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ORIGINAL PAPER

The Novel Usage of EPS Geofoam as Column Material: A Laboratory Study

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Abstract
The technique of stone column to improve the performance of soft soil is well established. However, an alternative material to enhance the performance of the soft soil by reinforcing with geofoam materials is suggested. Expanded polystyrene (EPS) geofoam is a superlight weight geosynthetic material used in various geotechnical engineering applications. This study deals with the innovative use of geofoam as a column material in soft soil for improving the bearing capacity. The method was developed in small-scale laboratory tests, and a series of loading tests were carried out on various single floating geofoam columns (normal geofoam and hollow geofoam) with two different diameters and the length-to-diameter ratio of 5. Next, a comparison was made with the results of ordinary stone columns and reinforced stone columns to obtain the benefits of geofoam columns. According to the results and by considering the bearing capacity, geofoam columns could be a good alternative material for improving the bearing capacity of soft soils. It was also found that the efficiency of the geofoam columns is almost similar to that of the ordinary stone columns and the usage of the geofoam is easy and economical. However, encasing the stone columns with geotextile results in further growth in the bearing capacity.

Keywords Geosynthetics · Geofoam · Stone column · Ground improvement · Laboratory study

Introduction

There are various techniques available for improving the soft soil capacity. One of these is stone columns. Most studies summarized the failure mechanisms of stone columns, including bulging failure, shear failure and punching failure [1–5]. However, stone columns may not work well in very soft soil due to the bulging of columns [6]. Encasement materials have been used to minimize the bulging of stone columns and improve their performance [7]. Many studies deal with the stone columns encased with geosynthetics [8–13]. The results of laboratory model tests on different types of geotextiles showed that by increasing the stiffness of geosynthetic, the bearing capacity also increases [8]. Also, the effect of geosynthetic length and modulus of geosynthetic on bearing capacity has been a subject of experimental studies [9–11]. The fully encased stone column behaves as a stiffened member and thereby effectively transmits the surcharge pressure onto the competent strata below, giving rise to extra performance improvement [12].

Despite those mentioned above, due to the increasing demand for conventional materials such as stone aggregates as well as the equipment required for construction of stone columns, the use of alternative materials seems necessary. Further, the technique of soil improvement using geosynthetics is extensively used in the construction of stone columns [14, 15]. In the case of alternative materials, researchers proposed different materials for the construction of columns. The use of a steel bar as reinforcement has been investigated in laboratory studies. The findings show that reinforced stone columns with bars have more stiffness in comparison with ordinary stone columns. Also, in the case of small area ratio, the performance of the bars is greater [16, 17].

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Moreover, by changing the number and the diameter of the bars, the increase in the bearing capacity was noticeable. This is because of the stiffness increases and the lateral bulging decreases [18]. The use of shredded waste tyres as an aggregate for the stone column in an experimental study shows that replacing 40–60% of the crushed stone aggregate with the tyre chips of the same size leads to the same increase in the bearing capacity as ordinary stone columns [19]. Also, improvement in the bearing capacity of the stone columns depends on the shape and the amount of the tire content [20]. The use of fly ash as a column material reduces the cost of column construction [21] and improves the shear strength and the consolidation of the soil [22]. Lightweight expanded clay aggregate (LECA) is a lightweight material made from a special plastic which has been used in geotechnical applications such as stone column construction [23]. A laboratory investigation of the load test shows that by using the LECA columns and the ordinary stone columns, the bearing capacity of the clay bed increased by 31.7% and 19.5%, respectively [24].

The newest type of geosynthetics is expanded polystyrene (EPS) geofoam blocks, which is a superlight weight material used for construction purposes. EPS geofoams have been used consistently in roads [25] and as a compressible inclusion behind soil retaining structures [26] as well as a method for protecting buried pipelines [27]. It is an elasto-plastic hardening material with plastic contractive volume changes under compressive loading [28], whose behaviour is dependent on the density and confining stress. Further, it has been shown that the volumetric strain and axial compression strain have a linear relation [29]. The growth of both geofoam density and thickness affects the reduction of settlements. However, the changes in the thickness factor of geofoam are more effective than the alteration of the density factor on reducing settlements [30]. Selvakumar and Soundara conducted one-dimensional swell experiments to evaluate the efficiency of the EPS geofoam column (GC) on the swelling behaviour of expansive soil [31]. The results revealed that by the increase in the diameter of the column, there is a significant reduction in the swelling potential.

