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Horizontally Layered and Vertically Encased Geosynthetic Reinforced Stone Column: An Experimental Analysis

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Abstract: Because of the smaller confinement of the neighbouring soil in very weak soils, the carrying capacity of stone columns may not substantially increase. Geosynthetics can be used to reinforce columns by employing vertical encasement or horizontal layers. In the present study, large-scale laboratory investigations were carried out to evaluate the efficacy of vertical encasement and horizontal layering geosynthetics on the performance behaviour of soft clay. A series of tests were carried out for a horizontal layering of a geotextile with an equal distance throughout the height of the column (the total height of the column is 'L'); horizontal layering over only the top half (i.e., 0.5 L from the head of the considered column); and horizontal layering over only the bottom half of the column (0.5 L from the centre to the foot of the column). Tests were also carried out for vertical encasement in the form of vertically encased stone columns (VESCs) that were employed for various lengths of encasement (i.e., L, 0.75 L, 0.5 L, 0.25 L). The tests were conducted for three different diameters of stone columns, i.e., 50 mm, 75 mm, and 100 mm. As per the findings, the utilisation of horizontal and vertical reinforcing layers enhances the carrying capability of stone columns. Moreover, because of their interlocking and frictional actions with the aggregates of stone columns, the layering decreases the lateral bulging of the considered stone columns. A comparison was performed to find the effectiveness of the horizontal and vertical types of reinforcement, and it was observed that VESCs with full-length encasement and a geotextile with a higher tensile strength for a 100 mm diameter of the stone column were the most desirable arrangements among all.

Keywords: stone column; soft soil; geosynthetics; horizontal and vertical reinforcement

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1. Introduction

Researchers have been searching for previously undiscovered methods of soft soil which, until recently, have been regarded as too costly to develop due to urban and metropolitan regions' infrastructure and economic advancements, as well as large increases in land values. Soft soil is typically spread across large regions and has a low carrying capacity, excessive compressibility, insufficient strength, and low permeability [1,2]. Compaction piles, replacement type, displacement type, prefabricated vertical drains, vacuum pre-consolidation, and soil reinforcement are some tactics that can be used to strengthen compressive soils [2].

Soil reinforcement using stone columns and geosynthetics has been widely used as an important method of soil reinforcement. There have been a wide number of studies based on analytical [3–7], experimental [8–23], and numerical [7,19,21,23–27] analyses on soil reinforcement. There are also various state-of-the-art studies which signify the need for such types of analyses [28–36]. Ambily and Gandhi [37] conducted a set of investigations and experiments to analyse the characteristics of single stone columns in groups. The authors experimented with characteristics such as stone column spacing, softer clay shear strength, and loading conditions for the soft clays, along with varying undrained shear strengths. Murugesan and Rajagopal [13] also performed various tests on single and grouped stone columns that were encased in various geosynthetics with and without encasement. The useful influence of this encasement on the VESCs' bearing capacity was confirmed through load testing. Mohanty et al. [38] conducted a set of studies on tanks with weaker soft clay and covered a somewhat strong and effective silty type of soil of varying thicknesses over the top layer to explore the behaviour of columns of stone in the layered soils. Along with the vertical encasement, another option of reinforcing the stone column is to use the help of horizontal geosynthetic layers [21,39]. A comparison has also been performed between vertically and horizontally encased stone columns [40–43].

The lateral stresses created due to the poor soil serve to limit stone columns. The lateral tension exerted from the nearby area containing softer soil determines the efficacy of the weight that is supported by stone columns. In particularly softer soils, extra confinement is required, which can be attained by enclosing the column of stones in geosynthetics [20]. Even in very soft soil, this encasement enhances the carrying capacity and rigidity and lowers the lateral swelling for the columns of stones.

In this research, the results of a set of tests using large-body experimental loading on solitary stone columns of different diameters are described. Testing on ordinary stone columns (OSCs), vertically encased stone columns (VESCs), and horizontally reinforced stone columns (HRSCs) was conducted to evaluate the effect of the reinforcement type and different reinforcement materials (two types of geosynthetics were used) on the soil's response. The major goal of the current study is to perform a comparison on the efficacy of VESCs and HRSCs in soft soil for various stone column diameters under the same conditions.

2. Experimental Analysis

2.1. Material Characteristics

Soft clay, crushed stones, and two varieties of geotextiles (G1 and G2) were employed as the materials in this study. The stone materials and clay were classed as GP and CL according to the Unified Soil Classification System. Crushed stone and geotextiles were chosen to improve the characteristics of the soft clay, and the materials were selected because of their feasible availability. Similar materials have been chosen by various researchers [11,13,19,34]. The numerous different characteristics of both materials are presented in Tables 1 and 2. To estimate the water content that is equivalent to a clay undrained a shear strength of 20 kPa, a set of unconfined compressive strength (UCS) experiments were performed on a cylindrical sample with a diameter of 38 mm and a height of 76 mm. Moreover, the laboratory vane shear test was performed to decide the water content that corresponded to a particular undrained shear strength, which was performed according to Indian Standard IS2720 part 30 [44]. Various test samples were prepared using different water contents, and the undrained shear strength was determined [44]. Figure 1 shows the variation in the undrained shear strength in response to the moisture content from the results of the laboratory vane shear test. The clay's moisture content was calculated as 26.13% (Figure 1), which was maintained throughout the experiments. The stone column material consisted of crushed stone aggregates that had diameters that varied from 2 to 10 mm.

Table 1. Characteristics of soft clay.

Characteristics	Data
Liquid Limit	50%
Plastic Limit	27%
Specific Gravity	2.56
Plasticity Limit	23%
Shrinkage Limit	10%
Optimum Moisture Content	19.23%

Table 1. *Cont.*

Characteristics	Data
Maximum Dry Unit Weight	17.16 kN/m^3
Bulk Unit Weight at 26.13% water content	18 kN/m^3
Undrained Shear Strength	20 kPa
Unified Classification System	CL

Table 2. Characteristics of stone column material.

Characteristics	Data
Specific Gravity	25
Maximum dry unit weight	16.4 kN/m^3
Minimum dry unit weight	14.4 kN/m^3
Bulk unit weight for the test at 68% relative density	15.8 kN/m^3
Internal friction angle (φ) at 68% relative density	42°
Uniformity coefficient (C_U)	2.14
Curvature coefficient (C_c)	1.10
Unified classification system	GP

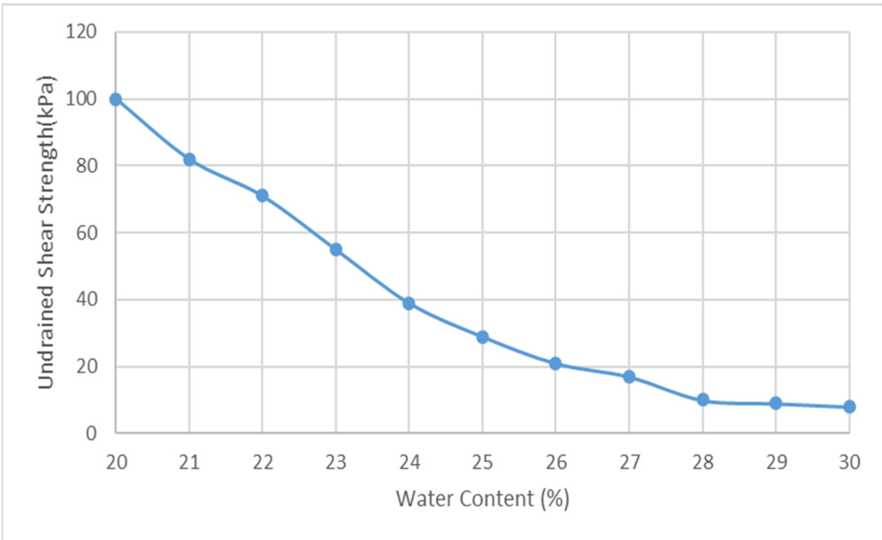


Figure 1. Clay's undrained shear strength variation with moisture content.

