spacing (50, 70, and 90 mm) between the SCs. In addition, the study was extended by providing an encasement to the stone column. Numerical analysis was also done to find the settlement of the column along its depth and also the stress concentration ratio. The following conclusions were arrived at:

(1) With an increase in diameter from 25.4 mm to 31.75 mm, the ultimate capacity or maximum load increases by 50% without encasement. With the influence of encasement, the capacity increases more than 3.6 times that of SCs without encasement. The area ratio increases from 2.86 to 4.4 when the column size increases.
(2) The spacing between columns varies between 5, 7, and 9 cm. The capacity increases by almost 40% for the 25.4 mm diameter column group and 25% for the 31.75 mm column group compared to a single column.
(3) The encasement works well for a larger diameter of the column i.e., 31.75 mm. There is a tremendous increase in capacity because of the larger surface area rendered by the column. Moreover, the encasement gives additional stiffness to the soil which helps in increasing the capacity.
(4) The LR for the conventional SC is higher for both the diameters compared to encasement condition. This may be due to the fact that the load capacity of an encased single SC is higher than the conventional SC, thereby resulting in a reduced LR.
(5) The stress concentration increases with an increase in diameter and encasement; it is mainly because there is an increase in modulus and it also behaves like a semirigid pile.

The major observation made from the study projected that rather than increasing the diameter or spacing of a SC, it is better to provide encasement to augment the performance of SCs.

Data Availability

The data are available within the manuscript.

Additional Points

Limitation of the Study. The unit cell concept is adopted in both experimental and numerical studies. There is a high possibility of a side wall effect when the spacing between the column increases. When the distance between the end column and the wall is less than 1.5 times the diameter of the column, the side wall effect is more pronounced. This is more significant when the spacing between the columns is 9 cm.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Sivapriya S.V. and Jijo James programed the experiments and wrote the paper. Pavithra. K., Renuka Devi. S., Sangeetha. K., and Sasikala. M. did the experiments.

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References

[1] S. Bhuvaneshwari, B. Soundara, R. G. Robinson, and S. R. Gandhi, "Stabilization and microstructural modification of dispersive clayey soils," in *First International Conference on Soil and Rock Engineering*, pp. 1–7, Srilankan Geotechnical Society, Columbo, Srilanka, 2007.
[2] S. Bhuvaneshwari, R. G. Robinson, and S. R. Gandhi, "Resilient modulus of lime treated expansive soil," *Geotechnical and Geological Engineering*, vol. 37, pp. 305–315, 2019.
[3] E. Guler, *Geosynthetic Reinforcement Applications*, InTech Open, 2023.
[4] A. Thakur, S. Rawat, and A. K. Gupta, "Experimental study of ground improvement by using encased stone columns," *Innovative Infrastructure Solutions*, vol. 6, Article ID 1, 2021.
[5] J. Han and S.-L. Ye, "Simplifed method for consolidation rate of stone column reinforced foundations," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 127, no. 7, pp. 597–603, 2001.
[6] H. A. Elshazly, D. H. Hafez, and M. E. Mossaad, "Reliability of conventional settlement evaluation for circular foundations on stone columns," *Geotechnical and Geological Engineering*, vol. 26, pp. 323–334, 2008.
[7] B. A. McCabe, G. J. Nimmons, and D. Egan, "A review of field performance of stone columns in soft soils," *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, vol. 162, no. 6, pp. 323–334, 2009.
[8] A. K. Das and K. Deb, "Response of stone column-improved ground under c-φ soil embankment," *Soils and Foundations*, vol. 59, no. 3, pp. 617–632, 2019.
[9] M. Y. Fattah, M. A. Al-Neami, and A. S. Al-Suhaily, "Estimation of bearing capacity of floating group of stone

columns," *Engineering Science and Technology, an International Journal*, vol. 20, no. 3, pp. 1166–1172, 2017.

[10] A. P. Ambily and S. R. Gandhi, "Behavior of stone columns based on experimental and FEM analysis," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 133, no. 4, pp. 405–415, 2007.

[11] A. M. Hanna, M. Etezad, and T. Ayadat, "Mode of failure of a group of stone columns in soft soil," *International Journal of Geomechanics*, vol. 13, no. 1, pp. 87–96, 2013.

[12] M. Almeida, B. Lima, M. Riccio, H. Jud, M. Cascão, and F. Roza, "Stone columns field test: monitoring data and numerical analyses," *Geotechnical Engineering*, vol. 45, no. 1, pp. 103–112, 2014.

[13] J. M. O. Hughes, N. J. Withers, and D. A. Greenwood, "A field trial of the reinforcing effect of a stone column in soil," *Géotechnique*, vol. 25, no. 1, pp. 31–44, 1975.

[14] S. Rajesh and M. Koch, "Performance assessment of geosyntheticencased stone columns in soft clay—A numerical study," in *Proceedings of 4th International Seminar on Forensic Geotechnical Engineering*, G. L. S. Babu, V. V. S. Rao, and M. R. Madhav, Eds., pp. 617–627, 2013.

[15] S. Murugesan and K. Rajagopal, "Shear load tests on stone columns with and without geosynthetic encasement," *Geotechnical Testing Journal*, vol. 32, no. 1, pp. 76–85, 2009.