The crushed stone aggregate is the most common material used for the construction of the stone column. However, little research has been done on the use of alternative materials as a column material. Moreover, the previous experimental study as mentioned above has been performed on end-bearing geofoam column using small circular tank (typical CBR sample), and the results were not compared with the other types of columns like ordinary stone columns to obtain its performance. In this study, to introduce a geofoam column as a suitable alternative material to other columns, some laboratory experiments were conducted on floating columns in a large tank. The primary purpose of the study is to evaluate the efficiency of geofoam columns (GCs) with different arrangements. Also, to show the effectiveness of this new approach, the tests were compared with the ordinary stone columns (OSCs) and vertical encasement stone columns (VESCs) using geotextile.

Laboratory Model Tests

In this section, the important factors affecting the performance of columns were highlighted from the materials, loading system and the installation process. In addition, the subject of experimental tests performed on geofoam columns, hollow geofoam columns with stone aggregate, ordinary stone columns and encased stone columns were discussed.

Material Used

Clay and Stone Column Material

The kaolin clay soil was used as a soil bed. A series of unconfined compression strength (UCS) tests were performed to determine the moisture content corresponding to a soil unconfined compression strength of 30 kPa. Figure 1 displays the water content with the variation of unconfined compression strength. The resulting water content of the clay was found to be 23%, and this amount was kept the same in all tests. Table 1 represents the properties of kaolin clay soil. Note that the tests have been conducted in accordance with relevant ASTM standards.

In practical works, stone columns with a diameter of $D = 60$–100 cm are constructed where the size of the crushed stone aggregates used to make these columns is between 25 and 50 mm. Thus, the ratio of the stone column diameter to crushed stone aggregates diameter varies from 12 to 40 [32]. In this study, crushed stone aggregates between 2 and 10 mm in size were used to fabricate the column with $D = 80$ and 100 mm. In this case, the ratio of the diameter of the column to crushed stone aggregates diameter varied from 8 to 50. Hence, the scaling effect was minimized. Table 1 lists the stone aggregates features. Also, Fig. 2 shows the particle size distribution for both the kaolin clay soil and stone aggregates.

EPS Geofoam and Geotextile Materials

The EPS geofoam blocks with a density of 18.4 kg/m^3 (EPS19) were used as a column material. In this case, the geofoam blocks were cut into cylindrical cross sections. Then, one of the geofoam cylinders became a hollow cylinder (Fig. 3a), while the other was used as a normal cylinder as shown in Fig. 3b. A hollow cylindrical geofoam column had a hole at the middle filled with stone aggregates where a

