



RESEARCH ARTICLE

Strength of Soft Soil Improved by Horizontal and Vertical Woven Geotextile

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ABSTRACT

With increasing coastal development, construction on weak and soft soils has become more prevalent. Stone columns are a common technique for improving ground; their effectiveness in very soft clay is often limited because of the insufficient lateral support. To overcome this limitation, geotextile reinforcement is frequently employed to enhance the strength and stability of stone columns. This study investigates the effects of various geotextile reinforcement layouts, including vertical encasement, horizontal layering, and a combination of both, on the stone columns' effectiveness in soft soil beds. Small-scale laboratory experiments were conducted in a model tank, with all stone columns designed to maintain a ratio of 4 for length-to-diameter to prevent bulging failure. The results indicated that woven geotextile significantly increases load-bearing capacity and reduces settlement. Among the tested configurations, the combined vertical and horizontal reinforcement yielded the best performance, whereas partial vertical encasement combined with moderately spaced horizontal layers provided an effective balance between performance and material efficiency. These findings offer valuable guidance for the cost-effective design of ground improvement solutions in soft soils.

Keywords: Soft soil, woven geotextile, settlement, strength, stone column

INTRODUCTION

Because of the recent increase in coastal development, several ports, factories, and other infrastructural facilities started to be constructed. Consequently, ground with weak strata has had to be used, and designers have encountered difficulties due to low-density soft soil layers. While pile foundations can meet all design requirements, the excessive length of the piles and the negative drag force can lead to prohibitively high costs. Therefore, ground improvement methods are typically preferred for economic reasons. Among the various available methods, stone columns are widely used. This ground improvement method has been effectively applied to reduce settlement and enhance the load-carrying capacity of soft soils. In cases when the soil's undrained shear strength is particularly low, stone columns may become ineffective, as the surrounding weak soil may not provide adequate confinement. This lack of confinement can lead to bulging or crushing of the upper sections of the columns.^[1] To enhance their stiffness, stone columns are often reinforced with geotextiles. Mohammed *et al.*^[2] conducted a small-scale laboratory experiment to investigate the load and the settlement characteristics of reinforced stone columns. The results showed that using geotextiles as reinforcement significantly enhances the bearing capacity and helps control settlement. According to results reported by Farah and Nalbantoglu, and Miranda *et al.*,^[3,4] reinforced stone columns can sustain a load 1.5–2.5 times more than those

without reinforcement. As indicated in the literature review by Chenari *et al.* and McCabe *et al.*,^[5,6] most research on stone column performance focuses on end-bearing stone columns. The ability of floating stone columns to support loads has not been thoroughly investigated. Previous studies have mostly employed small-scale laboratory tests according to the unit cell concept to study end-bearing granular columns. However, the effect of different geotextile placements within stone columns has not been fully explored in previous research. To evaluate the load-bearing capacities of a stone column reinforced with geotextile in three configurations: Horizontal layers, vertical encasement, and combined vertical–horizontal encasement. Small-scale laboratory experiments were carried out on floating stone columns placed in a soft clay bed. A minimum ratio of 4 for length-to-diameter was used to prevent bulging failure, as advised by Madhav.^[7] As a result, the tested columns

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were 400 mm long and 100 mm in diameter. The objective was to assess the effects of varying geotextile reinforcing locations on stone column performance.

MATERIAL

Soft Soil and Stone Column Material

To prepare the soil bed, remolded clay was used. The physical and mechanical properties of the remolded clay are presented in Table 1, and all data were obtained from laboratory testing conducted as part of the present study. The grain size distribution was determined using sieve and hydrometer analysis in accordance with ASTM D422. The soil classification was performed following the Unified Soil Classification System, and the soil was classified as (Lean Clay).

The maximum dry density and optimum moisture content were determined using the Modified Proctor compaction test in accordance with ASTM D1557, as shown in Figure 1. The soil was compacted in layers to achieve uniform density throughout the model tank up to a height of 650 mm.