With regard to the resemblance analysis concepts and the scale effect theory, selecting reinforcement material qualities is a significant task in laboratory model tests. For both large-scale site stone columns and small-scale model testing, the non-dimensional factors must have the same value according to similarity analysis [20] as shown in Equation (1):

$$\left(\frac{J_m}{\gamma_m D_m^2}\right) = \left(\frac{J_f}{\gamma_f D_f^{22}}\right), \tag{1}$$

where J is the stiffness of the geotextile, D is the diameter of the column, γ is the unit weight of the material to be used for the column of stones and the characters 'f' and 'm' signify the field and model conditions, respectively.

Two varieties of polypropylene (non-woven type) geotextiles were considered as a strengthening substance in the proposed testing. Table 3 shows the value of the tensile strength of considered geosynthetics as measured by standard wide-width tension testing.

Table 3. Properties of Geosynthetics.

Parameters	Geotextile 1 (G1)	Geotextile 2 (G2)
Ultimate tensile strength (kN/m)	8	12
Strain at ultimate strength (%)	52	36
Tensile modulus (kN/m)	14	31.5
Ultimate tensile strength from tests with seam (kN/m)	7	11.4
Strain at ultimate strength (%) from tests with seam	46.5	30.8
Tensile modulus (kN/m) from seam tests	14.8	35

Figure 2 shows a diagram of the three different kinds of columns employed in this study, which are Ordinary stone columns (OSC), Vertically reinforced stone columns (VESC), and Horizontally reinforced stone columns (HRSC) for different lengths of reinforcement considered in this study.

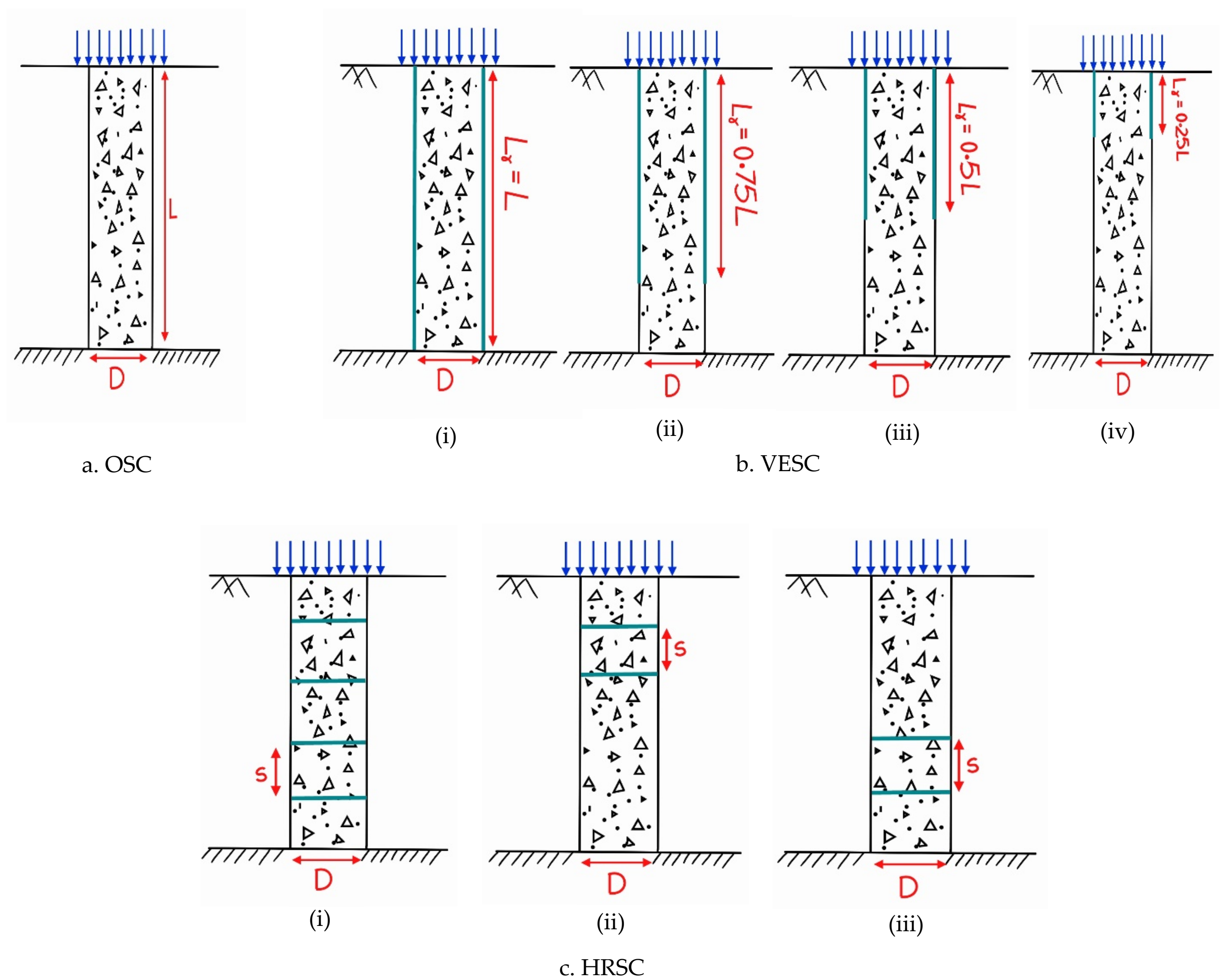


Figure 2. Schematic of (**a**) OSC, (**b**) VESCs with various L_r, (**c**)HRSCs with various geosynthetic arrangements.

2.2. Test Set-Up and Procedure

The plan dimension of the test box used for the test set-up was 1.5 m × 0.9 m × 0.6 m. The tank includes a strong loading frame and one loading system that allows soft soil and the stone column materials to be loaded (Figure 3). The present model tests were carried out in accordance with other researchers who carried out comparable testing. The footing loading was imposed on a stone column installed in the middle of a clay bed prepared in a big test tank [19,35]. The tank's plan dimension was chosen such that the test findings would not be influenced by the tank's boundaries. The loading system for this test was stress controlled, where the loading rate was established by a hydraulic jack with a capability of 20 kN. The test steps entail implementing a vertical monotonic load to the clay treated with a stone column and calculating the load-displacement behaviour of the softer clay. The vertical application of load was made after the column of stones was installed, utilising a plate placed at the centre of the column and a bed of clay.

Figure 3. Test setup and installation of the stone column with geosynthetics at the centre of the set-up.

