Hindawi
Advances in Civil Engineering
Volume 2023, Article ID 5039439, 12 pages
https://doi.org/10.1155/2023/5039439

Research Article

Numerical Analysis of a Dual-Layer Geosynthetic-Encased Stone Column Installed in Soft Soil

Neeraj Kumar,[1] **Rakesh Kumar**,[1] **Bhawani S. Nirola**,[2] **and Akash Jaiswal**[1]

[1]*Department of Civil Engineering, MANIT, Bhopal 462003, India*
[2]*College of Science and Technology, Royal University of Bhutan, Phuentsholing 21101, Bhutan*

Correspondence should be addressed to Bhawani S. Nirola; bhawani.cst@rub.edu.bt

Received 14 December 2022; Revised 18 January 2023; Accepted 29 March 2023; Published 19 April 2023

Academic Editor: Khaled Ghaedi

Stone columns are being used to reduce soft soil settlement and increase load-carrying capacity. Since there is inadequate lateral support from the local native soil, soft soil undergoes excessive settlement under vertical loading. This issue is effectively resolved by suitably encasing stone column material by geosynthetic with significant axial stiffness, which provides the required additional confinement reported in the literature. In the current study, an effort has been made to examine the load settlement behaviour of the dual-layered geosynthetic-encased stone column (DL-GESC) under vertical loading. In order to simulate the behaviour of stone column-reinforced soft soil, a FEM analysis was performed using PLAXIS-3D and three-dimensional (3D) models made utilising the unit cell idealisation technique for a single column. The stone column diameter, spacing to diameter (s/d) ratio, and encasement layers were varied to determine their influence on load-settling behaviour. The vertical load-carrying capacity of the ground was significantly improved when an additional layer of geosynthetic encasement was inserted into the stone column as compared to SL-GESC. Improvement of 15–25% was observed for the analysis of a single column installed in soft clay, according to the result obtained. Improvement ratios have been discussed in detail for various encasement conditions.

1. Introduction

Using soft clay deposits or fills as a foundation material is generally not suggested. The viability of construction there must be determined in light of the favourable economic conditions for land development brought on by the expansion of urban and industrial regions. Stone columns are, without a doubt, the most popular and desirable alternatives. When the load-carrying capacity of the soil rises, it is less probable that storage tanks, earthen embankments, raft foundations, and other foundations undergo failure due to settlement. Insertion of ordinary stone column increase soil to greater depth and minimise problems induced by settlement. Numerous geotechnical problems that might occur with poor soil can be resolved through ground improvement [1]. Columnar inclusion is among the most flexible and economical ground augmentation techniques available today. Compared to the soil around them, columnar inclusions are more durable and resilient. Stone columns, lime or cement columns, compacted sand piles, or other columnar inclusions can be considered as composite materials. Granular pile reinforcement in soft ground is used to improve field performance by increasing bearing capacity and reducing settlement [2, 3]. Over the past three decades, this method has seen extensive usage for a wide range of applications, including the compression of cohesionless soil and the insertion of stone columns of reinforcement into softer soil. It has outpaced most conventional deep foundation techniques, such as piling. Circumferential bulging of the stone column helps to transmit the longitudinal load, which increases the stiffness of the ground. The lateral confinement or bulging resistance offered by the intervening soil was found to be inadequate for particularly soft soil [4, 5].

The stone column method is economical and environmentally friendly for stabilising unstable ground so that it can withstand low-to-moderate stress situations [6]. It increases the stability and stiffness of the soil, reduces the likelihood of liquefaction and pore pressure, enhances shear strength and stability, and accelerates the consolidation of drained soil. Introducing tensile materials in horizontal, vertical, and inclined orientations is another well-known method of improving and strengthening soil. Geosynthetics have become a significant component in soil reinforcement because of advancements in polymer engineering and the development of innovative materials. Van Impe [7] was the first to suggest covering a stone column with a geosynthetic material. Since then, numerous research studies have been conducted to use reinforced stone columns to enhance the properties of soft soil by researchers [8–10], whereas Fathi and Mohtasham [11] demonstrated the stone column by increasing the stiffness of geosynthetic materials, improved soil stability, and load-bearing capacity.

In order to strengthen the stone column carrying capacity and prevent any related failures, it was thus necessary to increase the circumferential bulging resistance [12–16]. By adjusting the length of the encasement, Gniel and Bouazza [17] investigated small-scale geogrid-encased columns. In both single and group columns, encasement length reduced the upright strain [18, 19]. Below the encasement, there was a bulging collapse, fully enclosed columns minimise the strain by 80%. It has been proven to be very successful in increasing the bearing capacity in a vertically laden column to utilise a variety of geosynthetics as part of an encasement [20–29].

Various studies proposed that using horizontal layers of geosynthetics encasement helps to improve the bearing capacity and reduce lateral bulging [30–32]. Three-dimensional numerical studies reported that short end-bearing columns with GESC had higher bearing capacities than longer ones because they transmitted compressive load across their entire length and mobilised higher strains for a specified settlement. Also, the short geogrid-encased sand column exhibited less lateral expansion for a given settlement than larger-diameter encasement [33]. Miranda et al. [34] established the critical length using FEM analysis and found that extending the column past the critical length had no advantage. For enclosed stone columns, the required column length should be 1.3–2.5 times the footing's diameter; for OSC, it should be 1.1–1.9 times the footing's diameter. The length of ordinary, encased stone columns should be 2 to 5 times the diameter of the footing. The influence of stone columns coated with geosynthetics under cyclic loads was examined by Gao et al. [35] and concluded that by doing such reduces foundation settlement.

Ordinary stone columns (OSC) built on the soft ground could now be strengthened by using geosynthetic-encased stone columns (GESC), which has gained in importance. An ordinary stone column can also be loaded and arranged such that they do not slide laterally into the ground next to the building. Due to insufficient lateral pressure from the soil around them, GESCs come into play when OSCs in a soil environment are unable to maintain column integrity. The major factor determining which system—the GESC system or the OSC system—offers a lesser cost benefit when both systems are applicable at the same location is the project boundary's specific issues, such as settling requirements, installation difficulties, and loading conditions. As of now, the following criteria have been used to study geosynthetic reinforcement in general:

(a) Using horizontal layers of geosynthetic reinforcement positioned partially and entirely in relation to the length of the stone column to decrease lateral extension (bulging)
(b) Encasing the sand column completely and partially around with a geogrid sleeve
(c) Encasing geosynthetic sleeves circumferentially around the stone column periphery
(d) Reinforcing stone columns horizontally and vertically along with varying encasement lengths
(e) The dual layer idea, which was just recently presented and will be employed for the first time in vertical loading, is still the subject of investigation

The information, as shown, indicates that the encasing was only applied to the stone column periphery. On the other hand, Jaiswal and Kumar [36] recommended using a dual-layered encasement to improve a stone column shear resistance in situations where the column is susceptible to shear collapse. In order to load stone columns in a vertical position, the dual-layer enclosed stone column (DLESC) idea has yet to be used; hence, more research is needed in this area.