The undrained shear strength (c_u) was determined using the unconfined compression test in accordance with ASTM D2573. Cylindrical specimens with a height-to-diameter ratio of 2:1 were prepared at the same moisture content and dry density as the model soil bed. The axial load was applied at a constant strain rate until failure, and the undrained shear

strength was calculated as half of the unconfined compressive strength. The corresponding stress–strain curve is shown in Figure 2.

The internal friction angle of the stone column material was determined using the direct shear test in accordance with ASTM D3080 and was found to be 45° , as shown in Figure 3.

In the field, the stone column diameter (D) varies from 0.6 m to 1.0 m, and the particle size (d) ranges between 25 mm and 50 mm, resulting in a D/d ratio between 12 and 40.^[8] Therefore, in this investigation, a model stone column with a diameter of 100 mm and crushed stone with a median particle size $d_{50} = 4.2$ mm was used, resulting in a D/d ratio of 23.8, which falls within the reported field range. The grain size distribution of the soil and stone column is illustrated in Figure 4.

Geotextile Properties

The three main parameters that influence the effectiveness of stone columns are:

1. Stone columns diameter
2. Crushed stone unit weight
3. Stiffness of the reinforcement material

The relationship between these parameters is described by (1):^[9]

Table 1: Characteristics of soft soil used in this investigation

Properties	Unit	Value	Standards
Undrained shear strength	kPa	27.58	ASTM D 2573
Water content	%	10	ASTM D 2216
Liquid limit	%	36.08	ASTM D 4318
Plastic limit	%	19.62	ASTM D 4318
Plasticity index	%	16.46	ASTM D 4318
Total unit weight	kN/m ³	16.04	ASTM D 4914
Dry unit weight	kN/m ³	14.60	ASTM D 4914
Maximum dry unit weight	kN/m ³	16.31	ASTM D 1557
Optimum moisture content	%	20	ASTM D 1557
USCS classification symbol		CL	ASTM D 2487