In the current study, single stone columns were subjected to 48 tests. A robust plate of steel with a 200 mm diameter along with a thickness of 25 mm was utilised for the plate used for loading in all solitary stone column testing. Table 4 summarises the outcome of this testing. For all single stone column testing, an L/D ratio (stone column's length to its diameter) of the above five was employed; as a minimum, L/D = 4 is necessary to prevent the bulging collapse mode [43]. In the case of VESCs and HRSCs, various encasement lengths were used, as shown in Table 4 and Figure 2. Single stone column tests were conducted on the columns with 50, 75, and 100 mm diameters using a 200 mm loading plate. The area replacement ratio is determined as the proportion of the cross-sectional area of stone columns to the entire area of the foundations and is indicated in the literature. In these experiments, the percentages were 6.25, 14.06, and 25% for the columns with the diameters of 50, 75, and 100 mm, respectively.

2.3. Clay Bed Preparation

The weak clay bed preparation was carried out in a large testing box with a plan dimension of 1200 mm × 900 mm and a 600 mm height. The clay bed was laid out in layers of 50 mm thickness. The inside of the face walls of the testing box was covered in a thin layer of grease to reduce friction between the clay and the tank wall. At first, the clay's natural water content was assessed, and the amount of additional water needed to generate a moisture content of 26.13 percent in a big plastic box was calculated. This moisture content corresponds to a shear strength of 20 kPa when not drained. A nylon cloth was used to cover the box's exterior and secured for three days to achieve consistent water content within the softer clayey soil mass. The clay was poured into the tank at a precise weight to achieve a bulk unit weight of 18 kN/m^3. A customised tamper unit of 200 × 200 mm in plan was used to compact clay by lowering the tamper from a distance of 250 mm high. The clay bed's finished surface was levelled and trimmed in all tests to ensure adequate thickness and smoothness. All the tests followed the same approach to produce the desired clay bed. The water content profile was evaluated at 100 mm intervals for all tests to confirm that the moisture level in the clay remained constant. The change in the moisture within the clay bed was determined to be less than 1.5% in all tests.

Table 4. Outline of the various tests performed.

Test Type	Test Description	Reinforcement Length	Reinforcing Material	Diameter of the Column			Total No. of Tests
				50 mm	75 mm	100 mm	
Single Stone Column	Clay			✓	✓	✓	3
	Ordinary Stone Column (OSC)			✓	✓	✓	3
	Vertically Encased Stone Column (VESC)	$L_r = L$	G1	✓	✓	✓	3
			G2	✓	✓	✓	3
		$L_r = 0.75\ L$	G1	✓	✓	✓	3
			G2	✓	✓	✓	3
		$L_r = 0.5\ L$	G1	✓	✓	✓	3
			G2	✓	✓	✓	3
		$L_r = 0.25\ L$	G1	✓	✓	✓	3
			G2	✓	✓	✓	3
	Horizontally Reinforced Stone Column (HRSC)	Equal intervals throughout the depth	G1	✓	✓	✓	3
			G2	✓	✓	✓	3
		The top half (0.5 L from column head)	G1	✓	✓	✓	3
			G2	✓	✓	✓	3
		The bottom half (0.5 L from the centre to the foot)	G1	✓	✓	✓	3
			G2	✓	✓	✓	3

2.4. Construction and Installation Method of Stone Columns

The replacement approach was employed for building stone columns with diameters of 50, 75, and 100 mm in all the tests (OSC, VESC, and HRSC), including the creation of stone columns at the centre of a huge testing box. The tank's plan size was chosen in a way that the tank's boundarieank's boundaries would hardly influence the test findings. A similar approach was adopted by previous researchers [20]. Stone columns were constructed of slender, smooth pipes made up of steel with inner diameters of 50, 75, and 100 mm and a wall width of 2 mm. Both the inner and exterior sides of the steel pipes were treated with a thin coating of grease to allow for penetration and extraction without causing substantial disruption to the nearby soil, and then these steel pipes were then driven into the softer clay to reach the bottom. Different helical steel augers were built and employed to withdraw the clay from inside the pipe. To make clay removal easier and avoid a suction effect, extraction of the weak clay within the pipe was allowed to a maximum thickness of 50 mm at a single period. After removal of the clay from the pipe, the steel pipe was slightly pulled out. As a result, care was ensured so that the pipe and the hole's skin did not come into contact. The quantity of stone aggregates equivalent to a bulk unit weight value of 15.8 kN/m^3 was estimated and filled inside the hole in three equal layers to build the stone column. A unique circular tamper with a 1.5 kg weight and 20 mm of diameter was utilised to compact this stone material by releasing the tamper from about a distance of 100 mm height with 25 blows for every layer to achieve a homogeneous density. A tube with a diameter slightly smaller than the diameter of the dug hole was used to place vertical encasing reinforcement at the place of the excavated hole for VESC tests. HRSC followed the same design procedure as OSC. Horizontal geotextile sheets were installed at specific depths inside the column length in HRSC tests.

3. Results and Discussions

3.1. Failure Mode and Deformation

In several OSC and VESC tests, the distorted shape of the stone columns was captured by filling the stone column and the region of the loading plate with plaster of Paris paste. In HRSC experiments, however, filling with plaster of Paris paste was not possible due to the presence of horizontal sheets. As a result, after the test, the soft soil surrounding the column was meticulously sliced vertically to detect failure and deformation. The bulging failure mode was dominant in all the single stone column testing. Bulging failure happened at a depth of D to 2.5 D from the top of the stone column according to the findings in the case of OSC, which can be seen in Figure 4a. The result of this study is comparable to those made by Murugesan and Rajagopal [13] and Pandey et al. [34]. The rigidity of a stone column rises when it is enclosed because it provides greater protection from bulging by mobilising hoop stresses within the geosynthetic material. In the case of VESCs, just beneath the encasement length, bulging is readily discernible for L_r = 0.25 L, as shown in Figure 4b(iv). This bulging depth and the position of the bulge can be found as similar to that of the OSC case (Figure 4a). Bulging was minimal for the column with a 50% encasement length (L_r = 0.5 L). Only a minor lateral distortion was seen underneath the encased zone (Figure 4b(iii)). A similar observation was noticed for a 75% encasement length, i.e., L_r = 0.75 L (Figure 4b(ii)). The 100% encased column (L_r = L) failed the punching test because there was no bulging along its whole length (Figure 4b(i)). A similar deformation pattern was observed by previous researchers [11,13].

In the case of HRSCs, when horizontal strips were provided throughout the length of the column at equal intervals (i.e.,100 mm), the column collapsed due to localised swelling at around 1.5 D to 2.5 D, which was similar to that of OSC (Figure 4c(i)). This indicates the inadequacy of the spacing between the horizontal layers of geotextiles. Figure 4b(ii) shows subtle bulging after the reinforcement was conducted for the top half of the column (0.5 L from column head) at the intersection of the reinforced and unreinforced sections of the column length. When the reinforcement was performed for the bottom half (0.5 L from centre to foot), the bulging failure was similar to that of an unreinforced case.

