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Experimental Studies on Bearing Capacity of Geosynthetic Reinforced Stone Columns

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Abstract The stone column is a useful method for increasing the bearing capacity and reducing the settlements of foundations. The confinement provided by the native soft soils has an effective influence on the stone column bearing capacity. In this paper, laboratory tests were performed on unreinforced and reinforced geotextile-encased stone columns. Tests were performed on columns with diameters of 60, 80, and 100 mm and a length to diameter ratio of 5. Vertical encased stone columns (VESC) and horizontal reinforced stone columns (HRSC) were used for stone column reinforcement to investigate the effect of reinforcement type on the bearing capacity. The main objective of this research is to study the efficiency of VESC and HRSC under the same conditions for diameters of 60, 80, and 100 mm. Experimental results show that the bearing capacity of stone columns increases using vertical or horizontal reinforcing material. Moreover, the bearing capacity of reinforced stone columns increases by increasing the strength of reinforcement in both VESC and HRSC. Results show that bulging failure mechanism governed in all tests and that lateral bulging decreases using geotextiles and increasing strength of reinforcement. In addition, for both VESC and HRSC, the stress concentration ratio of the columns also increases.

Keywords Stone column · Bulging · Soft soil · Ground improvement · Soil reinforcement · Geosynthetic

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الخلاصة

تُعدُّ طريقة الحجر - العمود طريقة مفيدة لزيادة قدرة التحمل والحد من مستوطنات الأساسات. وللحجز المقدم من التربة الناعمة الأم تأثير فعال في قدرة تحمل عمود الحجر. وقد أجريت - في هذه الورقة العلمية - اختبارات مخبرية على الأعمدة الحجرية المموهة المغطاة غير المدعومة والمسلحة، كما أجريت الاختبارات على أعمدة بأقطار من 60، 80، و 100 ملم ونسبة طول إلى القطر بقيمة 5. واستخدمت الأعمدة الحجرية المغطاة العمودية (VESC) والأعمدة الحجرية المقواة الأفقية (HRSC) لتعزيزعمود الحجر لدراسة تأثير نوع التعزيز في قدرة التحمل. إن الهدف الرئيسي من هذا البحث هو دراسة كفاءة VESC وHRSC في ظل نفس الظروف للأقطار من 60، 80، و100 مم. وتظهر النتائج التجريبية أن قدرة تحمل الأعمدة الحجرية تزيد باستخدام مواد التسليح الرأسية أو الأفقية. علاوة على ذلك، فإن قدرة تحمل الأعمدة الحجرية المسلحة تزيد عن طريق زيادة قوة التعزيز في كل من VESC و HRSC. وتظهر النتائج أن آلية فشل الانتفاخ تحكم في جميع الاختبارات، وأن تلك الانخفاضات الجانبية تنخفض باستخدام مواد التكسية الأرضية وزيادة قوة التعزيز. بالإضافة إلى ذلك، ولكل من VESC وHRSC، فإن نسبة تركيز إجهاد الأعمدة تزيد أيضا.

1 Introduction

The construction of structures, such as a building, storage tanks, warehouse, etc., on weak soils usually involves excessive settlement or stability problems. In these cases, various methods may be used for soil improvement. Three methods of improvement which include column type elements, soil replacement, and consolidation may be considered [1]. One effective method involves the use of stone columns referred to as granular column or granular pile. In addition, the high permeability of stone column material results in an increase in the consolidation rate in soft clay. In stone column construction, usually 15–35 % of weak soil volume is replaced with stone column material.

Barksdale and Bachus [2] described three types of failures that may occur upon loading a stone column. These are bulging failure, shear failure, and punching failure.

Relationships for prediction of the ultimate bearing capacity of single stone columns are presented for bulging failure mechanism by Greenwood [3], Vesic [4], Hughes and Withers [5], Datye and Nagaraju [6], and Madhav et al. [7], for shear failure mechanism by Madhav and Vitkare [8], Wong [9], Barksdale and Bachus [2], and for punching failure mechanism by Aboshi et al. [10].

Various researchers have proposed methods for the analysis of granular pile reinforced ground. Bouassida et al. [11,12] presented a method for evaluation of the stone column bearing capacity using the limit analysis method. Lee and Pande [13] presented a numerical model using homogenization technique. Wood et al. [14] performed a series of model tests on a clay bed reinforced with group of stone columns to study the effect of reinforcement of clay bed and deformation mechanism of column groups under loading. A series of tests was also carried out by Ambily and Gandhi [15] to study the behavior of single and group of stone columns. They varied parameters such as spacing between stone columns, shear strength of soft clay, and loading condition for soft clays with different undrained shear strength. To investigate the behavior of stone columns in layered soils, Shivashankar et al. [16] performed a series of tests in tanks consisting of weak soft clay overlying a relatively stronger silty soil for various thicknesses of the top layer.

The confinement of stone columns is provided by the lateral stress due to the weak soil. The effectiveness of the load carried by stone columns essentially depends on the lateral stress exerted by the surrounding soft soil. In very soft soils, it is necessary to provide additional confinement, which may be achieved by encasing the stone columns with geosynthetics. The encasement increases the bearing capacity, increases stiffness, and decreases lateral bulging of stone columns even in very soft soil. Murugesan and Rajagopal [17], Lo et al. [18], Malarvizhi and Ilampauthi [19] and Fattah and Majeed [20] numerically studied the performance of vertical encased stone columns (VESC) with geosynthetics. Using the unit cell concept, Pulko et al. [21] presented an analytical method for analysis of reinforced ground with stone columns or vertical encased stone columns. Murugesan and Rajagopal [22] performed a series of single and group load tests on the stone columns with and without encasement with different geosynthetics. The positive effect of the encasement on the bearing capacity of VESC was verified using the load tests results. Gniel and Bouazza [23] studied the efficiency of alternative methods of encasement construction by a series of laboratory compression tests using different geogrids and stone column aggregates. Sivakumar et al. [24] reported the efficiency of encasement by performing a series of triaxial tests on model sand columns in clay.

Several researchers studied the effect of horizontal layers of reinforcement in stone column material on the bearing capacity of the stone column. For example, Sharma et al. [25] performed a series of tests on horizontal reinforced single stone column (HRSC) with 60-mm diameter in a small tank having a diameter of 300 mm and a height of 300 mm. Their results indicated an increasing bearing capacity with increasing number of reinforcement sheets and reducing distance between reinforcement sheets. In their tests, the clay bed and the stone columns were constructed in six 50-mm layers. A special casing with outer diameter equal to the diameter of the stone column was kept vertical when compaction each clay bed layer to make a stone column hole in the clay bed. Wu and Hong [26] presented an analytical method to analyze horizontal geotextile reinforced granular column expansion.