The ongoing research aims to create a design method that takes soil and the load distribution of a dual-layer, encased stone column into account. Numerical analysis was used to analyse the behaviour of a single stone column. The study was conducted using a unit cell concept, with clay deformations restricted to the unit cell, which is represented by the equivalent area of each column. The efficiency of stone columns in SL-GESC and DL-GESC soil was assessed in the current study to determine the impact of geogrid encasing.

2. Numerical Modelling

Using a FEM analysis in PLAXIS-3D using 10 nodes, numerical investigations were conducted as part of this research. This FEM package is made up of reliable computational techniques that have stood the test of time. It enables users to analyse and simulate soil behaviour through the creation of 3D soil models, allowing them to tackle challenging geotechnical engineering challenges. The load versus the settlement study, which was done on a single column, was based on the idea of a unit cell. This is due to the tightest packing provided by this layout.

The equivalent diameter (De) of an equivalent cylindrical unit cell is determined as follows: De $= 1.05 \times s$, where s is the column spacing, which is commonly 2 to 4 times the diameter (d). As indicated by the formulas $= 2d$ to $4d$, the distance between the stone columns was shifted in the current inquiry between two and four times their diameters. Investigations were conducted on columns with diameters of 50 mm, 75 mm, 100 mm, 125 mm, and 150 mm. A minimum L/d ratio of 4.5 is required to produce the full limiting axial stress on the stone column; nevertheless, no appreciable improvement in its capacity has been seen. In this analysis, the load versus settlement behaviour in soft soil reinforced by single-layer geosynthetic encased stone columns (SL-GESC) and dual-layer geosynthetic-encased stone columns (DL-GESC) were compared to that of unreinforced soil and ordinary stone column (OSC). This study used the Mohr–Coulomb model, which has been used by many scholars in the past to analyse the behaviour of soft soil and stone columns [27, 31, 37–39]. It was decided that the geosynthetic encasement should be modelled as a linear elastic material.

Studies on the effect of geosynthetic encasing on settlement behaviour in the stone column-reinforced soft soil of varying undrained shear strengths have shown that an interface element is not needed because column settlement is caused by the stone columns bulging to the periphery, which prevents shear [33, 40]. Therefore, interface elements were not used in the case of GESC; however, Rinter = 0.60 was used for the stone column and soil in this study because it yielded a more accurate validation result than the other values tested.

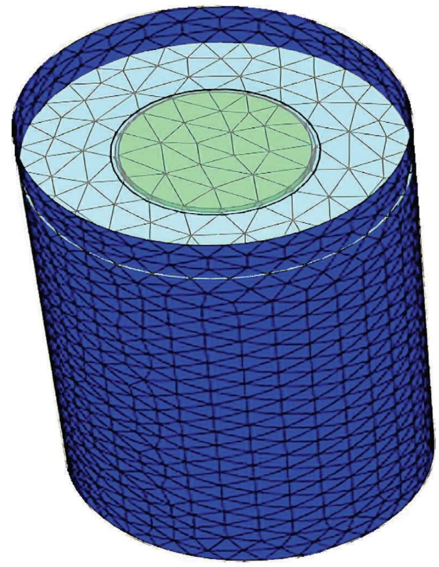


Figure 1: Schematic diagram of a soil bed with a single column modelled.

2.1. Validation of the Numerical Model. Perfectly elastic linear material clay was employed as the bed material, and stone aggregates as the column material and the behaviour of each was simulated using Mohr–Coulomb failure criteria. The Mohr–Coulomb model is applicable in the analysis of embankments and shallow foundations. Laboratory model studies on single configurations of stone columns surrounded by soft clays in a triangular pattern were used to approximate the load settlement behaviour of model tests carried out by Ambily and Gandhi [40], utilising the unit cell approach (Figure 1). This was achieved by simulating the load-settling behaviour seen in tests, which were done using stone columns with a 100 mm diameter and end-bearing columns with a 4.5 L/d ratio. In addition, a cylindrical tank with dimensions of 500 mm in height and 210 mm in diameter was selected following the unit cell idealisation concept to achieve an s/d ratio of 2. It was agreed that the end-bearing condition of loading only one column would be considered for the single-column criterion during the validation process.

Material properties used for validation purposes are the same as in Table 1, which was used by [40]. To simulate the test, a cylindrical mould was developed and given the characteristic of steel. Following that, a series of boundary conditions were used to keep the cylindrical mould fixed to restrict mould movement in any direction. A clay-filled mould and a stone column of 100 mm in diameter and 450 mm in length were used to create the model. As indicated in Figure 1, material characteristics were assigned after creating an interface at the boundary. The mesh was created when the necessary and appropriate properties were provided, as seen in Figure 2.

For the relevant conditions, the numerical analysis employed a maximum specified settlement of 35 mm [41]; above this settlement, the increase in axial stress seems to be constant [40]. Figure 3 depicts the vertical displacement applied to the stone column. The result obtained from the numerical study done by PLAXIS-3D is in good agreement with those of the earlier experimental examination by Ambily and Gandhi [40], which was conducted for $s/d = 2$, as shown in Figure 4.

Table 1: Material's properties as utilised by Ambily and Gandhi [40].

Parameters	Properties	
	Clay	Stone
Poisson's ratio (μ)	0.42	0.3
Shear strength, c_u (kPa)	30	0
Modulus of elasticity (kPa)	5,500	55,000
Angle of internal friction (ϕ)	0	38°
Dilatancy angle (ψ)	0	4°

3. Material Properties

Mohr–Coulomb failure criteria were used in the validation of the perfectly plastic linear elastic model used for the behaviour of clay as a bed material and stone aggregates as a column material. The Mohr–Coulomb model has been used by numerous researchers for investigations on stone columns that are similar to those on embankments and shallow foundations [27, 42–45]. The model's input parameters (E, c, φ, and ψ) were obtained from relevant laboratory tests. Five different stone columns, each with a diameter of 50 mm, 75 mm, 100 mm, 125 mm, and 150 mm, were used in the numerical analysis, with variable s/d ratios. Table 2 shows the physical characteristics of the material used in this study. Various parameters were altered to calculate their effects on the soil settling behaviour under various load intensities. The geosynthetic's axial rigidity (J) was fixed at 150 kN/m for both the inner and outer layer

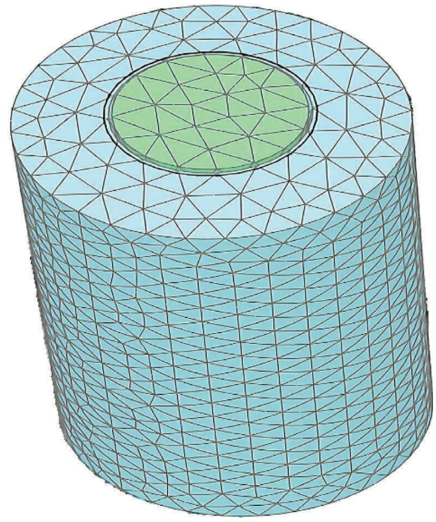


Figure 2: Generated mesh of the model with ordinary stone column (OSC).