3.2. Load-Settlement Analysis

Figure 4a–c shows the load-settlement behaviour of unreinforced and reinforced soft clay with columns made up of stone with diameters of 50, 75, and 100 mm and various methods of column reinforcement for VESCs and Figure 5a–c for HRSCs. OSCs, HRSCs, and VESCs were found to boost the soft soil's ultimate load-carrying capability. The ultimate carrying capacities of the three types of columns (OSCs, HRSCs, and VESCs) were raised by raising the a_s from 6.25 to 25%. Furthermore, their ultimate capacity rose when stone columns were strengthened by the geosynthetic material for vertical encasement or horizontal reinforcement. The vertical encasement for VESCs was studied for various lengths of reinforcement, i.e., L_r = L, L_r = 0.75 L, L_r = 0.5 L and L_r = 0.25 L. VESC data for two different geotextile materials with varying strengths are also displayed. Vertical encasement of the stone columns increases capacity and rigidity. Also, it was evident that the full length of the encasement, i.e., L_r = L, provides a higher capacity and stiffness than the other three L_r used. Furthermore, compared to OSCs, the ultimate carrying capacity of VESCs improves as the ultimate tensile strength of the encasement material increases. Prior researchers noticed a similar tendency [11,13,15,17].

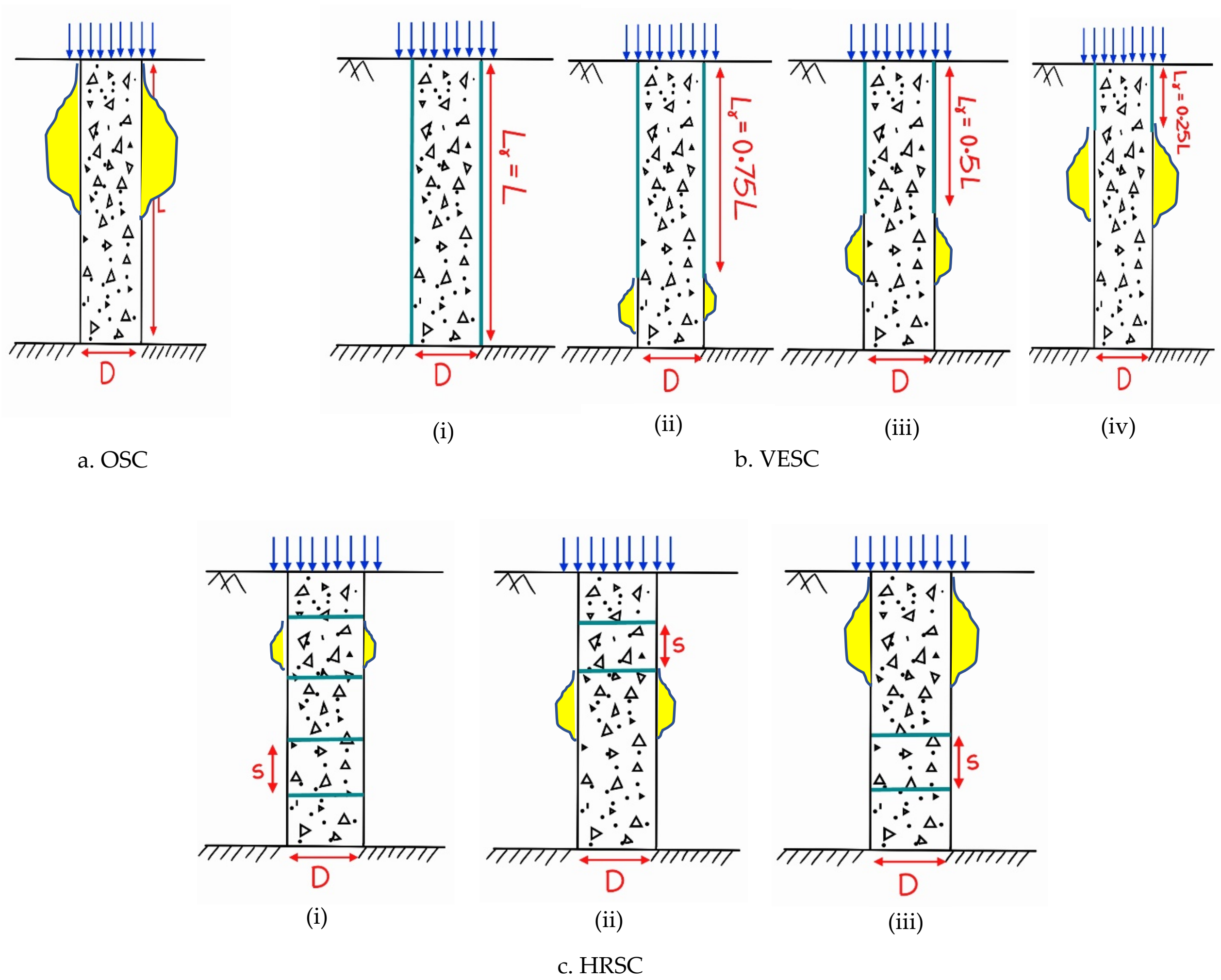
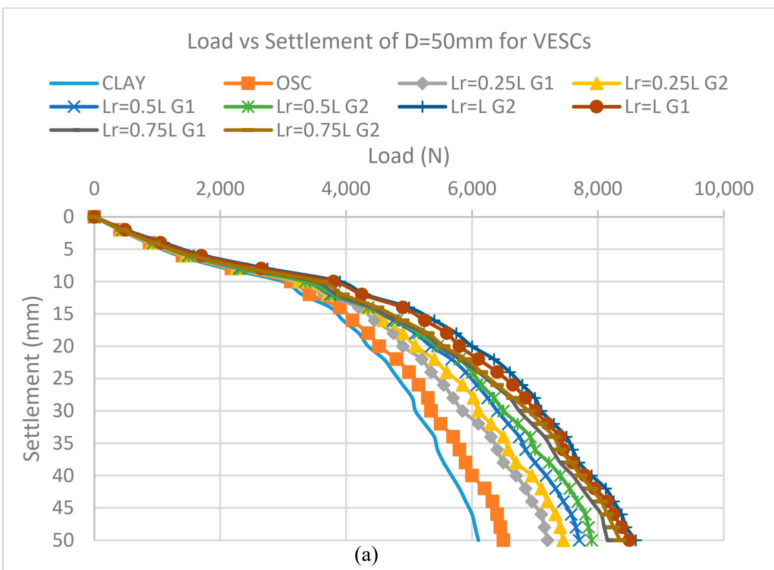


Figure 4. Sketch represents the various failure modes for 100 mm diameter column (**a**) OSC (**b**) VESC (**c**) HRSC.



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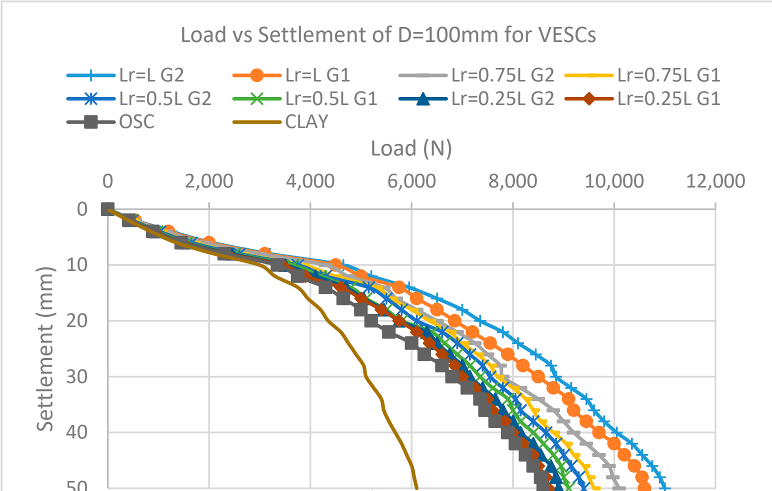