USCS: Unified Soil Classification System

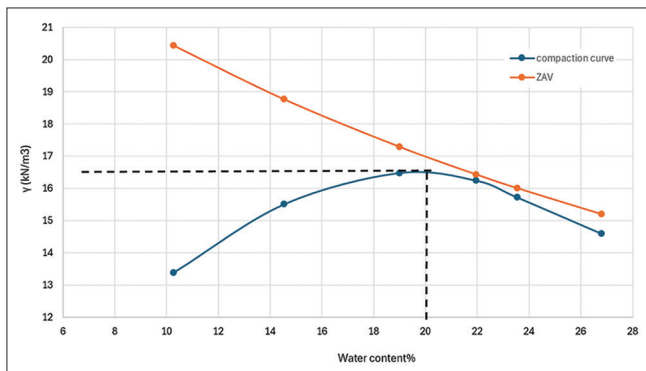


Figure 1: Compaction curve of the soil

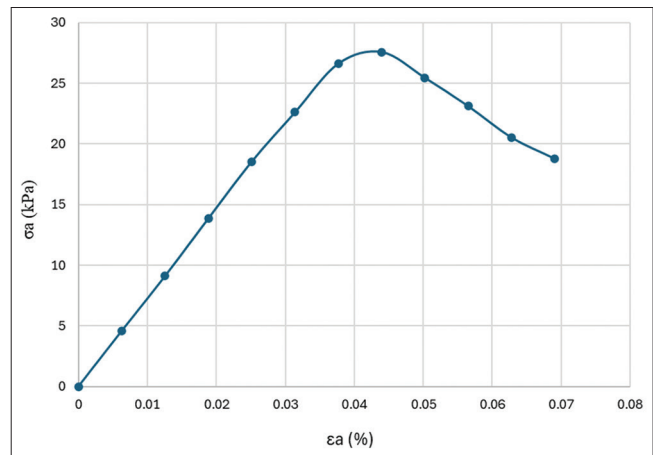


Figure 2: Stress–strain curve obtained from the unconfined compression test

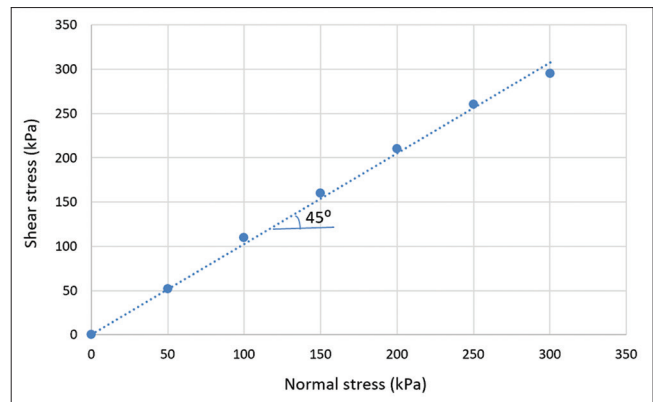


Figure 3: Direct shear test failure envelope for crushed stone

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

Where D refers to the diameter of the stone column, γ is the unit weight of crushed stone, and J is the stiffness of the reinforcement material. In addition, m and f refer to the laboratory and field conditions, respectively. Since the unit weight is the same in both the field and the laboratory, it does not affect the equation. The stone column diameter in the model was chosen to be equivalent to a stone column with a diameter of 625 mm in the field. Thus, the scale factor, according to (2),^[10] is:

$$\lambda = \text{field diameter/laboratory diameter} \tag{2}$$

The scaling factor for this study, with a stone column diameter of 100 mm, is 6.25. Therefore, the relation between J_m and J_f is expressed as:

$$J_m = \frac{J_f}{\lambda^2} \tag{3}$$

In the field, the stiffness of geotextiles ranges from 1000 kN/m to 4000 kN/m.^[11] Therefore, for this study, the scaled stiffness of geotextiles ranges between 25.6 kN/m and

102.4 kN/m. A polypropylene woven geotextile that has a stiffness of 96 kN/m has been employed in the model. Table 2 lists the characteristics of woven geotextile.

EXPERIMENTAL PROGRAM

Model Test Dimension

The test tank dimensions, the column's diameter and length, crushed stone sizes, and the kind of reinforcement material utilized in the laboratory tests were all determined after careful consideration of the specifics. The model tank dimensions were selected such that the generated stress becomes negligible at the boundaries.^[12] An equivalent footing is assumed to be positioned at 2/3 of the stone column depth with a 2:1 spread stress, as indicated in Figure 1. According to the stress distribution, the produced stresses near the boundary became very small.^[13,14]

The value 50 that is observed in Figure 5 refers to the stone column's maximum settlement. A 50 mm settlement refers to 12.5% strain for a stone column that has a length of 400 mm. In addition, since the maximum acceptable foundation settlement ranges between 25 mm and 50 mm for most structures, tests were carried out up to 50 mm.^[15] Thus, the model tank was constructed with a height of 700 mm and a diameter of 500 mm. The loading plate diameter was double the stone column diameter, corresponding to a 25% area ratio. In the field, the area ratio typically ranged from 10% to 40%. In addition, the loading plate was 25 mm thick to ensure that the soil and the stone column were uniformly loaded.

Soft Soil Bed Preparation

The soil was mixed with water to create a consistent paste. For the soft soil that has 14.6 kN/m³ dry unit weight used in this study, the amount of water needed to achieve 10% moisture content was calculated. The water was then mixed with the soil using a mechanical mixer. After mixing, the soil-water

Table 2: Units woven geotextile properties (according to factory specifications)

Properties	Unit	Values	Standards
Unit weight	g/m ²	200	ASTM D 5261
Tensile strength MD	kN/m	24	ASTM D 4595
Tensile strength TD		24	ASTM D4595
Elongation md/td	%	25±1	ASTM D 4595
Secant Stiffness at ultimate tensile strain	kN/m	96	
Tensile strength @ 2% strain	kN/m	10/15	ASTM D 4595
Tensile strength @ 5% strain	kN/m	19/20	ASTM D 4595
Tear strength MD/TD	N	800	ASTM D 4533
Grab strength MD	N	1700	ASTM D 4632
Grab strength TD	N	1200	ASTM D 4632