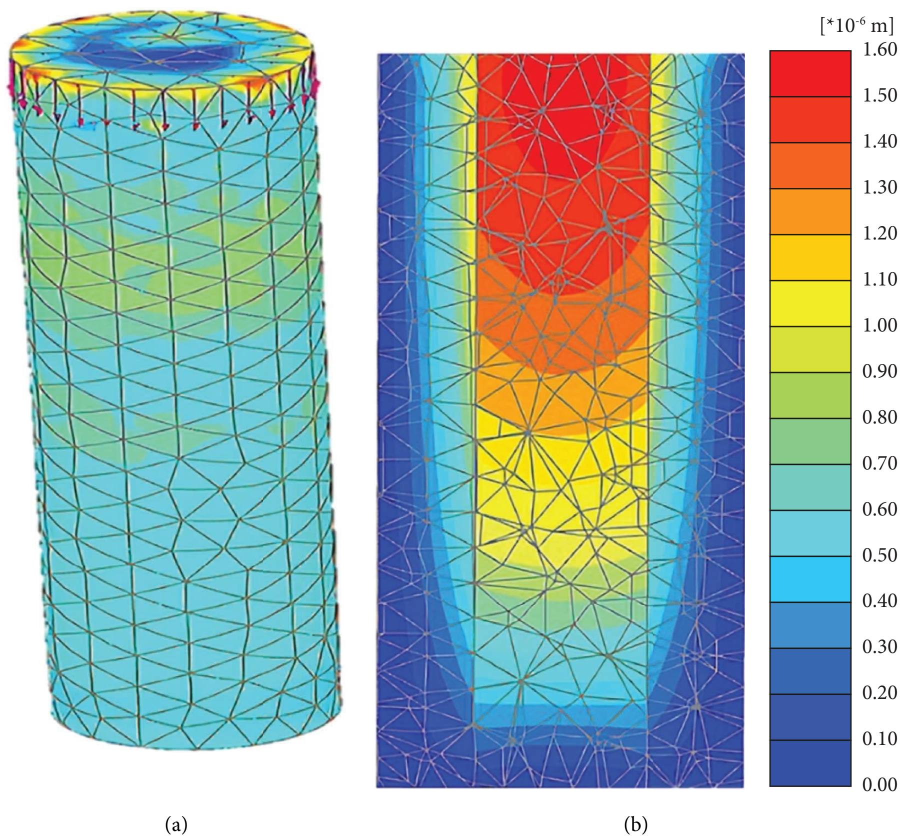


Figure 3: (a, b) Stone column with prescribed displacement.

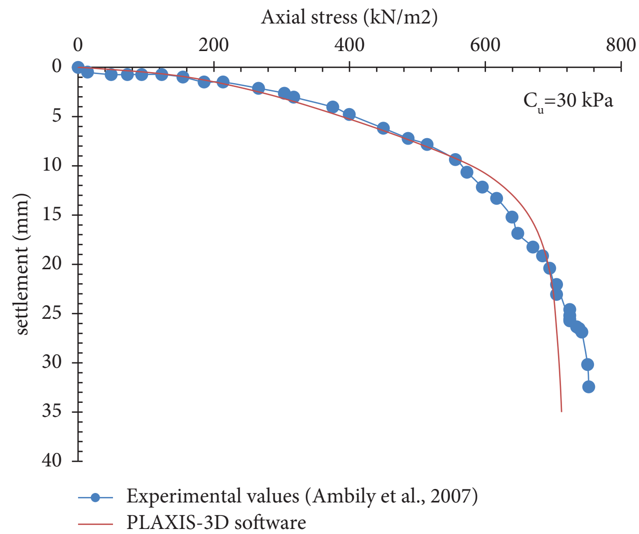


Figure 4: Validation of the axial stress versus settlement graph by Ambily and Gandhi [40].

Table 2: An overview of the FEM models generated.

Stone column dia. (mm)	*s*/*d* ratio	Single column test Model type			
		DL-GESC	SL-GESC	OSC	CLAY
50	$s/d=2$	✓	✓	✓	✓
	$s/d=3$	✓	✓	✓	✓
	$s/d=4$	✓	✓	✓	✓
75	$s/d=2$	✓	✓	✓	✓
	$s/d=3$	✓	✓	✓	✓
	$s/d=4$	✓	✓	✓	✓
100	$s/d=2$	✓	✓	✓	✓
	$s/d=3$	✓	✓	✓	✓
	$s/d=4$	✓	✓	✓	✓
125	$s/d=2$	✓	✓	✓	✓
	$s/d=3$	✓	✓	✓	✓
	$s/d=4$	✓	✓	✓	✓
150	$s/d=2$	✓	✓	✓	✓
	$s/d=3$	✓	✓	✓	✓
	$s/d=4$	✓	✓	✓	✓

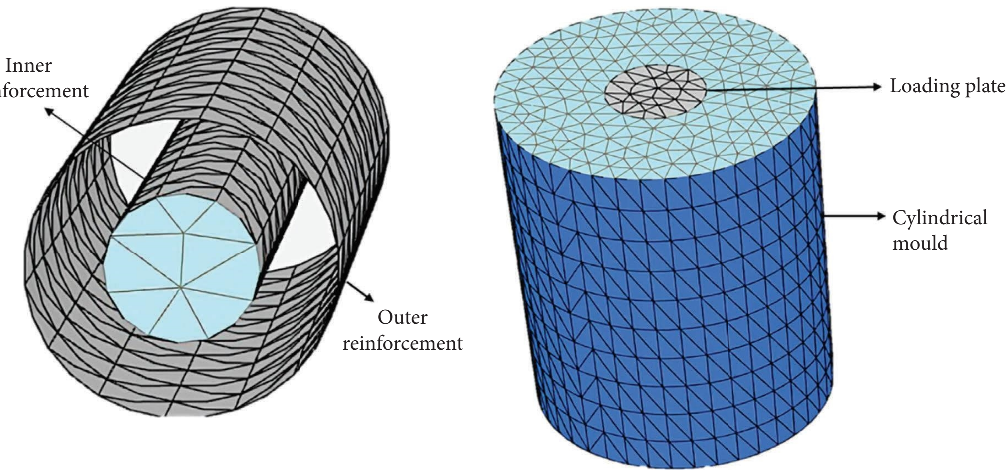
encasings. It was investigated how this dual-layer encasement affected the stone column bulging and load-settlement behaviour.