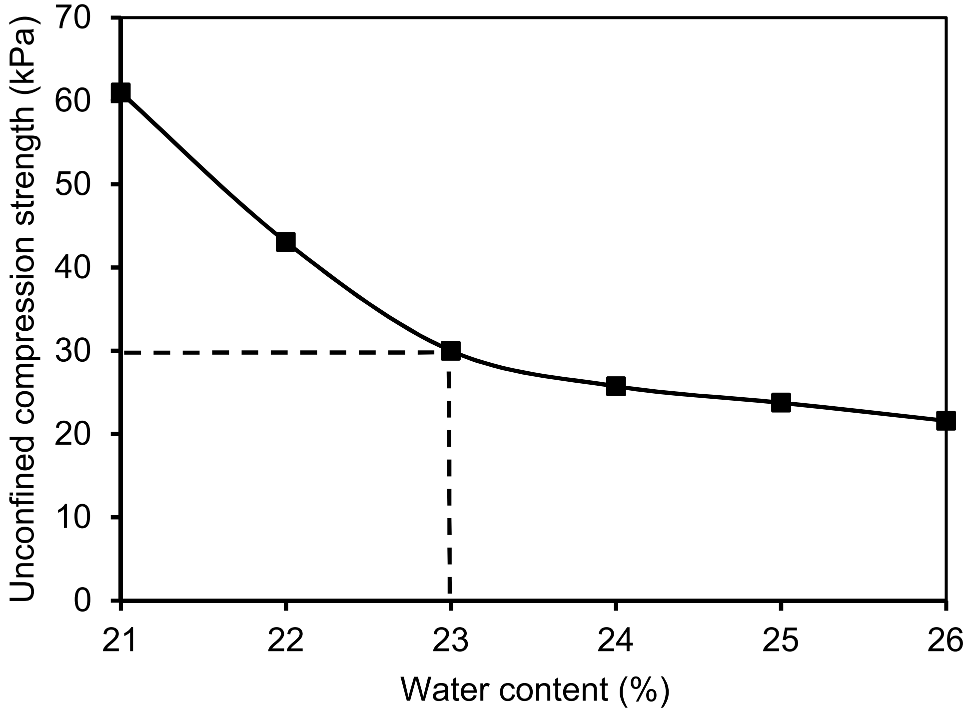


Fig. 1 Variation of unconfined compression strength of kaolin clay with water content

Table 1 Properties of the kaolin clay soil and crushed stone aggregates

Parameter	Kaolin clay	Stone aggregates
Maximum dry unit weight (kN/m^3)	15.5	16.9
Minimum dry unit weight (kN/m^3)	–	14.3
Optimum moisture content (%)	19	–
Unconfined compression strength (kPa)	30	–
Specific gravity	2.6	2.7
Liquid limit (%)	48	–
Plastic limit (%)	25	–
Plasticity index (%)	23	–
Bulk unit weight at 23% moisture content (kN/m^3)	19.1	–
Bulk unit weight for test at 70% relative density (kN/m^3)	–	16
Internal friction angle at 70% relative density (degree)	–	46
Uniformity coefficient (C_u)	–	2.25
Curvature coefficient (C_c)	–	1.62
USCS classification symbol	CL	GP

normal solid cylindrical geofoam column had not any hole, and it was used without any modifications. According to the scale effect problem in the laboratory model tests, Iai derived the following equation [33]:

$$(EA)_{\mathrm{f}} = \lambda^2 \cdot (EA)_{\mathrm{m}}, \tag{1}$$

where E represents the modulus of elasticity of the geofoam, A is the area of the geofoam, and $1/\lambda$ is the ratio of laboratory model test to actual model test where f and m represent the field and model conditions, respectively. In the current study, the ratio of the column diameter in the laboratory model to the real model is 0.1. Also, the modulus of elasticity of the reinforcement (geofoam) used in laboratory model is similar to real condition. It is clear that the area of reinforcement (geofoam) in the model test is 0.01 of the real one.

The selection of the geotextile material, as well as geofoam material, is an important task in laboratory model tests. Based on the scale effect concept, the unit weight of stone aggregates, column diameter and reinforcement stiffness,