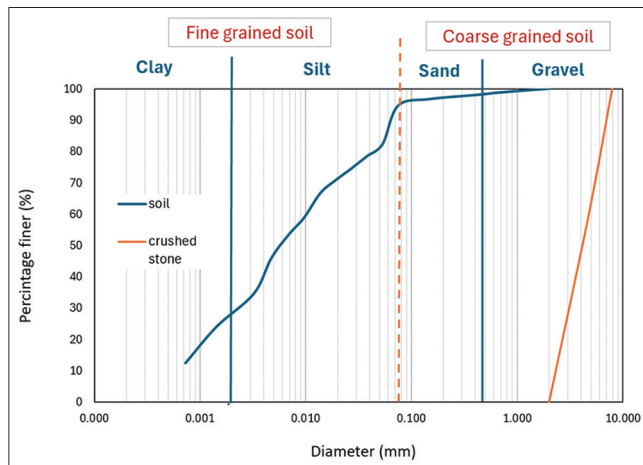


Figure 4: Particle size distribution of the soil and crushed stone

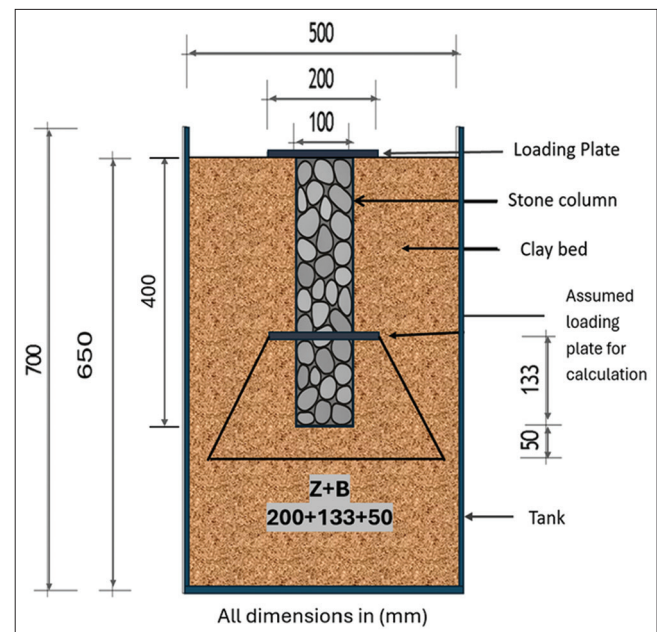


Figure 5: Model test dimensions

mixture was kept at a constant laboratory temperature for 24 h to allow moisture equalization. To minimize friction between the wall of the tank and the soil, a light coating of grease was applied.^[16] Subsequently, a 50 mm thick layer of clay was filled in the tank and compacted until its total density reached 16.04 kN/m³, as shown in Figure 6. After the tank was filled with soil, the nylon was used to cover the tank surface, and the compacted soil was maintained for a full day to keep a consistent moisture content. The moisture content was recorded to ensure it remained at 10%.

Stone Column Construction

This study employed the replacement technique for constructing the stone column. An auger was employed to drill a hole in the soil bed to the appropriate depth of 400 mm. A 50 mm thick layer of crushed stone was then added and compacted until it reached 50% of the maximum unit weight. This limitation was necessary because it was difficult to maintain a uniform column diameter beyond this compaction level.^[13] A total of eight crushed stone layers were required to achieve the full 400 mm length. The model test was then left for 24 h to allow bonding between the soil and the crushed stone. To construct the vertically encased stone column (VESC), the same procedure was followed, except that a steel tube covered with geotextile that has a diameter matching the stone column diameter was embedded within the soil bed to the specified depth and then filled with crushed stone, as illustrated in Figure 7. To build the horizontally reinforced stone columns (HRSCs), the same procedure as the unreinforced stone column was used, except that circular geotextile sheets having the same diameter as the stone column were inserted between each layer of crushed stone. An overview of the model testing is given in Table 3.