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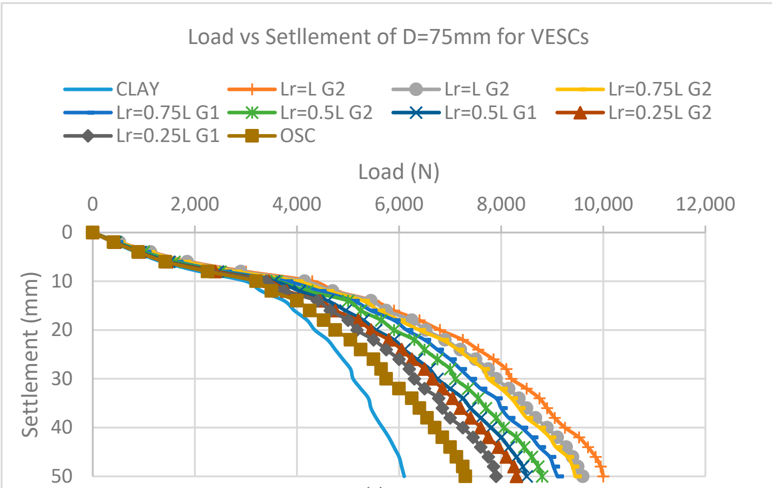


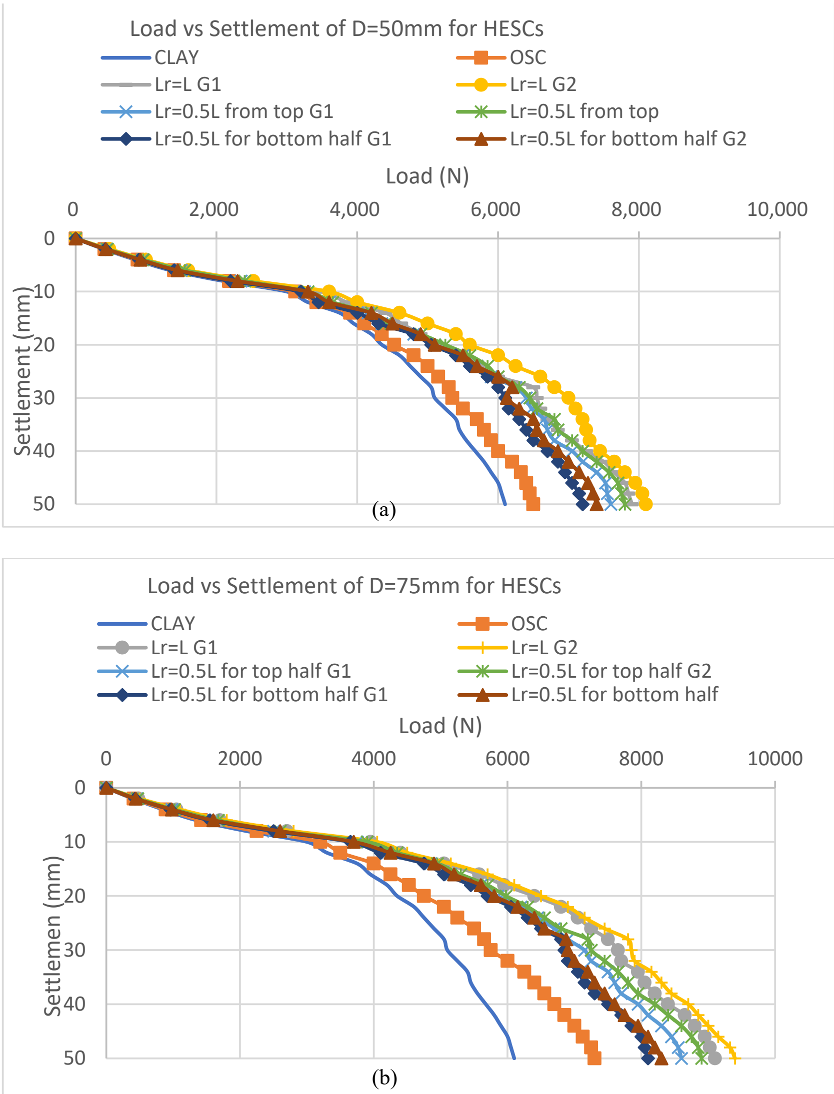
(c)

Figure 5. Load-Settlement variation of VESC for various L_r on single stone column with diameters (**a**) 50 mm, (**b**) 75 mm, and (**c**) 100 mm.

In comparison to OSC, certain tests were conducted to see how effective horizontal reinforcement is at enhancing the ultimate carrying capacity of HRSC. The outcome of experiments on HRSC with diameters of 50, 75, and 100 mm are shown in Figure 5a–c. The HRSCs were used at equal intervals throughout the length of the column (4 strips @ 0.1 m spacing), also at half of the column from the column head (2 strips @ 0.1 m spacing till 0.5 L from column head) and the bottom half of the column (2 strips @ 0.1 m spacing starting from the centre of the column along its length till the end). Because the horizontal reinforcement sheets constrain the materials of columns between the horizontal reinforcement layers and offer extra radial confinement due to the shear stresses generated between reinforcing sheets and granular materials of stone, the ultimate bearing capacity of columns improves as indicated. Also, it was found that providing HRSC throughout the column length was more effective [21] than the other two methods. However, the HRSC at the top half was more effective than it was when providing it at the bottom half as the initial load can be controlled effectively. As a result, the lateral bulging was reduced at an early stage. Furthermore, when the ultimate tensile strength of the horizontal reinforcement sheets is raised, the ultimate carrying capacity of HRSCs improves compared to OSCs.

3.3. Improved Load Ratio

The load ratio (LR) parameter can be used to analyse and estimate the efficiency of stone columns in terms of ultimate bearing capacity. It is the ratio of the ultimate load sustained by a stone-column-reinforced soil to the ultimate load carried by soft soil without a stone column.Figures 6a–c and 7a–c show the LR variation with settlement for stone columns with diameters of 5,7.5, 10 cm, and various reinforcing forms. As can be seen from the graphs, the LR for stone columns with diameters of 5, 7.5, and 10 cm for VESCs varies between 1.07 and 1.41, 1.20 and 1.64, as well as 1.41 and 1.8. The maximum LR is found for a full-length encasement (L_r = L) of VESCs with stronger geotextiles with a value of 1.8, and the minimum LR is for OSCs with a value of 1.07 in the present experimental study. The value of LR for various reinforcement lengths, along with the increasing diameter, progressively increases in the case of VESCs.