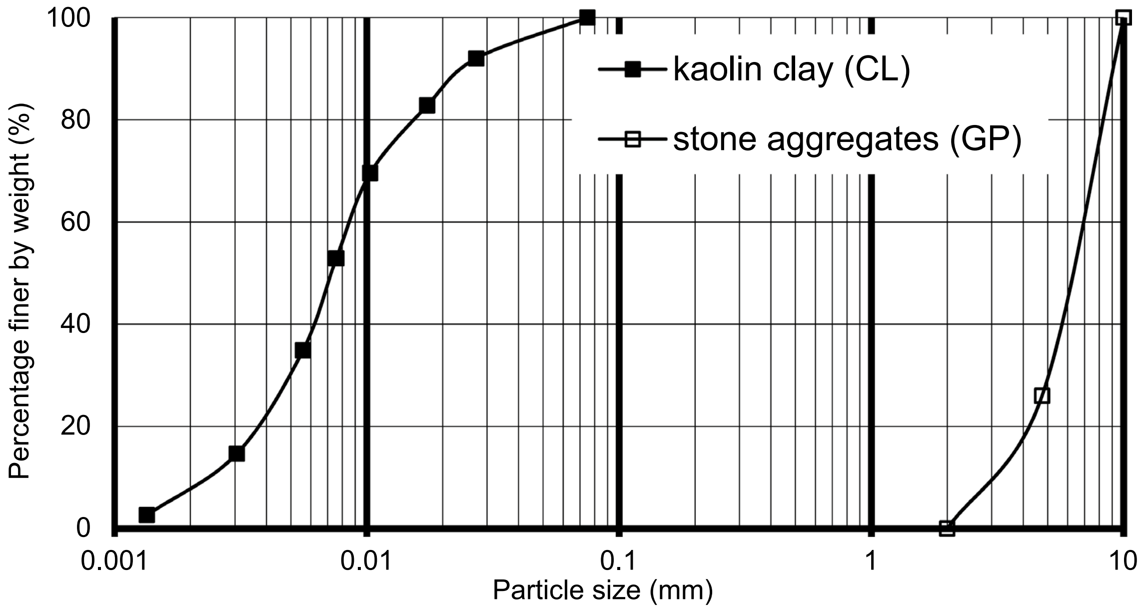


Fig. 2 Particle size distribution for crushed stone aggregates and kaolin clay materials

play a key role in the simulation of the experimental tests. The following equation is proposed to consider the relationship between these three parameters:

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

in which J, D, and γ represent the encasement stiffness, the diameter of the column, and stone aggregates unit weight, respectively. In addition, f and m denote the field and model conditions, respectively. The stone aggregates unit weights used for both model and field conditions are the same. In the present study, the column diameters were $D = 80$ and 100 mm which is regarded as 0.1 of the field conditions. This highlights that choosing the reinforcement material is an important factor. By considering the power of 2 in Eq. 2, the secant stiffness of reinforcement material for the model conditions was 0.01 field conditions. As the stiffness of the geotextile in practical works ranged from 1000 to 4000 kN/m [34], the nonwoven polypropylene geotextile with the properties presented in Table 2 was used as an encasement. As shown in Fig. 3c, a cylindrical geotextile was constructed with an overlap of 15-mm geotextile in the length for encasing the column [35].

Experimental Model

Similar to some researches [36–38], a large steel tank with steel rigid loading frame was made. The system of loading was based on displacement control, which contained a hydraulic jack and a rigid loading plate. The loading plate was rigid enough that vertical displacement through this rigid plate was transmitted evenly to the column and the surrounding soil. To achieve the minimum boundary effects on the results of the tests, the steel tank was built in a 1200 mm × 1200 mm × 1000 mm (length × width × height) (Fig. 4). The load cell and the displacement gauge were used to measure the loads and vertical displacement, respectively. For controlling the lateral deformation of the column, the minimum ratio of the column length to column diameter was suggested as 4 [1]. Thus, in the present study, the ratio of the column length to the column diameter of the columns was 5 [13, 14, 35–38].

Experimental Procedure

Preparation of Clay Bed

The kaolin clay soil was mixed with a water content of 23% in a container to obtain a homogeneous mixture. For decreasing the friction of the clay and the wall of the test tank, a layer of oil was used on the walls of the test tank. The kaolin clay soil was then filled to the appropriate weight in equal layers in the test tank, where each layer was properly compacted with a special tamper [39]. This procedure was continued until the test tank was filled. After that, the surface of the tank was covered and kept for 7 days to achieve uniform moisture content within the clayey soil mass. Moreover, for ensuring that the moisture content was 23% (corresponding to the unconfined compression strength of 30 kPa), several moisture contents of soil tests have been done while filling the test tank.