Many researchers investigated the behavior of vertical encased stone columns using analytical, numerical, and experimental methods. However, there are very limited analytical and experimental studies on horizontal reinforced stone columns. In the literature, most of studies on VESC and HRSC performed using the triaxial testing device with small specimens with a constant confinement pressure, knowing that, constant confinement cannot simulate real in-situ confinement of native soil.

This paper reports the results of a series of tests on single stone columns with various diameters. These tests comprise OSC, VESC, and HRSC to investigate the effect of reinforcement type with different reinforcement materials on the response of the soil. The main objective of this research is to compare the effectiveness of VESC and HRSC under the same conditions for various stone column diameters in soft soil.

2 Description of Experiment

2.1 Properties of Materials

Clay, crushed stone aggregates, and two types of geotextiles were used for the current experimental investigation. Table 1

Table 1 Properties of clay

Parameters	Value
Specific gravity	2.7
Liquid limit (%)	33
Plastic limit (%)	20
Plasticity index (%)	13
Optimum moisture content (%)	18
Maximum dry unit weight	16.8 kN/m^3
Bulk unit weight at 25.2 % water content	19 kN/m^3
Undrained shear strength	30 kPa
Compression index	0.17
Unified classification system	CL

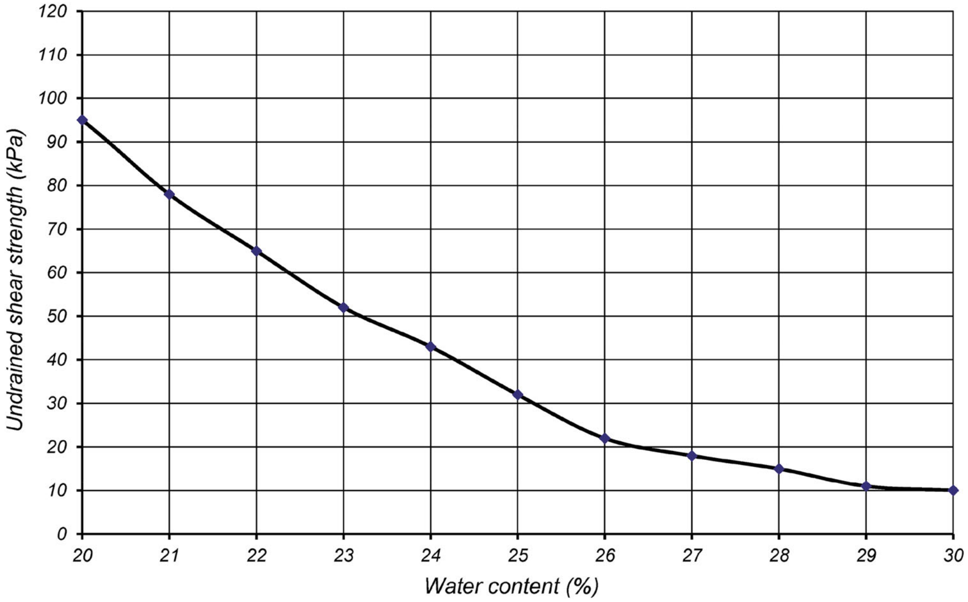


Fig. 1 Variation of undrained shear strength of clay with water content

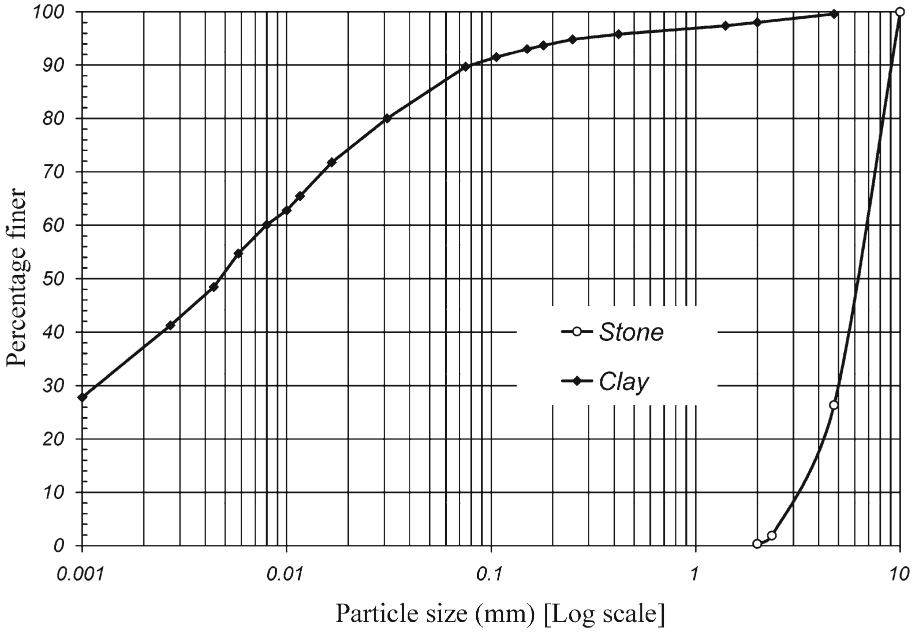


Fig. 2 Particle size distribution for stone column and clay materials

presents the properties of the clay. A series of unconfined compressive strength (UCS) tests were carried out on cylindrical specimens with a diameter of 38 mm and height of 76 mm to determine the moisture content corresponding to a clay undrained shear strength of 30 kPa. Figure 1 depicts the variation of the undrained shear strength with water content.

The resulting water content of the clay was found to be 25.2 % (Fig. 1) and this amount was kept the same in all tests. Crushed stone aggregates with sizes ranging from 2 to 10 mm were used as stone column material. The aggregate size distribution is shown in Fig. 2.

In addition, their properties are summarized in Table 2. Figure 3 depicts a schematic of the three types of columns (OSC, VESC, HRSC) used in this investigation.