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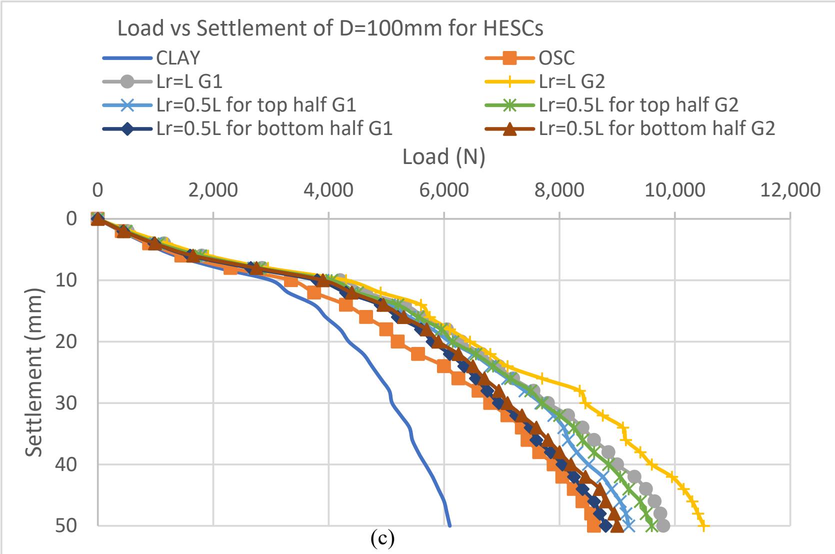

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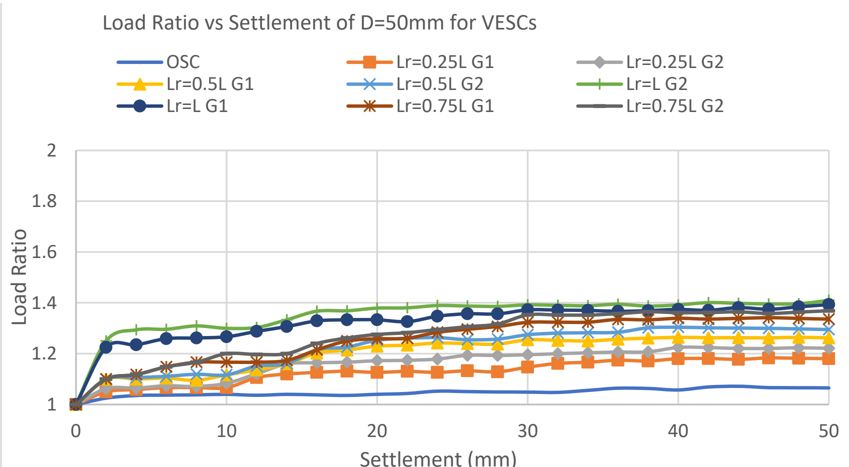
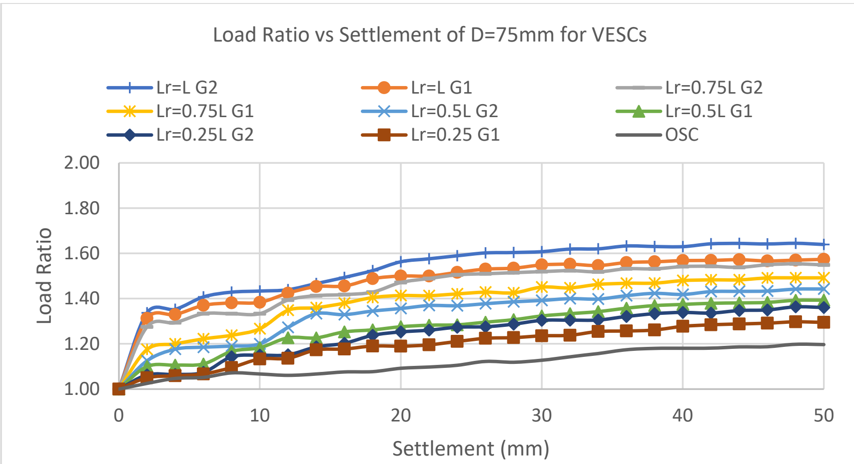
Figure 6. Load-Settlement variation of HRSC for various arrangements on single stone columns with diameters (**a**) 50 mm, (**b**) 75 mm, and (**c**) 100 mm.



(a)



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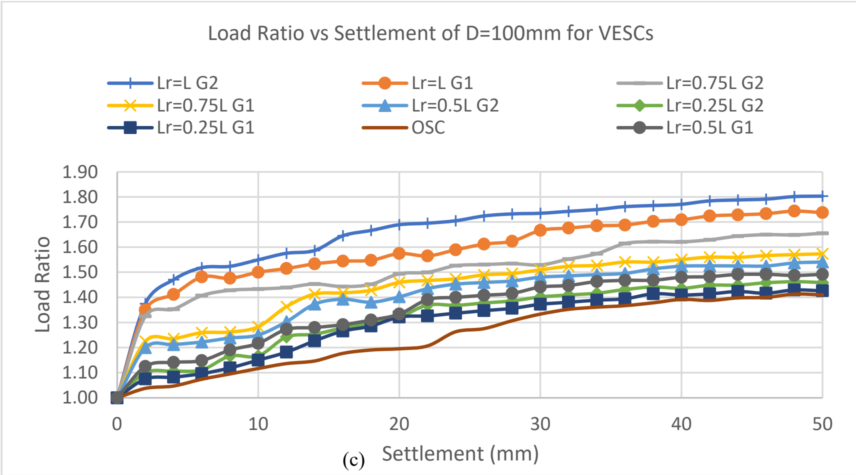


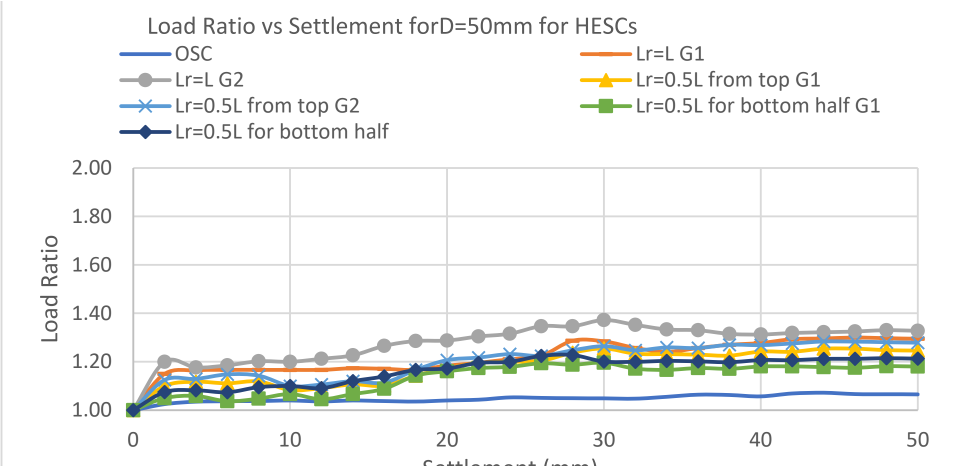
Figure 7. Load Ratio-Settlement variation of VESC for various L_r on single stone column with diameters (**a**) 50 mm, (**b**) 75 mm, and (**c**) 100 mm.

In the case of HRSC, the value of LR for stone columns with diameters 5, 7.5 and 10 cm varies between 1.07 and 1.33, 1.20 and 1.54 as well as 1.41 and 1.72, respectively. As explained earlier, the maximum LR was found for the full length of reinforcement at equal spacing, which was found to be 1.72 compared to the other two methods of HRSC installation. The LR value increases with the tensile strength of the reinforcing material in VESCs and HRSCs, as shown in Figures 6a–c and 7a–c. Because the reinforcement material offered lateral confinement on the columns, the degree of bulging was minimised.