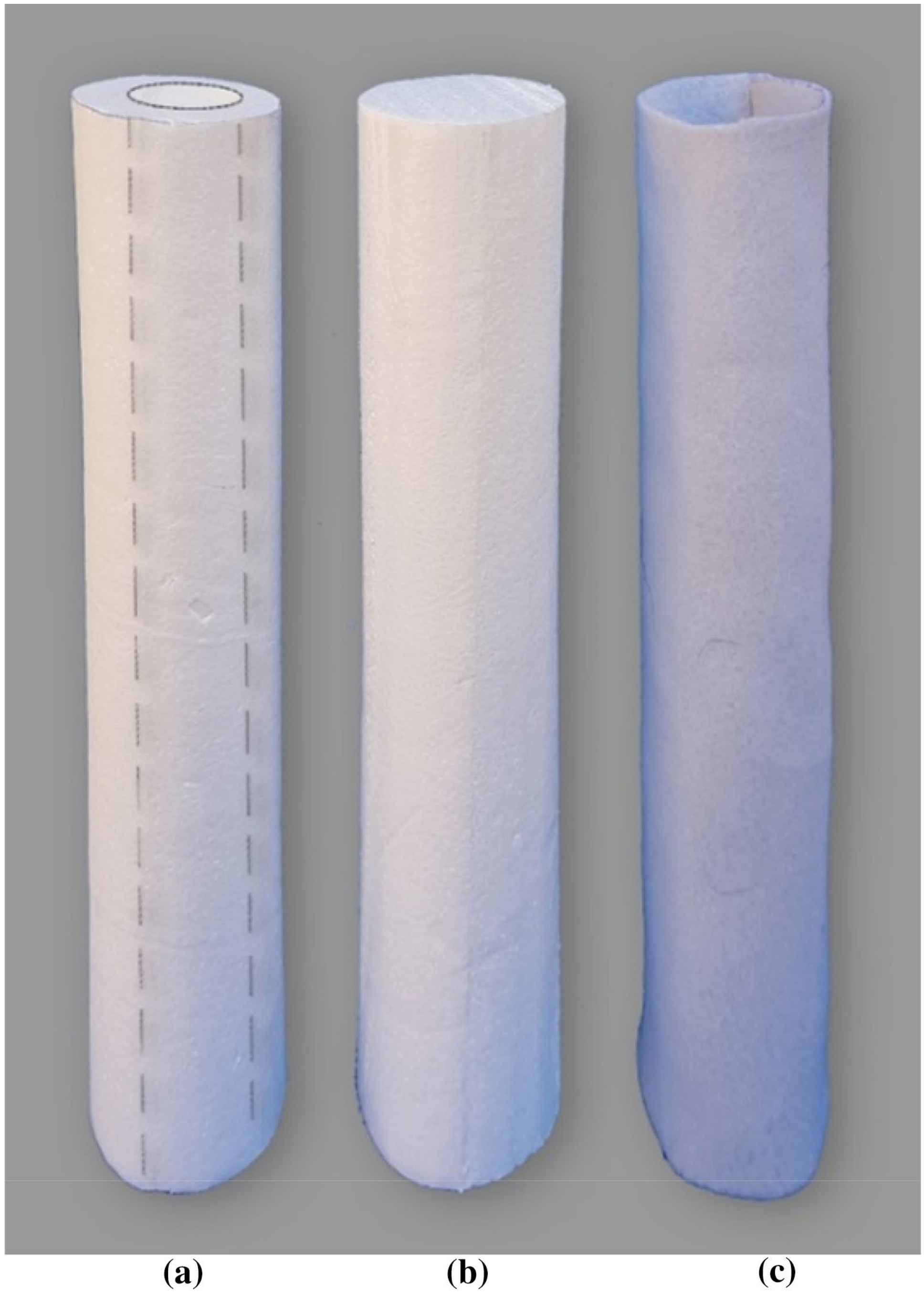


Fig. 3 Reinforcement materials: **a** hollow geofoam, **b** normal geofoam, **c** geotextile

Table 2 Properties of geotextile

Parameter	Value
Yarn material	Polypropylene
Ultimate tensile strength (kN/m)	10
Secant stiffness at ultimate Strain (kN/m)	15
Thickness (mm)	1.4
Mass per unit area (gr/m^2)	150

Preparation of Column

The technique of column construction in the present study is the replacement method. Two open-ended tubes with outer diameters of 80 and 100 mm with a thin wall were prepared and inserted into the soil bed [38]. To ease the problem of penetration and withdrawal, the surfaces of the pipe were covered with oil. Then, the helical auger was used for extracting the soil of the tube. To avoid any damages of the hole, the tube was gently lifted up. For constructing the