One main objective in laboratory tests on stone column reinforced ground is to somehow model the real situation by performing small-scale experiments. The selection of the scale of the physical model and tensile strength of the reinforcing material is important in results. In this research study, the adopted physical scale factor (ratio of physical dimensions of the test models to real dimensions) was about 0.1. In addition, the ultimate tensile strength of geotextile must

Table 2 Property of stone column material

Parameters	Value
Specific gravity (G_s)	27
Maximum dry unit weight	16.6 kN/m^3
Minimum dry unit weight	14.9 kN/m^3
Bulk unit weight for test at 68 % relative density	16 kN/m^3
Internal friction angle (ϕ) at 68 % relative density	46°
Uniformity coefficient (C_U)	2.16
Curvature coefficient (C_c)	1.15
Unified classification system	GP

be chosen in relation to the physical scale factor and the load exerted on the stone column. In practice, the tensile strength of reinforcement sleeves for vertical encasement of stone columns is produced with tensile strength of up to 400 kN/m, for column with diameter of 40–100 cm. As an example, a polyester woven geotextile used to encase the stone column, the diameter of the geotextile casing and tensile strength and stiffness of the geotextile were equal to 0.4 m, 200 kN/m, and 2,000 kN/m, respectively [27]. In the proposed tests, two types of non-woven polypropylene geotextiles were used as reinforcing material. The tensile strength properties of these geosynthetics determined from standard wide width tension tests (ASTM D 4595–05) are listed in Table 3.

In addition, geotextiles for this study had an ultimate tensile strength that falls in the range reported by Gniel and Bouazza [28], Wu and Hong [29], and Murugesan and Rajagopal [22], for the vertical encasement of stone columns.

The vertical cylindrical reinforcement was made by overlapping 15 mm of the rectangular geotextile along the length of the stone column and fixing the overlapping seam with special polypropylene glue.

Tension tests were performed to determine the seam strength of the geosynthetic, with geosynthetic specimens having a seam at midlength. The load deformation behavior observed from the tensile tests on different virgin and seamed geosynthetics is shown in Fig. 4. The failure observed in the tensile strength test of non-woven geotextiles with seam was due to tearing of the geotextile with the seam remaining intact. These test results verified the efficiency of the glue used for overlapping. In addition, two types of geotextiles were cut in a circular shape with a diameter equal to the diameter of the stone column to form the horizontal reinforcement sheets of stone columns (Fig. 3c).

2.2 Test Setup and Test Program

The test setup consists of a large test box with plan dimensions of 1,200 mm × 1,200 mm and 900 mm height. This

Table 3 Properties of geosynthetics (according to manufacturer)

Parameters	Geotextile 1	Geotextile 2
Ultimate tensile strength (kN/m)	9	14
Strain at ultimate strength (%)	55	40
Tensile modulus (kN/m)	16.4	35
Ultimate tensile strength from tests with seam (kN/m)	8.5	13.3
Strain at ultimate strength (%) from tests with seam	50.3	33.5
Tensile modulus (kN/m) from seam tests	16.9	39.7
Thickness (mm)	1	1.8
Mass (g/m^2)	140	180