4. Comparison between VESC and HRSC

For the comparison between VESC and HRSC, a full-length encasement in the case of VESC and horizontal reinforcement at equal intervals throughout the depth of the column was studied for both types of geotextiles taken for the study. A graph was plotted for the diameters of 50, 75 and 100 mm, as shown in Figures 8a–c and 9a–c. As it can be seen from the graph, VESC for the full-length encasement with the G2 type of the geotextile for a 100 mm diameter of stone column was most desirable among all. The maximum value of load ratio was found to be 1.80 for the 100 mm diameter of the stone column for the G2 textile for full-length VESC, whereas it was 1.72 for the HRSC for the same specification. The values of load ratio for 50 mm and 75 mm diameter columns for the G2 type of textile for VESC were 1.41 and 1.64, and those for HRSC were 1.33 and 1.54, respectively, as observed from Figure 10a–c.

Vertical encasing reinforcement, in contrast to horizontal reinforcement sheets, necessitates using specialised equipment. In comparison to VESCs, HRSCs do not require improvement initiatives. In this study, the amount of geosynthetic used in HRSCs is much lesser than that used in VRSCs. As a result, compared to VESCs, HRSCs save more than half of the reinforcing material. HRSCs may be one of the cost-effective alternatives, particularly in big projects, due to the ease of constructing horizontal sheets as a reinforcing element in HRSCs. They are also a good approach for reinforcing stone columns, enhancing the ultimate capacity of columns, and decreasing ground settling.



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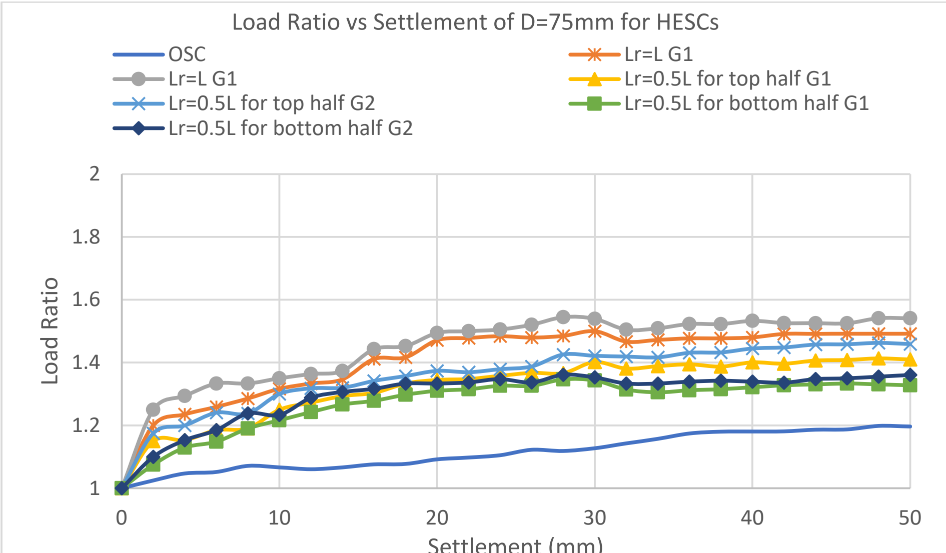

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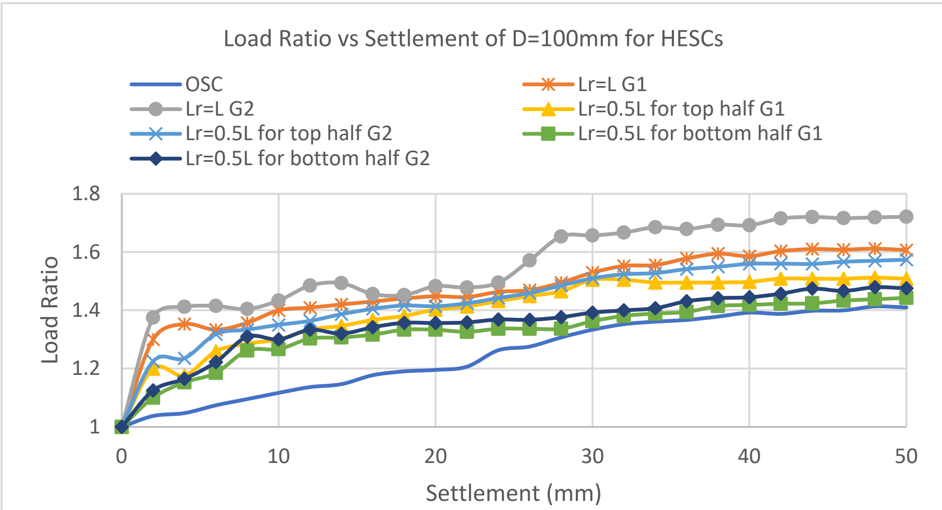

(c)

Figure 8. Load Ratio-Settlement variation of HRSC for various arrangements on single stone columns with diameters (**a**) 50 mm, (**b**) 75 mm, and (**c**) 100 mm.