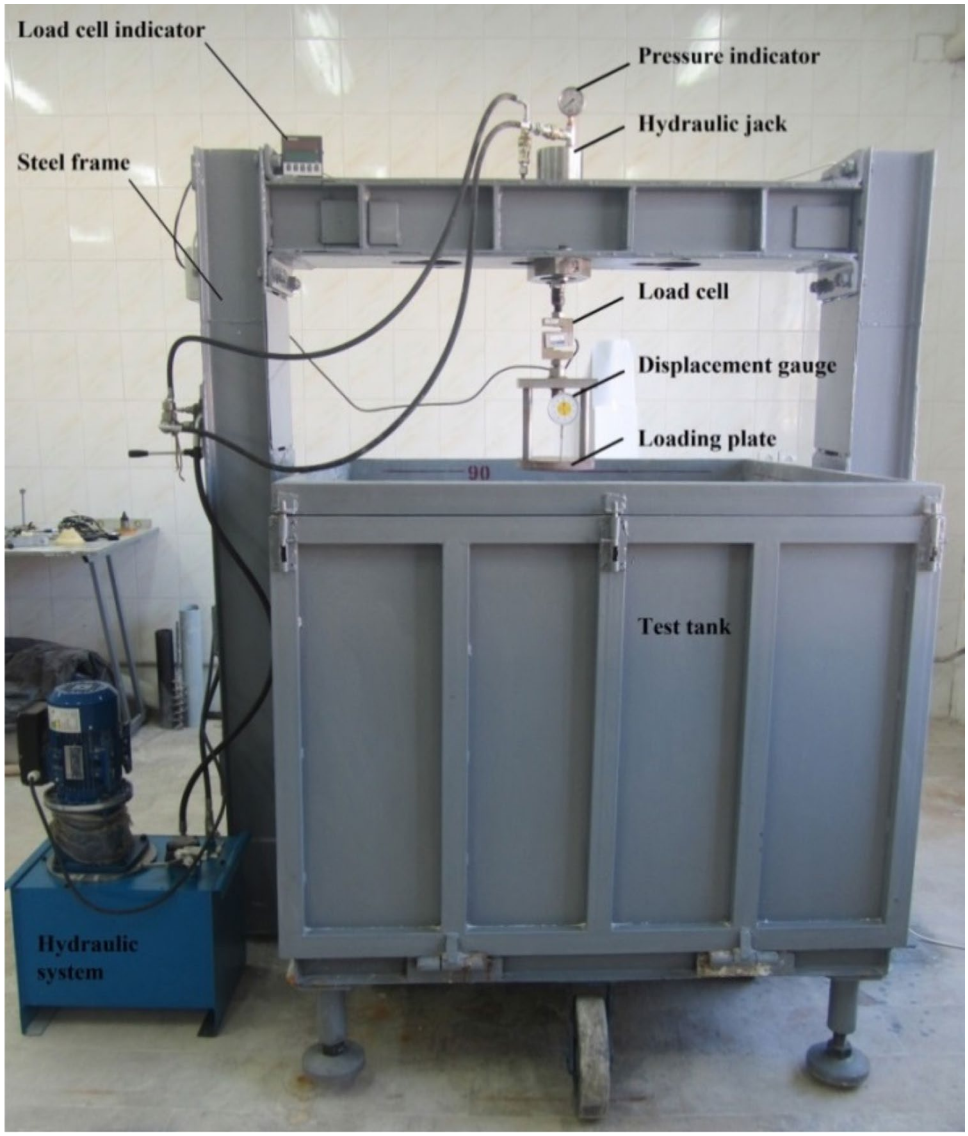


Fig. 4 Test tank

columns, as for OSCs, the formed borehole was filled with the stone aggregates in ten equal layers. In this case, a special compactor was used to achieve a uniform density. This compactor was a 2-kg tamper falling through a distance of 10 cm [35]. This particular compaction has some advantages, including no significant lateral deformation and no penetration of the stone aggregates into the clay bed during the construction of the stone column.