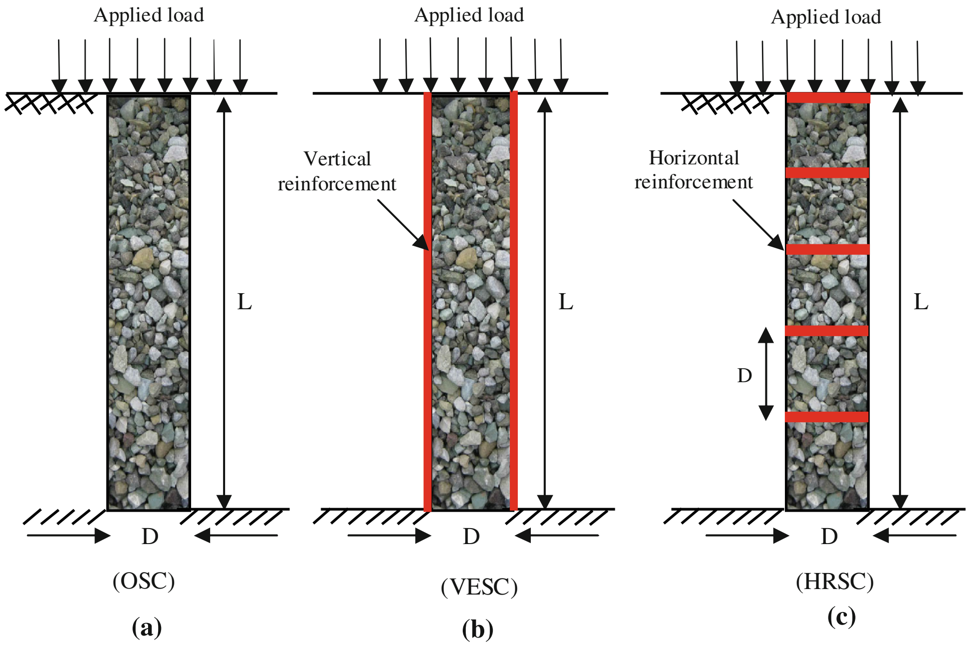


Fig. 3 Schematic of: **a** OSC, **b** geosynthetic VESC, **c** geosynthetic HRSC

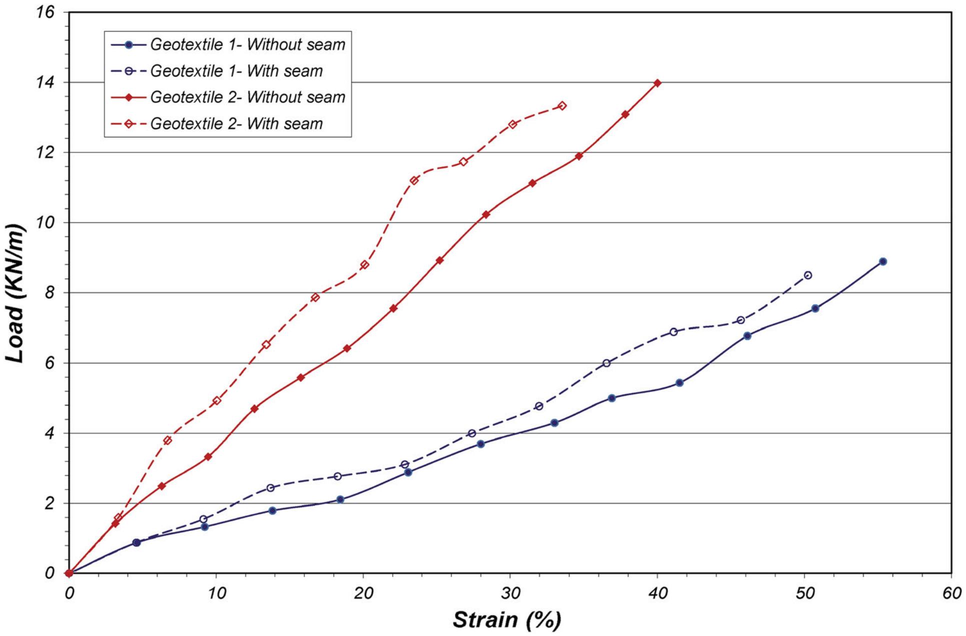
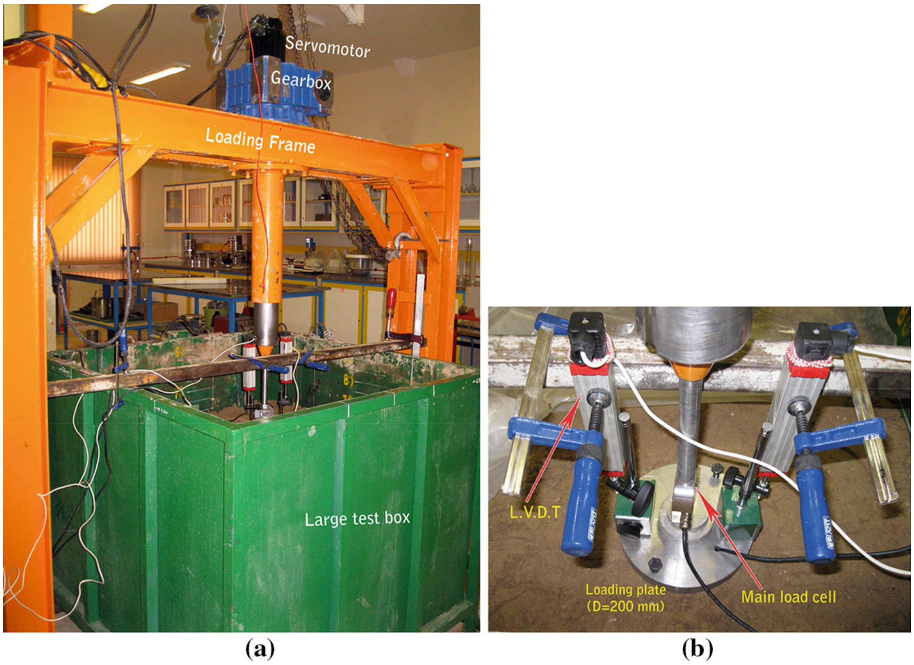


Fig. 4 Tensile load-strain behavior of geotextile samples with and without seam



(a) (b)

Fig. 5 Testing setup: **a** loading frame and large test box, **b** single stone column loading plate and data acquisition instruments

tank has a rigid loading frame with a loading system and provides space for soft soil and stone column materials (Fig. 5a). The loading system in this study was based on displacement control with the speed of displacement being controlled by a servomotor (Fig. 5a).

In the current investigation, 18 tests were performed on single stone columns. In all single stone column tests, a rigid steel plate with a diameter of 200 mm and a thickness of 30 mm was used as a loading plate (Fig. 5b). Table 4 presents a summary of these tests. A ratio of L/D (length to diameter of the stone column) of 5 was used for all single stone column tests, because a minimum $L/D = 4$ is required for control of bulging failure mode (Barksdale and Bachus [2]). It should be mentioned that in all tests full length of reinforcement was introduced for VESC and HRSC. In HRSCs, the distance between reinforcing layers was taken as D (Fig. 3c).

To measure the ratio of the stress on the stone column to that on the soft soil bed, a miniature load cell was mounted in the center of the loading plate on the down side. Some repeated tests were performed on single stone columns to

Table 4 Outline of load tests on stone columns

Test type	Test description	Reinforcing material	Diameter of stone column (mm)			Total number of tests
			60	80	100	
Single stone column	Clay bed	–	✓	✓	✓	3
	OSC	–	✓	✓	✓	3
	VESC	Geotextile 1	✓	✓	✓	3
		Geotextile 2	✓	✓	✓	3
	HRSC	Geotextile 1	✓	✓	✓	3
		Geotextile 2	✓	✓	✓	3
Area replacement ratio (a_s): for loading plate with diameter of 200 mm			9 %	16 %	25 %	

OSC ordinary stone column, *VESC* vertical encased stone column, *HRSC* horizontal reinforced stone column

ensure that the results are repeatable. Two linear variable differential transformers (LVDTs) were used to measure the vertical displacement of the loading plate. Single stone column tests were performed with a 200 mm loading plate on columns with different diameters of 60, 80, and 100 mm.

In the literature, the ratio of the cross-sectional area of stone columns to the total area of foundations is defined as the area replacement ratio and denoted by a_s. The values of a_s in these tests were 9, 16, and 25 % for columns with diameters of 60, 80, and 100 mm, respectively.

2.3 Preparation of Soft Clay Bed

The preparation of the soft clay bed was performed in large test box with a plan dimensions of 1,200 mm × 1,200 mm. Three thicknesses of 300, 400, and 500 mm were used as soft clay surrounding stone columns with diameters of 60, 80, and 100 mm, respectively. The clay bed was prepared in 50-mm thick layers. Initially, the natural water content of the clay was determined and the amount of additional water was added to the clay to achieve a water content of 25.2 % in a large plastic box. The water content corresponds to the undrained shear strength of 30 kPa. To achieve uniform water content within the clayey soil mass, the surface of the box was sealed with a nylon sheet for 5 days. To reduce the friction between the clay and the tank wall, a thin layer of grease coated the inner face walls of the test box. To achieve a certain bulk unit weight of 19 kN/m^3, the clay was poured in the tank with a measured weight. A uniform compaction effort was used on the entire surface of each clay layer to achieve a 5-cm height and uniform required density. For compaction of clay, a special tamper was used with 150 × 150 mm in plan and 10 kg mass by dropping the tamper from a height of 200 mm (Fig. 6). To reduce leftover air voids in the test bed and connect clay layers to each other, five steel bars with 10-mm diameter and 20-mm length were fixed to the bottom of the tamper, for kneading each clay layer. The final surface of the clay bed was leveled and trimmed to have a proper thickness and surface in all tests. The same procedure was used in all tests for preparation of the clay bed. For all tests, the water content profile was determined at 100-mm intervals to ensure that the moisture content in the clay was kept the same. It was found that in all tests, the variation of moisture content was less than 1 % in the clay bed.