Loading Procedure

To guarantee undrained conditions, a strain-controlled compression loading at a rate of 1 mm/min was applied to the model. The load was maintained until the settlement reached 50 mm. For a 100 mm stone column diameter, a settlement of 50 mm corresponds to a strain of 10%, which is commonly considered the acceptable limit for structural settlements.^[15]



Figure 6: Compaction of soft soil

MODEL TEST RESULT AND DISCUSSION

Ordinary Stone Column (OSC)

As shown in Figure 8, the pressure–settlement relationship exhibits a typical stress–strain response characterized by an initial approximately linear region at small settlements, extending up to about 5–7 mm. This stage is followed by a gradual non-linear response, in which settlement continues to increase with increasing applied pressure, without a sudden or abrupt failure point. At higher settlement levels, the curve becomes progressively flatter, indicating continued deformation accompanied by a reduced rate of stress increase, which is commonly associated with the mobilization of soil yielding rather than a distinct collapse mechanism. The ultimate bearing (yield) stress was determined using the bi-linear tangent method, by drawing one tangent along the initial linear portion of the pressure–settlement curve and a second tangent along the post-yield segment. The intersection of these tangents yielded an ultimate bearing stress of approximately 85 kPa for the plain clay, occurring at a settlement of about 15–18 mm.

For the specimen reinforced with OSCs, the pressure–settlement response shows a clear enhancement in load-carrying



Figure 7: Geotextile and crushed stone aggregate

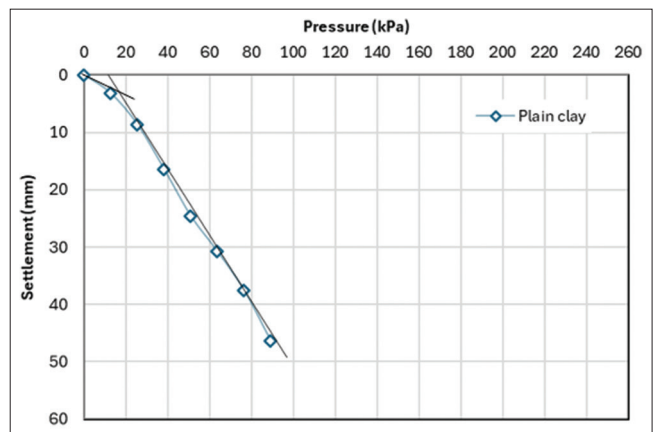


Figure 8: Applied vertical stress against settlement of plain clay

Table 3: Test details

Reinforcement type	Length of stone column (mm)	Length of reinforcement (mm)	Space between horizontal layers (mm)	Number of geotextile horizontal layers
Soft clay bed	---	---	---	---
OSC	400	---	---	---
VESC 1	400	400	---	---
VESC 2	400	300	---	---
VESC 3	400	200	---	---
HRSC 1	400	---	100	5
HRSC 2	400	---	50	9
HRSC 3	400	---	25	16
HVRSC 1	400	400	100	5
HVRSC 2	400	100	100	5

OSC: Ordinary stone column, VESC: Vertically encased stone column, HRSC: Horizontally reinforced stone column, HVRSC: Horizontally and vertically reinforced stone column

behavior. Using the same tangent method, the ultimate bearing (yield) stress increased to approximately 12 a, corresponding to an improvement factor of about 1.41 compared with the plain clay. Moreover, a noticeable reduction in settlement at equivalent stress levels was observed, which can be attributed to the increased lateral confinement and improved load transfer mechanism provided by the granular stone column, as shown in Figure 9.