In the case of geofoam columns, after making a borehole in the kaolin clay bed, the geofoam column was simply located into the hole. Moreover, in the case of using a hollow geofoam, the stone aggregate was used to fill the borehole of geofoam column. For encasing vertical geotextile, a thin-walled tube (casing) with a diameter equal to the diameter of the geotextile sock was driven into the hole. Then, the geotextile was located into the casing and filled with stone aggregates by considering the procedure which was discussed above for OSCs. After that, the casing was pulled up, while the geotextile was left in the place [34].

Tests Conducted

The columns, which formed in the kaolin clay bed, were subjected to vertical loading through a loading plate displaced at a constant strain rate of 1 mm/min up to a settlement of 50 mm. The loading plate was 2 times larger than the diameter of the columns and had a thickness of 30 mm. The experiments were performed on an unreinforced kaolin clay bed, OSCs, VESCs and GCs (Figs. 5, 6). To evaluate the efficacy of the columns, as listed in Table 3, 11 tests were conducted on two different diameters with the length of *5D*, which were installed in kaolin clay bed without ground water level.

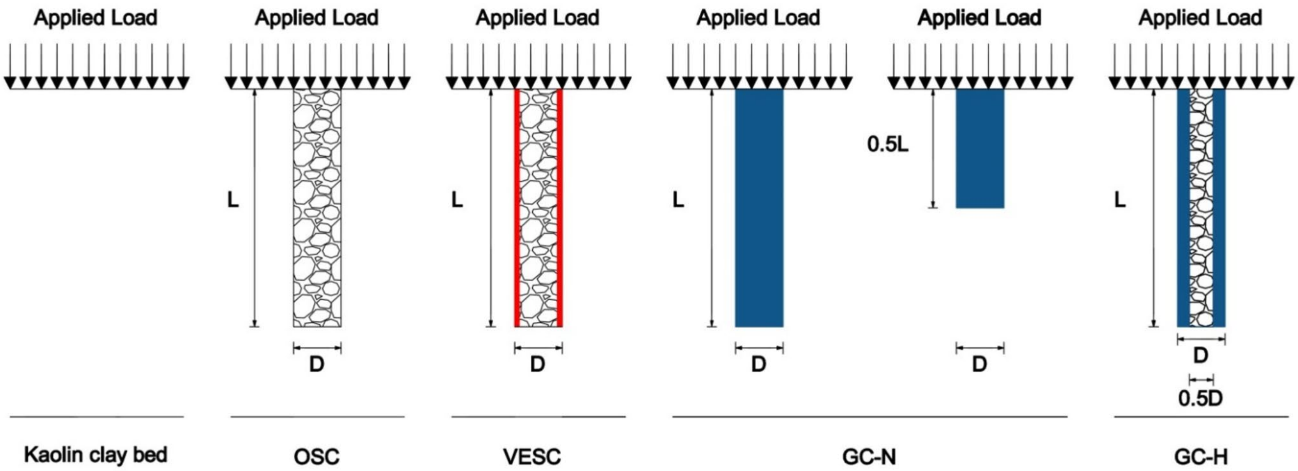


Fig. 5 Schematics of different types of columns testing

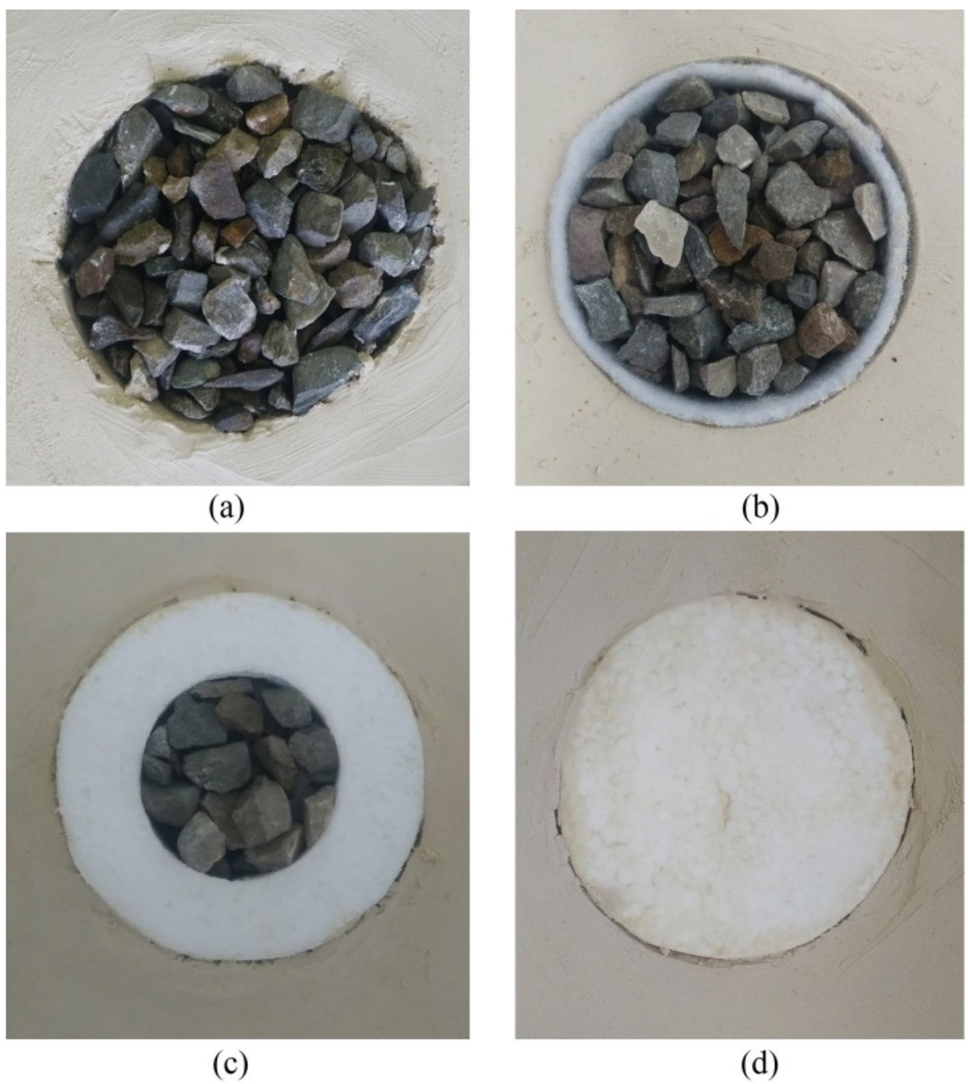


Fig. 6 Different types of column: **a** OSC, **b** VESC, **c** GC-H, **d** GC-N

Table 3 Details of tests conducted