Fig. 6 Compaction procedure using special tamper

2.4 Construction of Reinforced and Unreinforced Stone Column

In all tests (OSC, VESC, and HRSC), the replacement method was used for construction of stone columns with diameters of 60, 80, and 100 mm with the stone columns being constructed at the center of the large test box. The plan dimension of the tank was selected such that results of the test would not be affected by boundaries of the tank. Thin seamless steel pipes with outer diameters of 60, 80, and 100 mm and a wall thickness of 2 mm were used for stone column construction. To allow for penetration and withdrawal

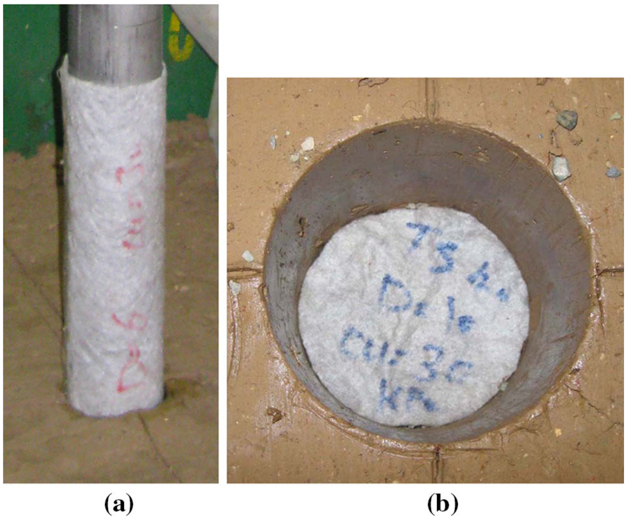


Fig. 7 **a** Insertion of vertical encasement, **b** placement of horizontal reinforcing sheet

without significant disturbance to the surrounding soil, both the inner and the outer surfaces of the steel pipes were coated with a thin layer of oil and then the steel pipe was pushed into the clay to reach the bottom. Three different helical steel augers were designed and used for excavation of the clay inside the pipe. Excavation of the clay inside the pipe was limited to a maximum thickness of 50 mm at a time to make the clay removal easy and this ensured that no suction effect occurred. The steel pipe was completely pulled out slightly after removing the clay within the pipe. Therefore, care was taken to prevent disturbance between the pipe and the skin of the hole. For construction of stone column, the quantity of stone aggregates corresponding to a bulk unit weight of 16 kN/m^3 was calculated and charged into the hole in layers of half column diameter (0.5 *D*). To get a uniform density, a special circular tamper with 2 kg weight and 20-mm diameter was used to compact the stone material by free dropping the tamper from a height of 100 mm with 15 blows. This light compaction effort was chosen such that no significant lateral bulging during column construction and no disturbance of the surrounding soft clay occurred. For VESC tests, vertical encasing reinforcement was positioned in the excavated hole by a tube with a diameter a little less than the diameter of excavated hole (Fig. 7a). The construction sequence of HRSC was the same as OSC. However, in HRSC tests, horizontal reinforcement sheets were placed at special depths within the column length (Fig. 7b).

3 Test Procedure

In this study, the test procedure was based on the application of the load and determination of load-displacement behavior of the stone column reinforced soft clay bed. After construction of the stone column, the load was applied using a plate placed in the centre of the column and clay bed. As the loading system was based on displacement control, the load was applied on the plate with a constant displacement rate of 1 mm/min. The loading of each test was continued until the vertical settlement of the plate reached up to 50 mm.

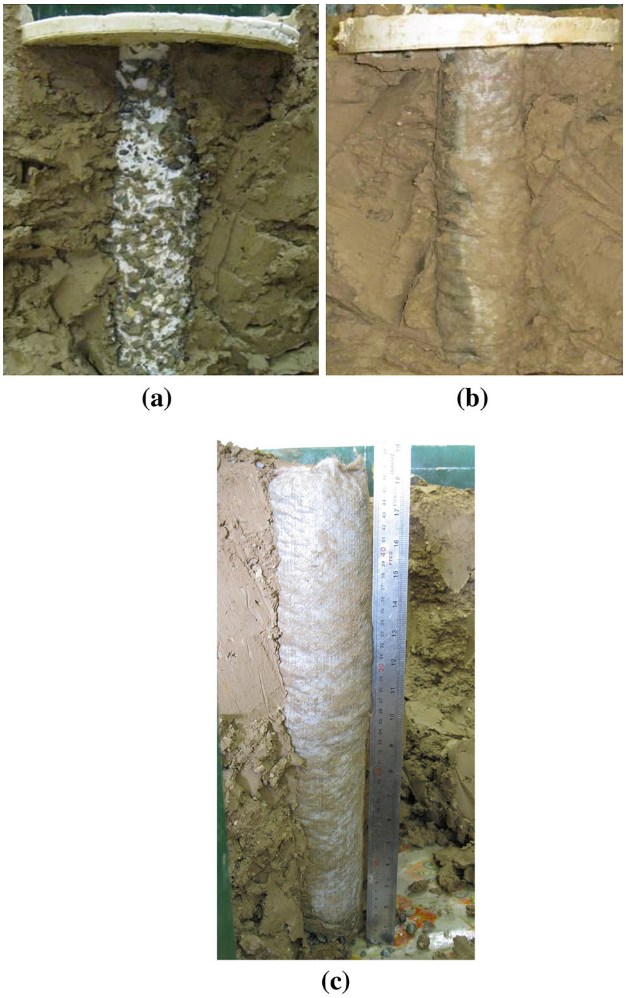


Fig. 8 Shape of stone column after test: **a** OSC, *D* = 60 mm, **b** VESC, *D* = 60 mm, **c** VESC, *D* = 100 mm

4 Results and Discussion

4.1 Deformation and Failure Mode

In some tests, the deformed shape of stone columns in OSC and VESC tests was captured by filling paste of plaster of Paris in the stone column and dented place of the loading plate (Fig. 8). However, in HRSC tests, filling the paste of plaster of Paris could not be applicable because of the presence of horizontal sheets. Thus, the soft soil surrounding the column was carefully cut vertically after the test to observe the deformation and failure mode. Bulging failure mode governed in all tests on single stone columns. The results indicated that bulging failure occurred at a depth of D to $2.5D$ from the top of the stone column. In addition, in all single VESC and HRSC tests, bulging was also observed but at a smaller scale compared to OSC tests.

4.2 Load-Settlement Behavior

The load-settlement behavior of unreinforced and reinforced soft clay with stone columns, is shown in Fig. 9a–c, for columns with diameters of 60, 80, and 100 mm with different types of column reinforcement. The ultimate load-carrying capacity of the soft soil was found to increase using OSCs, HRSC, and VESCs. By increasing the a_s from 9 to 25 %, the ultimate capacities of the three types of columns (OSCs, HRSC, and VESCs) increased. Moreover, the ultimate capacity of stone columns increased when the columns were reinforced with geosynthetic material for vertical encasement or horizontal reinforcement. Furthermore, results of VESCs for two different strengths of geotextile material are shown. It is clear that vertical encasement of stone columns presents greater ultimate capacity and stiffness. Moreover, with increasing the ultimate tensile strength of encasement material, the ultimate bearing capacity of VESCs increases compared with OSCs.