4. Encasement Conditions

The two types of encasements employed for the single ordinary stone column research were Single-layered geosynthetic-encased stone column (SL-GESC) and dual-layered geosynthetic-encased stone column (DL-GESC). In the case of a single-layer encasement, the encasing layer is placed on the column's outermost periphery, enclosing the whole stone column, as depicted in recent research. While dual-layered encasement employs two layers of encasement, the first layer is the same as that used in single-layered encasement (at the periphery), and this layer remains consistent throughout all DLGE samples. The second layer of encasement is inserted within the body of the stone column, 0.5d from the stone column axis, as shown in Figure 5(a). This leads to a gap of 0.5d between the two layers of encasement, which is equal to the spacing between the two layers of the encasement.

5. FEM Modelling by PLAXIS-3D

The diameter and height of the single-column cylindrical tank were maintained by using the unit cell concept and maintaining the L/D ratio of about 4.5. Based on the diameter of a stone column, the PLAXIS-3D software was used to create a cylindrical tank with varying length and diameter. The component of the tank was made of plate elements, and the boundaries of the tank were confined in all three



(a) (b)

Figure 5: (a) Cross-sectional view of dual-layered encasement for a single stone column and (b) single-stone column setup.

dimensions. The loading plate and its properties were allocated to steel plates with a thickness of 12 mm. A stone column with the requisite diameter was generated in the tank's centre, interacting with the attribute Rinter = 0.6 that is maintained on the column periphery for ordinary stone column (OSC). Encased stone columns (ESC) with a specified tensile strength of 150 kN/m for both the inner and outermost encasement were provided by geogrids. Meshing was done using a medium coarseness, and a predetermined vertical displacement of 50 mm was provided, as shown in Figure 2. On single columns with varied encasement conditions and diameters, 60 FEM models were created and numerically examined. Table 2 displays the general structure of the model, and Figure 5(b) depicts the model of a single ordinary stone column setup with encasement.

6. Results and Discussion

The effect of various factors on the load-intensity versus settlement behaviour of GESCs was analysed using 3D FEM models. Based on their experimental investigation, Ambily and Gandhi [40] suggest that the length of stone columns nearly 4.5*d* is optimum. In this study also, an end-bearing column with a length to diameter (L/d) ratio of 4.5 was chosen for a single column analysis. The load was applied on top of the stone column in terms of a prescribed displacement of up to 50 mm. The parameters varied included the diameter of stone column, encasement conditions, and s/d ratio. The properties used for the materials modelled in the study are shown in Table 3. Various aspects and outcomes of parametric studies are discussed in detail as follows:

6.1. Effect of Spacing. On the unreinforced soil, ordinary stone column, SL-GESC, and DL-GESC with various diameters and spacings, various FEM analyses were conducted. Figure 6 presents the findings as graphs illustrating the variation in axial stress and axial load for various model parameters. From the result obtained through the FEM analysis, it shows that the load-carrying capacity of the stone column decreases as the spacing between stone columns increases, this phenomenon continues up to the s/d ratio of 3, beyond which the change becomes negligible. These findings are consistent and in agreement with that of [40, 46]. According to Table 4, which compares the improvement percentage of the DL-GESC to the SL-GESC, there is a considerable improvement when we move from $s/d = 2$ to $s/d = 3$, while the change from $s/d = 3$ to $s/d = 4$ is marginal.

The FEM results for a 100 mm column with various s/d ratios are discussed in detail below, as shown in Figure 7. It has been observed that DL-GESC greatly outperforms OSC and SL- GESC in resisting the vertical load. Similar patterns are observed for columns with diameters of 50, 75, 125, and 150 mm; hence, the prior finding holds true for all of the column diameters stated.

6.2. Effect of Encasement. As seen in Figure 8, the encasement significantly increased the capacity of soft soil to withstand loads after being reinforced with a stone column. The results of FEM for various s/d ratios and variations in diameter are displayed in the accompanying graphs, respectively. For the DL-GESC, it can be seen that the load-carrying capacity significantly improves as the ordinary stone column diameter increases. Results from the experimental study [26] and numerical study [47] also indicates, compared to ordinary stone columns, encased stone columns have a substantially higher stress concentration. Overall, there was an improvement of 15–25% from DL-GESC to SL-GESC. There has been an increase in load-carrying capacity, with $s/d = 3$ producing the best results and accommodating all diameter variations.

The axial load-carrying capacity for various stone column diameters with varying s/d ratios is detailed in Table 5 and well depicted in Figure 6(b); when compared to an ordinary stone column, the axial load-carrying capability of column improves. According to the results of the FEM

Table 3: Properties of the materials used for PLAXIS 3D.

Parameters	Properties	
	Clay	Stone material
Poisson's ratio (μ)	0.4	0.3
Shear strength, cu (kPa)	14	0
Modulus of elasticity (kPa)	4000	45,000
Angle of internal friction (ϕ)	0	38°
Dilatancy angle (ψ)	0	8°