VESCs

Figure 10 presents the pressure–settlement behavior of the soil beds reinforced with VESCs. The ultimate bearing (yield) stress for each configuration was interpreted using the bi-linear tangent method. Based on the tangent method, the ultimate bearing stress was approximately 85 kPa for VESC1, decreasing to about 71 kPa for VESC2 and 63 kPa for VESC3. These results indicate a clear influence of encasement length on the interpreted ultimate stress. Reducing the geotextile length from full encasement (VESC1) to 75% length (VESC2) led to a decrease in ultimate stress of approximately 16.5%, whereas further reduction from 75% (VESC2) to 50% (VESC3) resulted in a smaller decrease of about 11.3%. Overall, reducing the encasement length from full to 50% caused an ultimate stress reduction of approximately 25.9%.

The observed trend suggests that extending the encasement length improves the mobilized capacity by providing greater restraint against lateral deformation along the column, thereby enhancing confinement and stress transfer. From a practical perspective, the results imply that increasing the encasement length yields measurable gains in ultimate stress; however, the marginal improvement becomes smaller as the encasement already covers the most critical zone where bulging is typically mobilized.

HRSCs

Figure 11 illustrates the pressure–settlement response of the soil beds reinforced with HRSC systems. To provide a consistent definition of the ultimate response, the ultimate (yield) stress for each configuration was identified using the bi-linear tangent method.

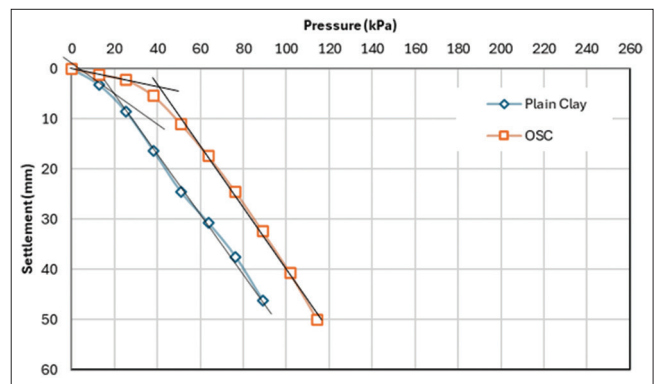


Figure 9: Applied vertical stress against the settlement of ordinary stone column

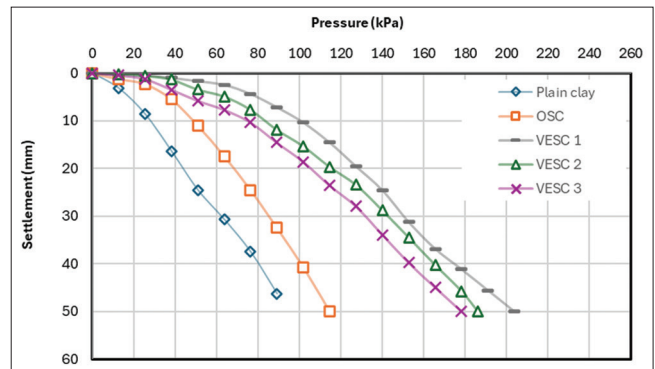


Figure 10: Variation of applied vertical stress against settlement of vertically encased stone columns

Based on this interpretation, the ultimate stress obtained from the tangent method was approximately 39 kPa for HRSC1, increasing to about 50 kPa for HRSC2, and further to approximately 72 kPa for HRSC3. These results indicate a pronounced enhancement in the mobilized bearing stress with the increase in the extent of horizontal reinforcement.

Quantitatively, increasing the reinforcement configuration from HRSC1 to HRSC2 resulted in an increase in ultimate stress of approximately 28%, whereas a further increase from

HRSC2 to HRSC3 led to a substantially greater improvement of about 44%. Overall, the ultimate stress of HRSC3 was approximately 85% higher than that of HRSC1, highlighting the significant contribution of horizontal reinforcement to the load-carrying mechanism.

The observed trend suggests that extending the horizontal reinforcement enhances confinement and stress redistribution within the reinforced zone, leading to a higher mobilized capacity as interpreted by the tangent method. The non-linear increase in ultimate stress also indicates that the effectiveness of reinforcement becomes more pronounced as the reinforced zone expands.