Some tests were performed to study the efficiency of horizontal reinforcement in increasing the ultimate bearing capacity of HRSC in comparison to OSC. Figure 9a–c presents results of tests performed on HRSC with three diameters of 60, 80, and 100 mm. As shown, the ultimate bearing capacity of columns increases by use of horizontal reinforcement sheets, because horizontal reinforcement sheets restrict column materials between horizontal reinforcement layers and provide additional radial confinement due to shear stresses mobilized between reinforcing sheets and granular stone materials.

This results in a reduction the lateral bulging. Moreover, the ultimate bearing capacity of HRSCs increases, compared with OSCs, when the ultimate tensile strength of horizontal reinforcement sheets are increased.

In practice, the use of Horizontal reinforcement sheets in HRSC may be easier and the placement of reinforcement layers is easy and can be done as the stone column construction progresses. The compaction of the stone between reinforcement layers is possible and easy to implement. The use of stone columns reinforced with horizontal layers may be seriously considered in practice to increase the load-carrying capacity reasonably. In comparison to horizontal reinforcement sheets, the construction of vertical encasing reinforcement requires special equipment. HRSCs do not need to have a special procedure, device, or material in comparison with VESCs. In all ground improvement projects, economical consideration is important. In the current investigation, the ratio of reinforcing material area in HRSCs to VESCs in a stone column was about 0.25. Thus, the use of HRSCs saves about more than 50 % of reinforcing material compared with VESCs. It can be said that because of easiness of construction of horizontal sheets as reinforcing elements in HRSCs, HRSCs may be a cost effective solution, especially in large projects and useful method in reinforcing stone columns and increasing ultimate capacity of columns and reducing ground settlement.

4.3 Improved Load Ratio

To investigate and determine the efficiency of stone columns from the viewpoint of the ultimate bearing capacity, the load ratio (LR) parameter may be defined as:

$$\mathrm{LR} = \frac{\text{Ultimate load obtained from stone column reinforced soil}}{\text{Ultimate load obtained from soft soil with no stone column}} \tag{1}$$

The LR variation with settlement for stone columns having diameters of 6, 8, and 10 cm with different types of reinforcement is depicted in Fig. 10a–c. As seen, the LR varies in the ranges of 1.07–1.43, 1.22–1.71, and 1.50–1.82 for stone columns having diameters of 6, 8, and 10 cm, respectively. The maximum LR is for full-length encasement of VESCs with stronger geotextile used in the current study and the minimum LR is for OSCs. As seen from Fig. 10a–c, in VESCs and HRSCs, the LR value increases with increasing the tensile strength of reinforcing material. This is because reinforcement material provided lateral confinement on the columns and reduced the amount of bulging. As mentioned above, in the current investigation, the ratio of reinforcing material area in HRSCs to VESCs in a stone column was about 0.25. Therefore, it seems that the use of HRSCs may be more beneficial than VESCs, with the same reinforcement area; however, an additional experimental test is needed to investigate load carrying behavior of HRSCs and VESCs with the same area ratio of reinforcement.

4.4 Stress Concentration Ratio

The external load is distributed between the stone columns and the soft soil in relation to the ratio of the column and soft soil stiffness. Because of higher stiffness of columns with respect to the soft soil, the stresses on the columns are greater than those in the surrounding soft soil.

In the literature, the ratio of the stress in stone columns to the stress in soft surrounding soil is defined as the stress concentration ratio (SCR) and denoted by n.

The variation of SCR with settlement is depicted in Fig. 11a–c for various columns (OSC, VESC, and HRSC)

Fig. 9 Load-settlement variation of single stone columns with diameters: **a** 60 mm, **b** 80 mm, **c** 100 mm