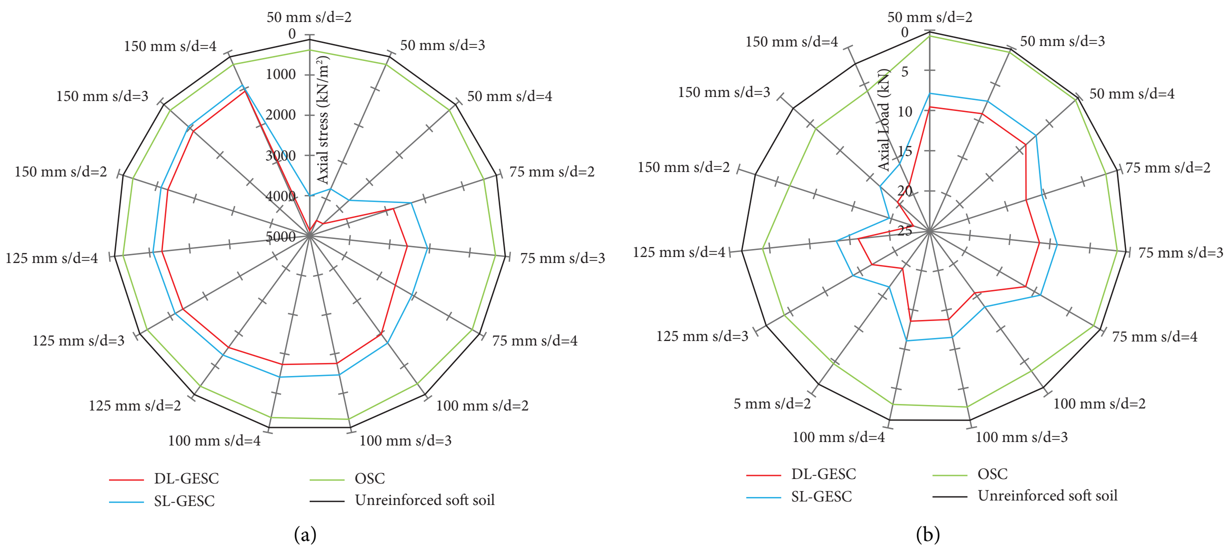


Figure 6: Effect of spacing on a single column: (a) axial stress (kN/m^2) and (b) load (kN).

Table 4: Improvement in DL-GESC compared to SL-GESC.

s/d	Improvement (%)				
	50 mm	75 mm	100 mm	125 mm	150 mm
2	21.49	19.95	15.97	17.44	15.95
3	23.18	24.72	19.63	19.51	17.61
4	23.66	23.25	22.71	20.55	18.37

study, in comparison to the ordinary stone column, an improvement of 2.15–12.75 times for DL-GESC and 1.6–10 times for SL-GESC has been observed. There has been a rise in axial load capacity of DL-GESC for all the considered cases for various diameters, it has been observed that, with spacing to diameter ratio 3 yielding the optimum results for load-bearing capacity if compared with spacing to diameter ratio of 2 and 4.

The dual-layered, geosynthetic-encased column outperforms the stone column installed in soft soil by a significant margin. The axial stress decreases as the diameter of the stone column grows for varied s/d ratios, as shown in Figure 6(a), illustrating that the load-carrying capacity of the soil increases as a direct result of this modification.

6.3. Effect of Stone Column Diameter on Improvement Ratio (I.R.). The FEM modelling results were analysed and reported as a bearing capacity improvement ratio (q_r/q_u), where q_r is the vertical stress of reinforced soil at a settlement of 50 mm and q_u is the vertical stress of unreinforced soil at the same settlement. Figure 9 shows the trendlines of the DL-GESC, SL-GESC, and OSC for varying diameters and s/d ratios, and it was observed that when compared to unreinforced soil, the load-carrying capacity of ordinary stone column improve 2.6–3.7 times, for SL-GESC improves 7–33.5 times, and for DL-GESC improves 8.5–40.8 times.

6.4. Failure Mechanism. The length of the column has a crucial role in the failure mechanism of a single stone column loaded across its region. In situations where end-bearing and floating columns are utilized and the length of the column exceeds the critical length, which is estimated to be approximately four times the diameter, the column may experience collapse due to bulging [48]. Similar observations

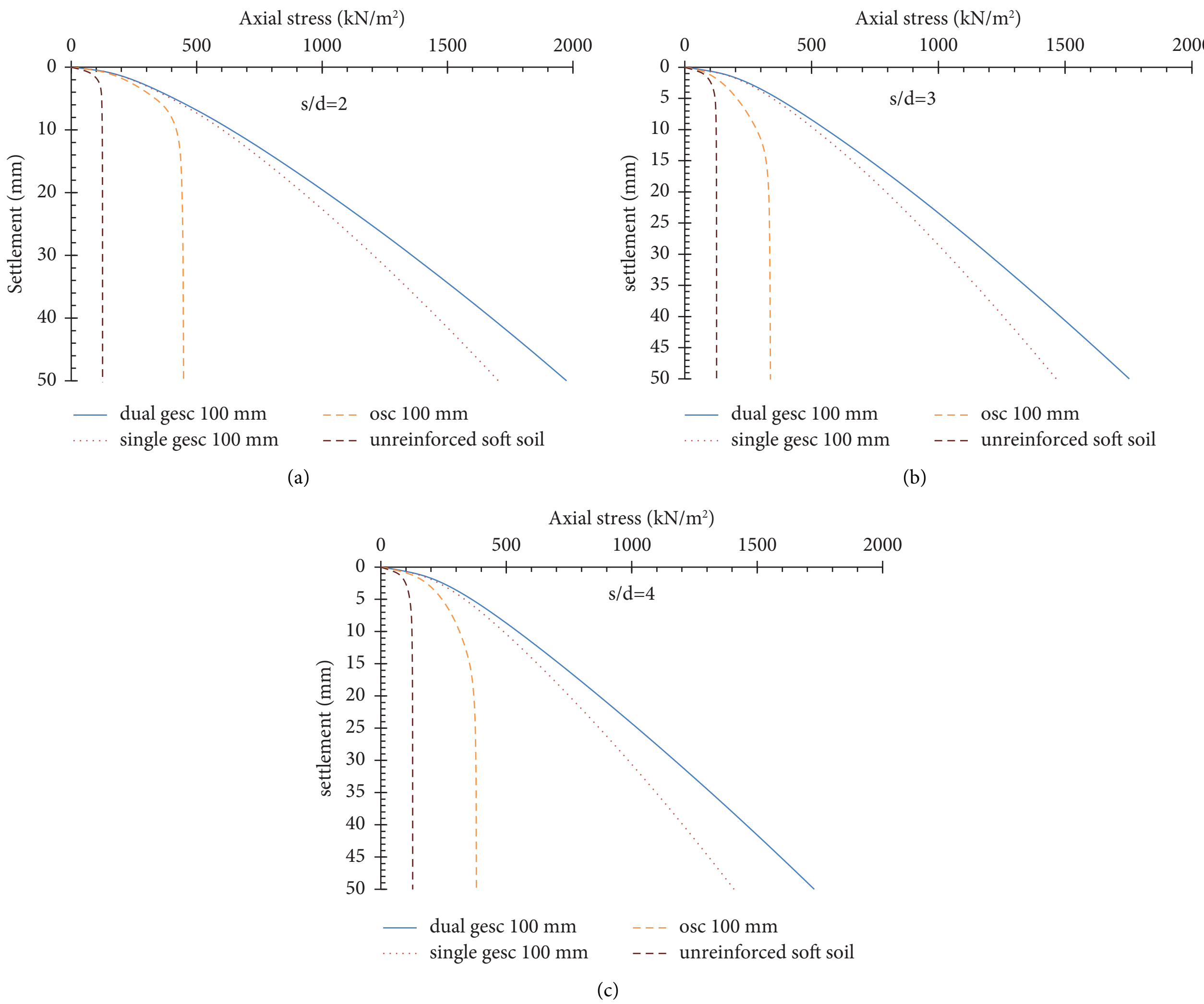


Figure 7: Axial stress vs. settlement of single column: (a) $s/d = 2$, (b) $s/d = 3$, and (c) $s/d = 4$.