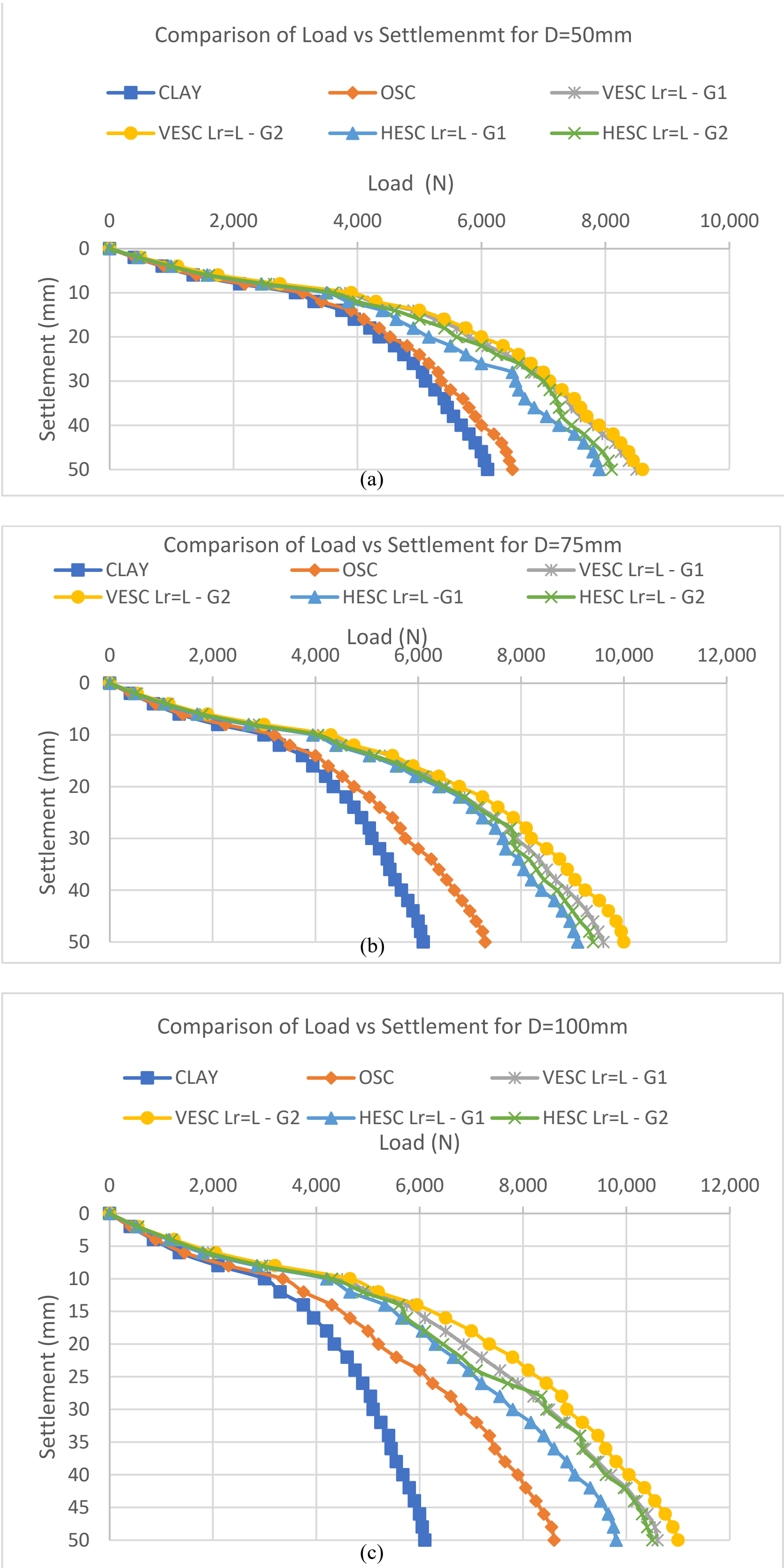

Figure 9. Comparison of Load-Settlement behaviour between VESC and HRSC for L_r = L on single stone column with diameters (**a**) 50 mm, (**b**) 75 mm, and (**c**) 100 mm.

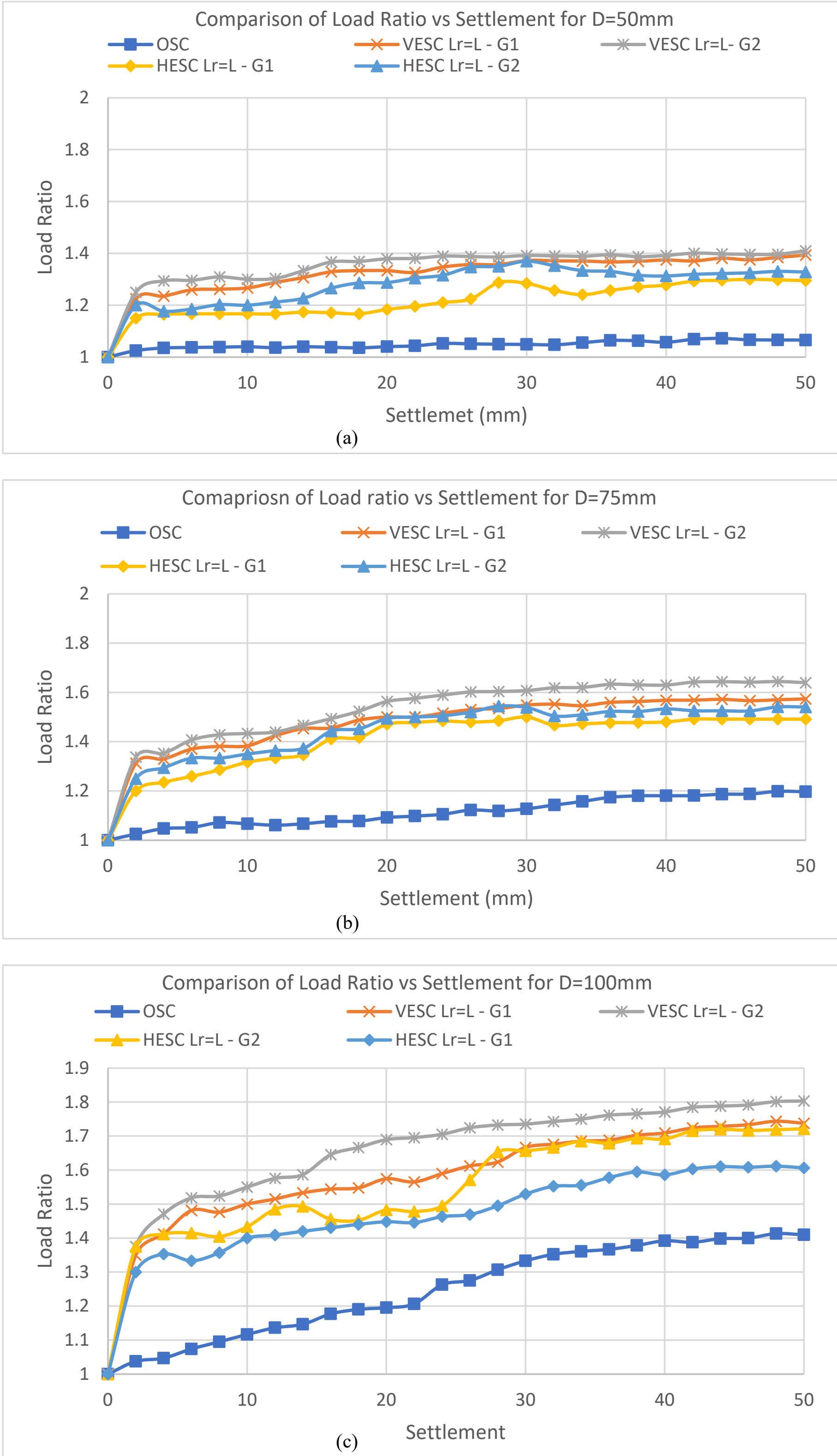

Figure 10. Comparison of Load Ratio-Settlement behaviour between VESC and HRSC for L_r = L on single stone column with diameters (**a**) 50 mm, (**b**) 75 mm, and (**c**) 100 mm.

5. Conclusions

Laboratory tests on single stone columns with diameters of 50, 75, and 100 mm were conducted as part of this study effort. In testing, different lengths of encasement for VESCs and HRSCs were employed, along with two different reinforcing materials, and the findings were compared to those obtained from OSC experiments and also compared among themselves. The following conclusions can be drawn based on the findings of the experimental programme:

1. The governing failure mechanism in all tests was bulging. The bulging failure occurred at a depth of D to 2 D from the stone column head. Limited bulging occurs in the column materials between the reinforcing layers in single HRSCs. Limited bulging occurs when the vertical space between the reinforcing layers is reduced to about the same length as the overall length of the HRSCs.
2. Due to the enhanced lateral constraint given by the considered geosynthetics material, the degree of lateral bulging in VESCs and HRSCs is reduced compared to that of OSCs.
3. When OSCs are employed to reinforce the softer clay, the foundation's ultimate bearing capacity rises. Using vertical (VESCs) or horizontal (HRSCs) reinforcing material enhanced the ultimate load even more. The same can be comprehended with the increasing load ratio value obtained as the maximum value of load ratio was found as 1.80 for the 100 mm diameter of the stone column.
4. The ultimate capacity of VESC and HRSC grows as the reinforcing geotextiles' tensile strength increases. The ultimate capacity and stiffness of stone columns are increased in VESCs and HRSCs by raising the stiffness of horizontal and vertical reinforcing sheets, increasing the length of the reinforced part of the columns (i.e., length of encasement), and lowering the interval gaps between reinforcement layers in case of HRSC. It was visible with the G2 type of geotextile used in the current study.
5. The best HRSCs were found most effective when the reinforcement sheets were provided at equally spaced interval throughout the length compared to partial reinforcements. In the case of VESCs, the total length of encasement ($L_r = L$) was found to be most effective compared to partial reinforcement.
6. The VESC for full-length encasement with G2 type of geotextile for a 100 mm stone column diameter was most desirable among the various tests conducted.

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