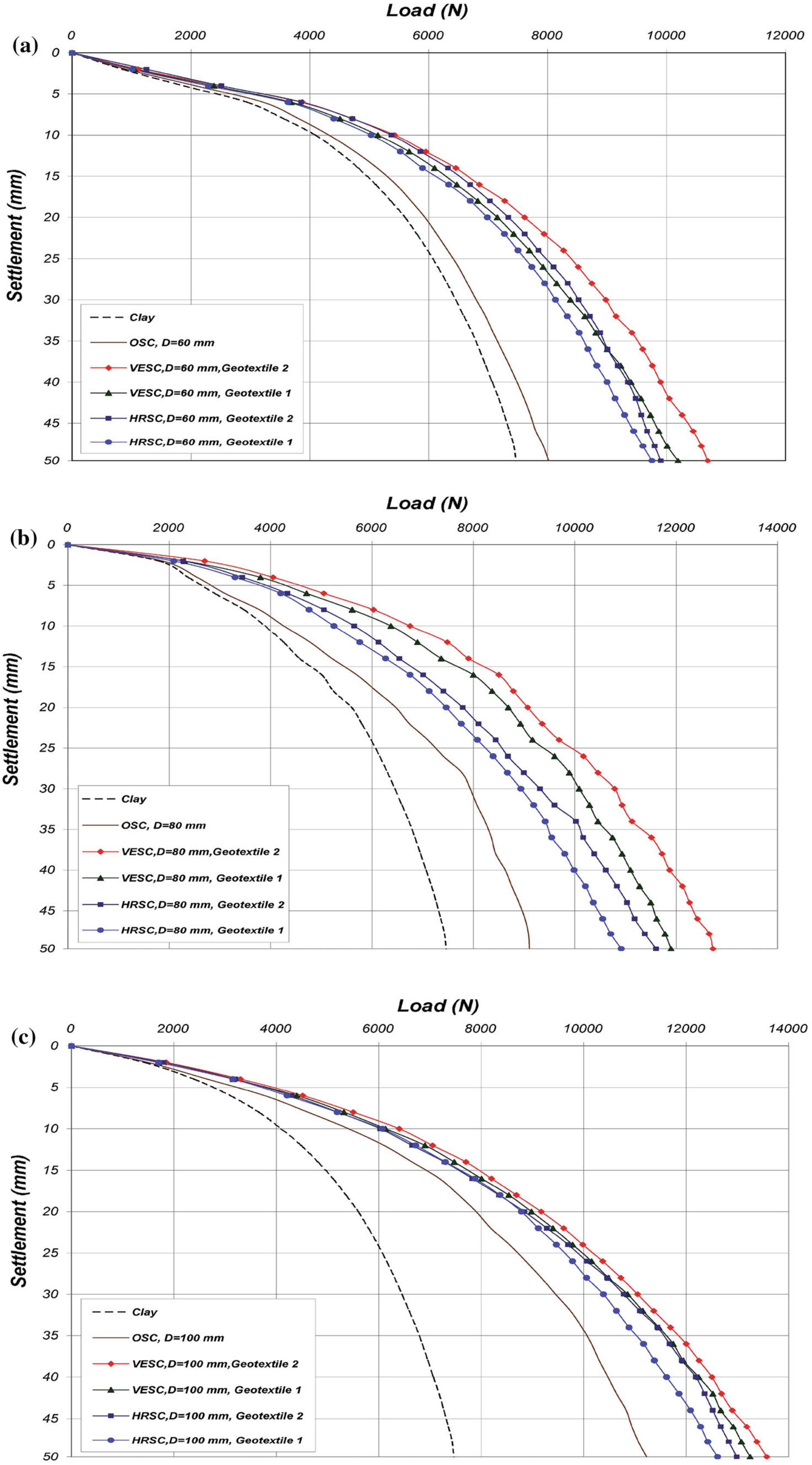


Fig. 10 Variation of load ratio versus settlement for various stone columns with diameters: **a** 60 mm, **b** 80 mm, **c** 100 mm

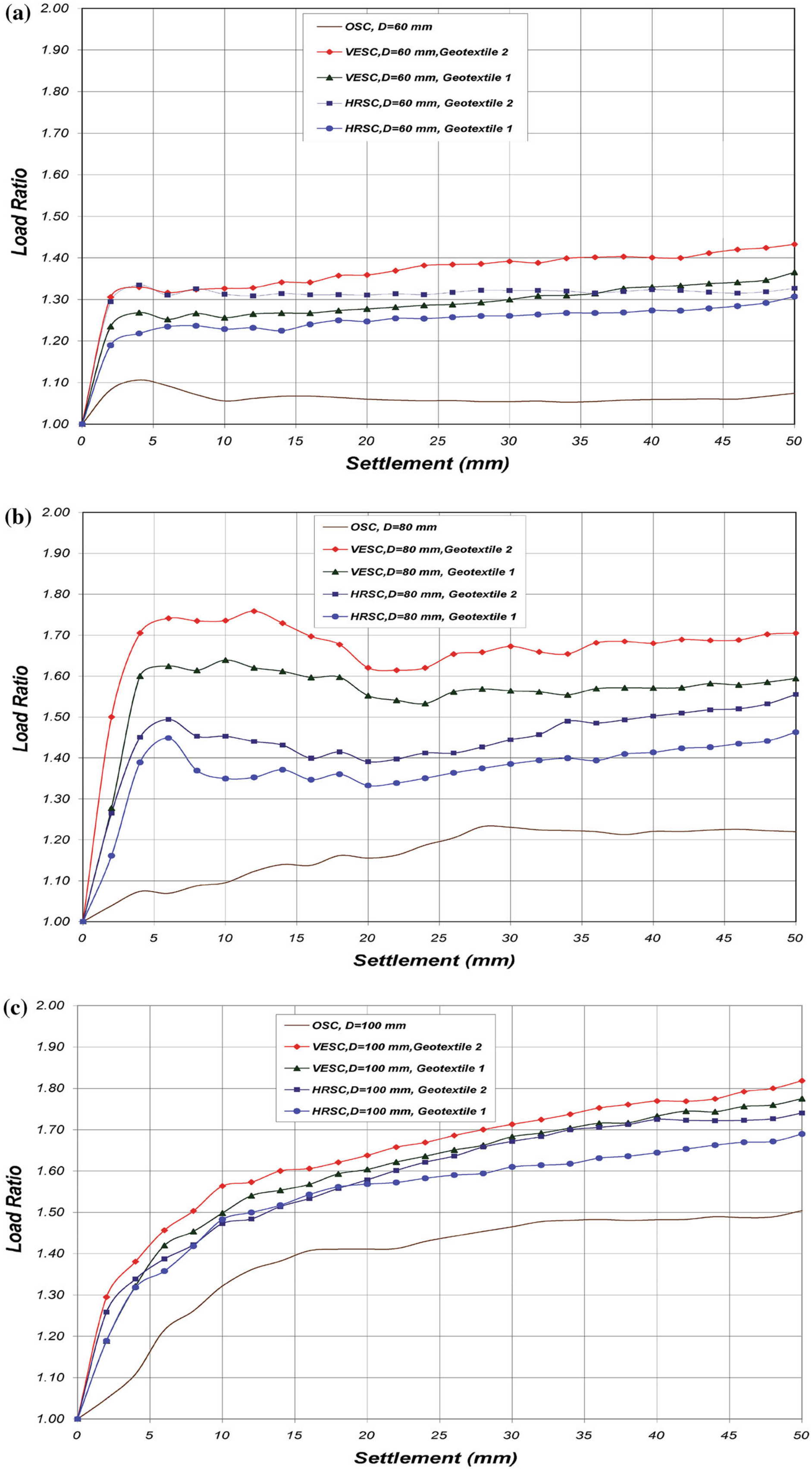
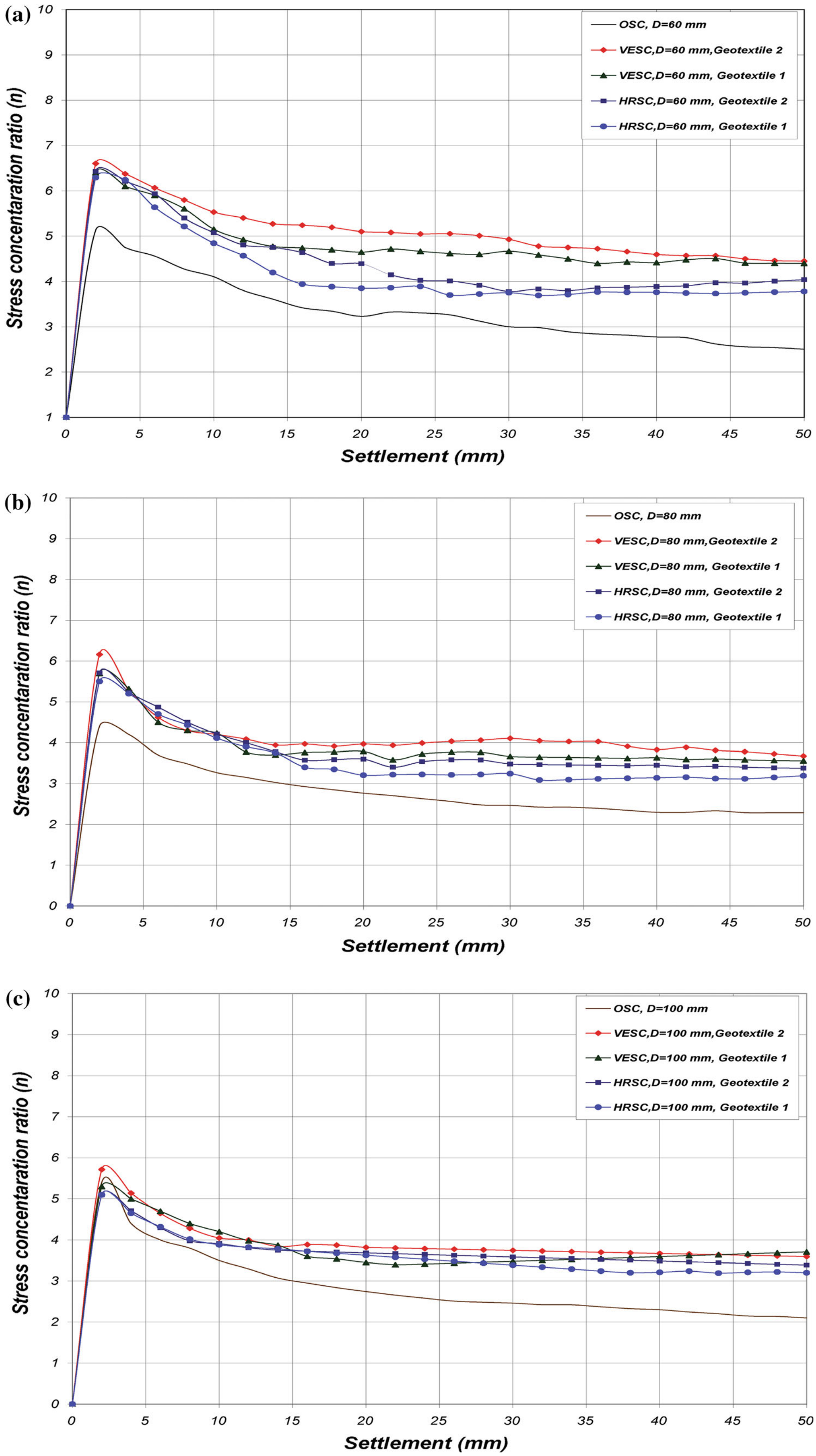