have also been made in the current study. The outcomes of this numerical study demonstrated that an ordinary stone column without an encasing was bulging along its periphery. Figure 10 depicts the bulging failure, and it can be noticed that there was less bulging in the case of the provided encasement and also that the encasement material did not rupture. While the external reinforcement, in the form of encasing the column in a geofabric, will prevent the column from collapsing by bulging or shearing; it will not let the column to dilate and hence raise the in situ stresses [49]. When compared to SL-GESC, DL-GESC lessens bulging, which reflects the goal of the current study. If this encasement arrangement is maintained, the stone column will not fail due to bulging under various loading circumstances. The analysis of stone columns with varying diameters and s/d ratios revealed that the load-carrying capacity of OSC increases for single-layered and dual-layered encasement, which can be seen from Table 5. From observations, it has been deduced that the insertion of an encasement into an ordinary stone column increases its capacity to withstand several loading conditions.

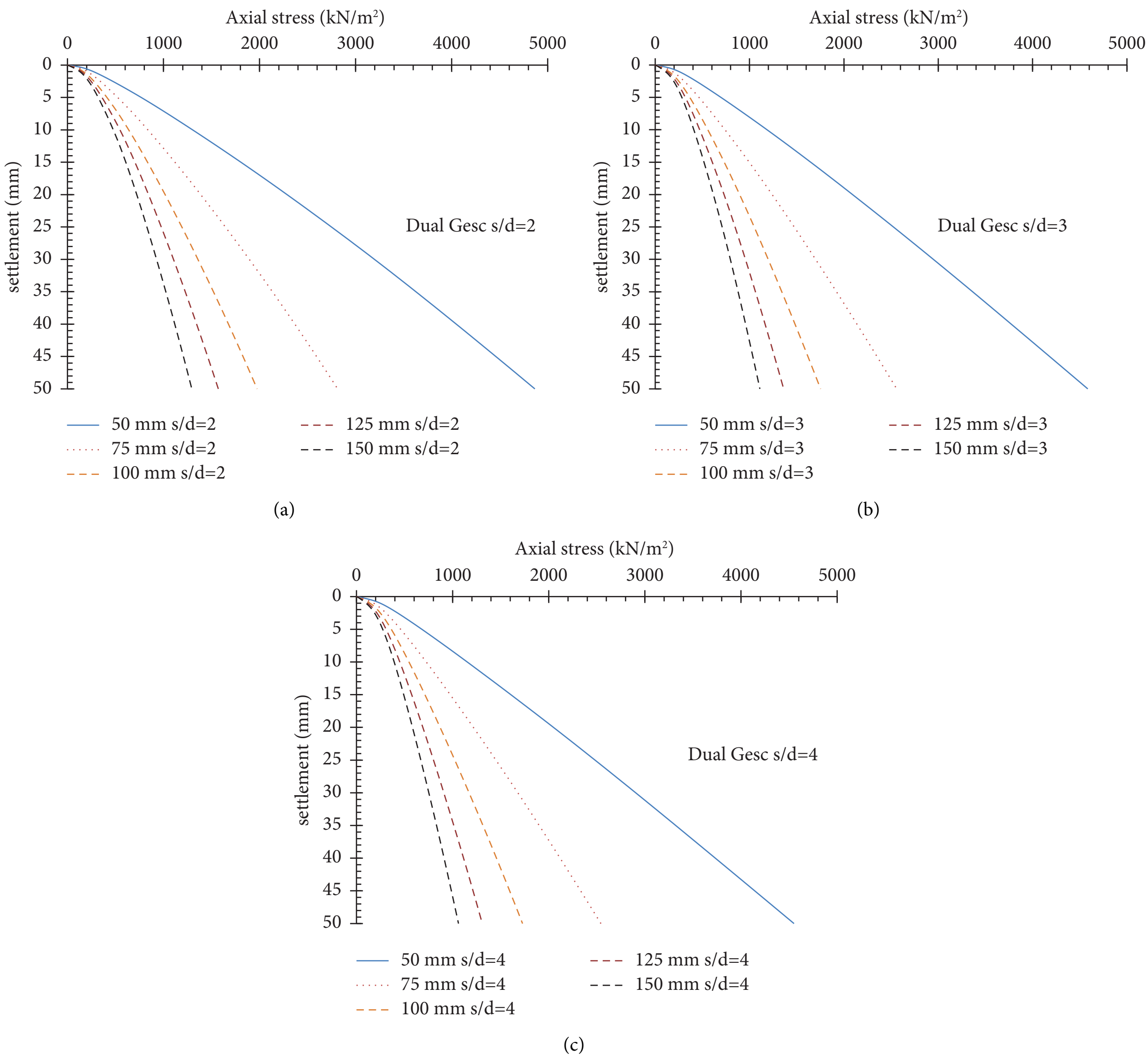


Figure 8: Effect of encasement on axial stress vs. settlement for single column of various diameter of stone column: (a) $s/d = 2$, (b) $s/d = 3$, and (c) $s/d = 4$.

Table 5: Improvement in DL-GESC and SL-GESC compared to OSC.