Horizontal-VEsCs (HVEsCs)

Figure 12 presents the pressure–settlement behavior of soil beds reinforced with horizontally and vertically reinforced stone column (HVRSC) systems. The ultimate bearing (yield) stress for each configuration was interpreted using the bi-linear tangent method.

Based on this interpretation, the ultimate bearing stress obtained from the tangent method was approximately 99 kPa for HVRSC1, whereas a lower value of about 81 kPa was recorded for HVRSC2. This indicates that reducing the extent of reinforcement in the HVRSC system leads to a noticeable reduction in the mobilized bearing capacity.

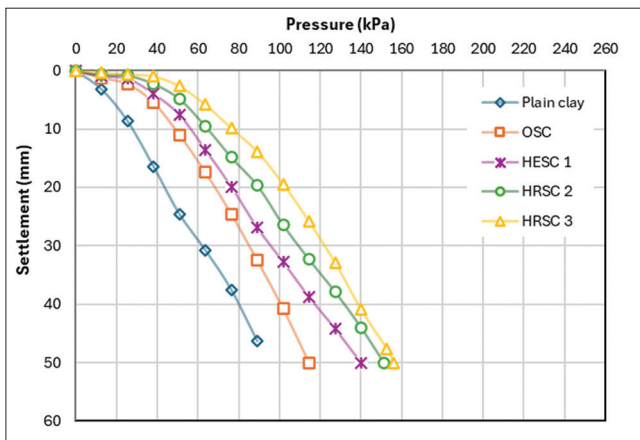


Figure 11: Variation of applied vertical stress against settlement of horizontally reinforced stone columns

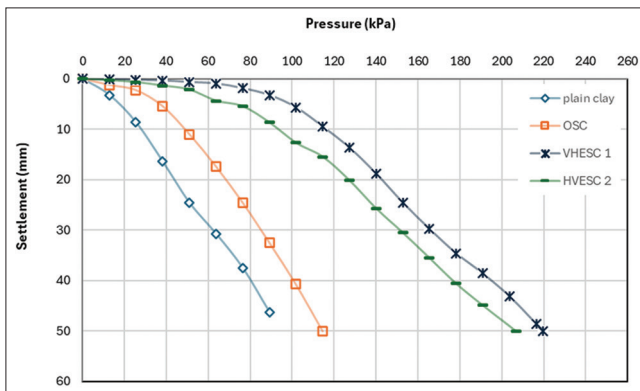


Figure 12: Vertical stress–settlement characteristics of horizontal-vertically encased stone columns

Quantitatively, the ultimate bearing stress of HVRSC1 exceeded that of HVRSC2 by approximately 22%, highlighting the significant role of the reinforcement configuration in controlling the load-carrying behavior. The higher capacity observed for HVRSC1 can be attributed to improved confinement and more effective stress redistribution within the reinforced zone, as reflected by the rightward shift of the pressure–settlement curve.

Overall, the tangent method interpretation confirms that increasing the degree of reinforcement in HVRSC systems results in a higher mobilized ultimate stress and a stiffer pressure–settlement response.

CONCLUSION

This study demonstrated that geotextile reinforcement markedly improves the effectiveness of stone columns installed in soft soil.

- 1) OSCs provided a moderate improvement in load-bearing capacity, whereas VEsCs achieved a substantially higher enhancement, with the mobilized bearing capacity being strongly dependent on the length of the geotextile encasement. Horizontal reinforcement also showed notable benefits, particularly when geotextile layers were spaced at 0.5 times the column diameter
- 2) The horizontal-vertical reinforcement (HVEsCs) resulted in the greatest load-bearing improvements
- 3) However, the incremental gains diminish beyond a certain reinforcement level, suggesting that partially reinforced configurations such as VEsC2 and HRSC2 offer the best balance between performance and material efficiency
- 4) Overall, the study confirms the critical role of geotextile configuration in optimizing stone column effectiveness in soft soils and provides practical recommendations for economically viable ground improvement.

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