Fig. 11 Variation of stress concentration ratio versus settlement for stone columns with diameters: **a** 60 mm, **b** 80 mm, **c** 100 mm



having diameters of 60, 80, and 100 mm. As seen in Fig. 11a–c, the SCR value varies with increasing settlement and is not a constant for all stone columns. Figure 11a–c also shows that the ultimate value of SCR varies in the ranges of 2.5–4.4, 2.8–3.7, and 2.1–3.7 for columns with diameters of 60, 80, and 100 mm, respectively.

The minimum and maximum value of SCR is for OSCs and VESCs, respectively. Moreover, the SCR value increases by increasing the stone column stiffness with increasing the tensile strength of reinforcement material. The SCR value increases with settlement up to 3 mm of settlement and then decreases with increasing the settlement and then approaches almost a constant value. In OSCs, at the first stage of loading up to 3-mm displacement, the stone column moves downward and causes rearrangement of stone column grains. With increasing settlement, the SCR decreases, because granular material tends to move laterally toward the surrounding soft soil and this causes a gradual transfer of the load to the soft soil and a slight relaxation in stress of stone columns occurs. In VESCs and HRSCs, the SCR value decreases slightly compared with OSCs, because of additional lateral confinement that is provided by vertical or horizontal reinforcing material. As seen in Fig. 11a–c, with increasing stone column diameter, the benefit of encasement decreases. Thus, the SCR value of reinforced columns with smaller diameters is higher than that of columns with larger diameters for the same encasement. This may be attributed to the mobilization of higher confining stresses in smaller diameter stone columns.

5 Discussion

There are other important issues about HRSCs and VESCs that could be mentioned. It seems that locating horizontal reinforcement layers in HRSCs may be much easier than vertical encasement of columns in VESC. Horizontal reinforcement sheets may be installed with the progress of the column construction. As mentioned, horizontal placement of reinforcement sheets is very important in practice. In the current research, the horizontal placement of reinforcement was controlled by care and eye-observation as much as possible. When granular material is poured into the excavated ground, it must be re-arranged horizontally before the placement of reinforcement sheets. In the current research, since the stone columns were small, the horizontal placement of reinforcement sheets was not difficult. In HRSCs, if a horizontal reinforcing sheet fails in installation or in loading, the other layers may be in operation and thus the stone column may still function partly.

Another issue about HRSCs is that the reinforcement layers gradually come into operation due to gradual lateral deformation of the stone column material because of monotonic loading of the column. However, in VESCs, the encasing reinforcement comes into operation when sufficient deformation is induced into the stone column material. 1–4 %, circumferential strains are generally required to mobilize circumferential forces in the geotextile encasement [30] that may result in significant radial expansion and therefore settlement during loading.

Meanwhile, the vertical encasement by geotextiles helps in filtration and drainage functions and prevents the contamination of the stone aggregate by soft clay particles. This helps in preserving the strength of stone aggregate. This is an advantage for VESC compared to HRSC.

6 Conclusions

In this research program, laboratory tests have been performed on single stone columns with diameters of 60, 80, and 100 mm. Two types of VESCs and HRSCs with different reinforcing material were used in tests and the results were compared with those obtained from tests on OSCs. Based on the results from experimental program, the following conclusions can be drawn:

1. In all tests, bulging was the governing failure mechanism. The bulging failure occurred at a depth of D to $2.5D$ from the stone column head.
2. The degree of lateral bulging decreases in VESCs and HRSCs compared with OSCs due to the additional lateral confinement provided by the geosynthetics material.
3. The ultimate bearing capacity of the foundation increases when OSCs are used to reinforce the clay. The ultimate load was further increased by the use of vertical (VESCs) or horizontal (HRSCs) reinforcing material.
4. The ultimate capacity of VESC and HRSC increases with increasing the tensile strength of the reinforcing geotextiles.
5. The value of the SCR in VESCs and HRSCs is higher than that in OSCs. This ratio decreases with increasing the settlement and stone column diameter.
6. With the same reinforcement area, the use of HRSCs may be more beneficial than VESCs. However, additional tests are required to investigate the load carrying behavior of HRSCs and VESCs with the same area ratio of reinforcement.

Although the results obtained from the current research work are interesting, it is suggested to perform large-scale tests to investigate the application of horizontal reinforcing layers and compare results with columns reinforced with encased reinforcement.

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