(mm)		Axial load (kN)			Improvement (%)	
	s/*d* ratio	OSC	SL-GESC	DL-GESC	SL-GESC	DL-GESC
50	2	0.74	7.87	9.56	963.51	1191.89
	3	0.66	7.31	9.00	1007.58	1263.64
	4	0.65	7.23	8.94	1012.31	1275.38
75	2	1.99	10.36	12.43	420.60	524.62
	3	1.58	9.07	11.31	474.05	615.82
	4	1.49	9.11	11.23	511.41	653.69
100	2	3.52	13.37	15.51	279.83	340.63
	3	2.65	11.51	13.77	334.34	419.62
	4	2.99	11.06	13.57	269.90	353.85
125	2	4.64	16.41	19.27	253.66	315.30
	3	4.12	13.98	16.71	239.32	305.58
	4	4.11	13.32	16.06	224.09	290.75
150	2	6.70	19.73	22.88	194.48	241.49
	3	5.94	16.67	19.61	180.64	230.13
	4	5.94	15.84	18.75	166.67	215.66

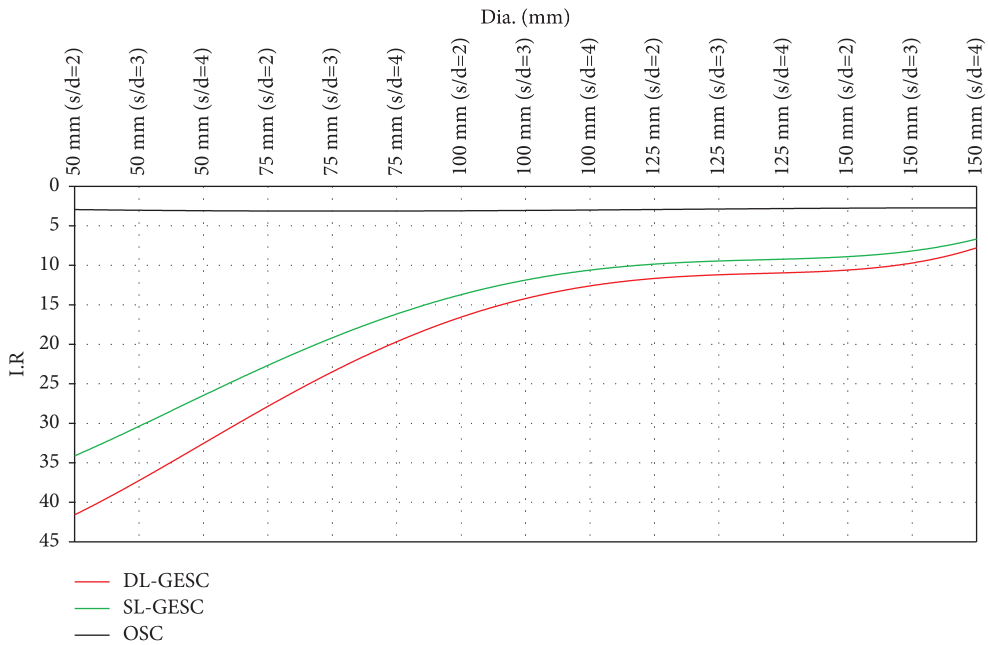


Figure 9: Trendline of I.R. of single column.

Figure 10: Effect of bulging: (a) SL-GESC and (b) DL-GESC.

7. Conclusions

(i) The spacing-to-diameter ratio influences the axial stresses that occur within the body of the stone column; as the ratio increases, so does the load-carrying capacity of the system, with a spacing-to-diameter ratio of 3 being optimal.

(ii) Insertion of the OSC results in higher axial load values at lower settlement values when compared to the clay bed, an enhancement of 2.5 to 3 times is observed for various cases of the stone column diameter; a higher improvement is observed for the larger diameter.

(iii) The encasement of the stone column resists the bulging of the stone column body, which helps in increasing the load-carrying capacity, in cases where single-layered encasement is used, the load-carrying capacity increases by 1.6–10 times in comparison to ordinary stone column cases.

(iv) Introducing an additional layer of encasement into the body of stone column assists in preventing bulging and promotes the confinement of the stone material. Dual-layered encasements provide a 15–25% greater mobilisation of stress than single-layered encasements.

(v) The analysis of stone columns with varying diameters and s/d ratios showed that DL-GESC exhibits less bulging than SL-GESC, indicating that the load-carrying capacity of OSC is enhanced in cases where dual encasement is provided under various loading conditions.

Data Availability

The authors have agreed to provide the information used and/or analysed during the current work upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] R. Ghanti and A. Kashliwal, *Ground Improvement Techniques – with a Focused Study on Stone Columns*, vol. 30, Dura Build Care PVT LTD, Patna, Bihar, 2008.

[2] 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.

[3] C. J. Serridge, "Some applications of ground improvement techniques in the urban environment," *Iaeg2006*, vol. 296, pp. 1–14, 2006.

[4] 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.

[5] M. C. Alfaro, A. S. Balasubramaniam, D. Bergado, and J. C. Chai, *Improvement Techniques of Soft Ground in Subsiding and Lowland Environment*, Taylor & Francis, Milton Park, Oxfordshire, 1994.

[6] P. Andreou, W. Frikha, R. Frank, J. Canou, V. Papadopoulos, and J. C. Dupla, "Experimental study on sand and gravel columns in clay," *Proceedings of the Institution of Civil Engineers - Ground Improvement*, vol. 161, no. 4, pp. 189–198, 2008.

[7] W. F. Van Impe, *Soil Improvement Techniques and Their Evolution*, Taylor & Francis, Milton Park, Oxfordshire, 1989.

[8] D. T. Bergado and C. Teerawattanasuk, "2D and 3D numerical simulations of reinforced embankments on soft ground," *Geotextiles and Geomembranes*, vol. 26, no. 1, pp. 39–55, 2008.

[9] R. P. Chen, Y. M. Chen, J. Han, and Z. Z. Xu, "A theoretical solution for pile-supported embankments on soft soils under one-dimensional compression," *Canadian Geotechnical Journal*, vol. 45, no. 5, pp. 611–623, 2008.

[10] A. Lunzhu Li and R. Kerry Rowe, "Effects of viscous behavior of geosynthetic reinforcement and foundation soils on the performance of reinforced embankments," *Geotextiles and Geomembranes*, vol. 26, no. 4, pp. 317–334, 2008.

[11] E. Fathi and R. Mohtasham, *Numerical Analysis of the Reinforced Stone Column by Geosynthetic on Stability of Embankment*, Avestia Publ, Orléans, ON, Canada, 2016.

[12] D. Alexiew, D. Brokemper, and S. Lothspeich, "Geotextile Encased Columns (GEC): Load Capacity," *Geotextile Selection and Pre-Design Graphs*, vol. 23, pp. 1–14, 2005.

[13] D. Lee, C. Yoo, and S. Park, *Model tests for analysis of load carrying capacity of geogrid encased stone column*, OnePetro, Richardson, TX, USA, 2007.

[14] D. Lee, C. Yoo, S. Park, and S. Jung, "Field load tests of geogrid encased stone columns in soft ground," in *Proceedings of the International Offshore and Polar Engineering Conference*, vol. 8, pp. 521–524, Danvers, MA, USA, May 2008.

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

[16] M. Raithel and H. G. Kempfert, *Calculation models for dam foundations with geotextile coated sand columns*, OnePetro, Richardson, TX, USA, 2000.