[16] S. N. Malarvizhi and Ilamparuthi, "Comparative study on the behavior of encased stone column and conventional stone column," *Soils and Foundations*, vol. 47, no. 5, pp. 873–885, 2007.

[17] B. Indraratna, "Technical session 4a: ground improvement/grouting/dredging," in *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering (Volumes 1, 2, 3 and 4)*, pp. 3319–3335, IOS Press Ebooks, 2009.

[18] A. Marto, R. Moradi, F. Helmi, N. Latifi, and M. Oghabi, "Performance analysis of reinforced stone columns using finite element method," *Electronic Journal of Geotechnical Engineering*, vol. 18, pp. 315–323, 2013.

[19] M. Khabbazian, V. N. Kaliakin, and C. L. Meehan, "Numerical study of the effect of geosynthetic encasement on the behaviour of granular columns," *Geosynthetics International*, vol. 17, no. 3, pp. 132–143, 2010.

[20] M. A. Nav, R. Rahnavard, A. Noorzad, and R. Napolitano, "Numerical evaluation of the behavior of ordinary and reinforced stone columns," *Structures*, vol. 25, pp. 481–490, 2020.

[21] S. Murugesan and K. Rajagopal, "Model tests on geosynthetic-encased stone columns," *Geosynthetics International*, vol. 14, no. 6, pp. 346–354, 2007.

[22] Y. Zhuang, S. Hu, X. Song, H. Zhang, and W. Chen, "Membrane effect of geogrid reinforcement for low highway piled embankment under moving vehicle loads," *Symmetry*, vol. 14, no. 10, Article ID 2162, 2022.

[23] S. Murugesan and K. Rajagopal, "Geosynthetic-encased stone columns: numerical evaluation," *Geotextiles and Geomembranes*, vol. 24, no. 6, pp. 349–358, 2006.

[24] C. H. Abdullah and T. B. Edil, "Behaviour of geogrid-reinforced load transfer platforms for embankment on rammed aggregate piers," *Geosynthetics International*, vol. 14, no. 3, pp. 141–153, 2007.

[25] S. Murugesan and K. Rajagopal, "Studies on the behavior of single and group of geosynthetic encased stone columns," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 136, no. 1, pp. 129–139, 2010.

[26] S. Murugesan and K. Rajagopal, "Investigations on the behaviour of geosynthetic encased stone columns," in *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering (Volumes 1, 2, 3 and 4)*, pp. 2411–2414, IOS Press Ebooks, 2009.

[27] S. G. Kumar, R. G. Robinson, and K. Rajagopal, "Improvement of soft clays by combined vacuum consolidation and geosynthetic encased stone columns," *Indian Geotechnical Journal*, vol. 44, pp. 59–67, 2014.

[28] A. Gholaminejad, A. Mahboubi, and A. Noorzad, "Encased stone columns: coupled continuum–discrete modelling and observations," *Geosynthetics International*, vol. 27, no. 6, pp. 581–592, 2020.

[29] S. Dutta, M. B. Nadaf, R. R. Lal Birali, and J. N. Mandal, "Encased stone columns for soft ground improvement," in *ASCE: Geo-Chicago*, pp. 746–755, ASCE Library, 2016.

[30] M. Khabbazian, V. N. Kaliakin, and C. L. Meehan, "3D numerical analyses of geosynthetic encased stone columns," *Geosynthetics International*, vol. 17, no. 3, pp. 132–143, 2009.

[31] N. Mehrannia, F. Kalantary, and N. Ganjian, "Experimental study on soil improvement with stone columns and granular blankets," *Journal of Central South University*, vol. 25, pp. 866–878, 2018.

[32] Bureau of Indian Standard(BIS), "IS 2720 (Part III/I) determinationof specific gravity of fine granied soil," March 1981. 1997, pp. 1–10, 1997.

[33] Bureau of Indian Standard, "IS 2720 (Part IV) methods of test for soil-grain size analysis." pp. 1–40, 1995.

[34] Bureau of Indian Standard, "IS 2720 (part V) determination of liquid and plastic limit." pp. 1–17, 1995.

[35] Bureau of Indian Standard, "IS 2720-part 8: determination of water content-dry density relation using heavy compaction," pp. 1–14, 2006.

[36] Bureau of Indian Standard, "IS 1498-1970 (reaffirmed 2002): classification and indentification of soil," pp. 1–28, 2002.

[37] J. James and S. V. Sivapriya, "Load-settlement behaviour of stone column with varied spacing," in *Recent Developments in Sustainable Infrastructure (ICRDSI-2020)—Structure and Construction Management*, B. B. Das, C. P. Gomez, and B. G. Mohapatra, Eds., vol. 221 of *Lecture Notes in Civil Engineering*, pp. 27–31, Springer, Singapore, 2022.

[38] Plaxis 3D, "User manual, plaxis," Netherlands, 2012.

[39] S. M. M. N. Rao and Y. V. S. N. Prasad, "Influence of bearing area on the behavior of stone columns," in *Proceedings of Indian Geotechnical Confererence*, pp. 235–237, 1992.

[40] S. V. Sivapriya and J. James, "Numerical study on static behaviour of a stone column under uniformly distributed load," *AIP Conference Proceedings*, vol. 2161, Article ID 020058, 2019.