[17] J. Gniel and A. Bouazza, "Improvement of soft soils using geogrid encased stone columns," *Geotextiles and Geomembranes*, vol. 27, no. 3, pp. 167–175, 2009.

[18] P. Debnath and A. K. Dey, "Bearing capacity of geogrid reinforced sand over encased stone columns in soft clay," *Geotextiles and Geomembranes*, vol. 45, no. 6, pp. 653–664, 2017.

[19] K. Tilva Vikunj, "Study on geosynthetic reinforced stone column with soft & stiff clay," *International Research Journal of Engineering and Technology*, vol. 4, no. 7, pp. 593–595, 2017.

[20] K. Ali, J. T. Shahu, and K. G. Sharma, "Model tests on geosynthetic-reinforced stone columns: a comparative study," *Geosynthetics International*, vol. 19, no. 4, pp. 292–305, 2012.

[21] K. Ali, J. T. Shahu, and K. G. Sharma, "Model tests on single and groups of stone columns with different geosynthetic reinforcement arrangement," *Geosynthetics International*, vol. 21, no. 2, pp. 103–118, 2014.

[22] S. K. Dash and M. C. Bora, "Improved performance of soft clay foundations using stone columns and geocell-sand mattress," *Geotextiles and Geomembranes*, vol. 41, pp. 26–35, 2013.

[23] 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.

[24] S. R. Lo, R. Zhang, and J. Mak, "Geosynthetic-encased stone columns in soft clay: a numerical study," *Geotextiles and Geomembranes*, vol. 28, no. 3, pp. 292–302, 2010.

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

[26] 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.

[27] B. Pulko, B. Majes, and J. Logar, "Geosynthetic-encased stone columns: analytical calculation model," *Geotextiles and Geomembranes*, vol. 29, no. 1, pp. 29–39, 2011.

[28] P. A. Suriya, P. Subathra, P. Gopiprasath, and V. Lakshminarayana, "Stabilization of soft soil using stone column – the review," *Journal of Industrial Pollution Control*, vol. 33, no. 1, pp. 1214–1217, 2017.

[29] C. Yoo and S. B. Kim, "Numerical modeling of geosynthetic-encased stone column-reinforced ground," *Geosynthetics International*, vol. 16, no. 3, pp. 116–126, 2009.

[30] T. Ayadat, A. Hanna, and M. Etezad, "Failure process of Stone columns in Collapsible soils," *International Journal of Engineering, Transactions B: Applications*, vol. 21, no. 2, pp. 135–142, 2008.

[31] M. Ghazavi, A. Ehsani Yamchi, and J. Nazari Afshar, "Bearing capacity of horizontally layered geosynthetic reinforced stone columns," *Geotextiles and Geomembranes*, vol. 46, no. 3, pp. 312–318, 2018.

[32] S. Siva Gowri Prasad and P. V. V. Satyanarayana, "Improvement of soft soil performance using stone columns improved with circular geogrid discs," *Indian Journal of Science and Technology*, vol. 9, no. 30, 2016.

[33] S. T. Kadhim, R. L. Parsons, and J. Han, "Three-dimensional numerical analysis of individual geotextile-encased sand columns with surrounding loose sand," *Geotextiles and Geomembranes*, vol. 46, no. 6, pp. 836–847, 2018.

[34] M. Miranda, J. Fernández-Ruiz, and J. Castro, "Critical length of encased stone columns," *Geotextiles and Geomembranes*, vol. 49, no. 5, pp. 1312–1323, 2021.

[35] J. Gao, Y. Zhang, C. Wang, and C. Yuan, "Behavior characteristics of geosynthetic-encased stone column under cyclic loading," *Transportation Geotechnics*, vol. 28, Article ID 100554, 2020.

[36] A. Jaiswal and R. Kumar, "Finite element analysis of granular column for various encasement conditions subjected to shear load," *Geomechanics Engeeniring*, vol. 29, no. 6, pp. 645–655, 2022.

[37] M. Hasan and N. K. Samadhiya, "Experimental and numerical analysis of geosynthetic-reinforced floating granular piles in soft clays," *International Journal of Geosynthetics and Ground Engineering*, vol. 2, no. 3, p. 22, 2016.

[38] J. F. Chen, L. Y. Li, J. F. Xue, and S. Z. Feng, "Failure mechanism of geosynthetic-encased stone columns in soft soils under embankment," *Geotextiles and Geomembranes*, vol. 43, no. 5, pp. 424–431, 2015.

[39] P. Mohanty and M. Samanta, "Experimental and numerical studies on response of the stone column in layered soil," *International Journal of Geosynthetics and Ground Engineering*, vol. 1, no. 3, pp. 27–14, 2015.

[40] 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.

[41] S. Mitra and B. C. Chattopadhyay, "Stone columns and design limitations," in *Proceedings of the Indian Geotechnical Conference*, pp. 201–205, Calcutta, India, June 1999.

[42] M. Ghazavi and J. Nazari Afshar, "Bearing capacity of geosynthetic encased stone columns," *Geotextiles and Geomembranes*, vol. 38, pp. 26–36, 2013.

[43] M. S. S. Almeida, I. Hosseinpour, M. Riccio, and D. Alexiew, "Behavior of geotextile-encased granular columns supporting test embankment on soft deposit," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 141, no. 3, 2015.

[44] M. Hasan and N. K. Samadhiya, "Performance of geosynthetic-reinforced granular piles in soft clays: model tests and numerical analysis," *Computers and Geotechnics*, vol. 87, pp. 178–187, 2017.

[45] R. Jamshidi Chenari, M. Karimpour Fard, M. Jamshidi Chenari, and J. Shamsi Sosahab, "Physical and numerical modeling of stone column behavior in loose sand," *International Journal of Civil Engineering*, vol. 17, no. 2, pp. 231–244, 2019.

[46] L. A. Dar and M. Y. Shah, "Three dimensional numerical study on behavior of geosynthetic encased stone column placed in soft soil," *Geotechnical & Geological Engineering*, vol. 39, no. 3, pp. 1901–1922, 2021.

[47] C. Yoo, "Performance of geosynthetic-encased stone columns in embankment construction: numerical investigation," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 136, no. 8, pp. 1148–1160, 2010.

[48] Civil Planets, "Design and construction for ground improvement-Guidelines," *Burn. Indian Standard*, vol. 15284, pp. 1–20, 2003.

[49] T. Ayadat, A. M. Hanna, and A. Hamitouche, "Soil improvement by internally reinforced stone columns," *Proceedings of the Institution of Civil Engineers - Ground Improvement*, vol. 161, no. 2, pp. 55–63, 2008.