Reinforcement type	Column diameter (mm)	Column length (mm)
Clay bed	–	–
OSC1	80	400
VESC1		400
GC-N1		400
GC-N2		200
GC-H1		400
OSC2	100	500
VESC2		500
GC-N3		500
GC-N4		250
GC-H2		500

As shown in Fig. 5, in OSCs, the tests were applied on two diameters (*D*) and lengths (*L*), $D = 80$ mm and $L = 400$ mm (OSC1) and $D = 100$ mm and $L = 500$ mm (OSC2). In VESCs, as the OSCs, two tests were conducted on the stone columns with full-length geotextile encasement with two diameters and lengths (VESC1 and VESC2). The GCs consist of two groups. The first group includes four different tests which were performed using different lengths of the normal geofoam columns: GC-N1 ($D = 80$ mm and $L = 400$ mm), GC-N2 ($D = 80$ mm and $L = 200$ mm), GC-N3 ($D = 100$ mm and $L = 500$ mm), and GC-N4 ($D = 100$ mm and $L = 250$ mm). The second group includes two different tests which were conducted using hollow geofoam columns: GC-H1 ($D = 80$ mm, $L = 400$ mm) and GC-H2 ($D = 100$ mm, $L = 500$ mm). In this case, there was a hole at the middle of the column with a diameter of *0.5D*, which was filled with the aggregates material.

Results and Discussion

The main focus in this section is a comparison of the behaviour of the geofoam columns with that of the ordinary stone columns and vertical encasement stone columns installed in kaolin clay bed of identical properties. To bring out their relative performances, the experimental results obtained from the model tests are analysed and discussed in this section.

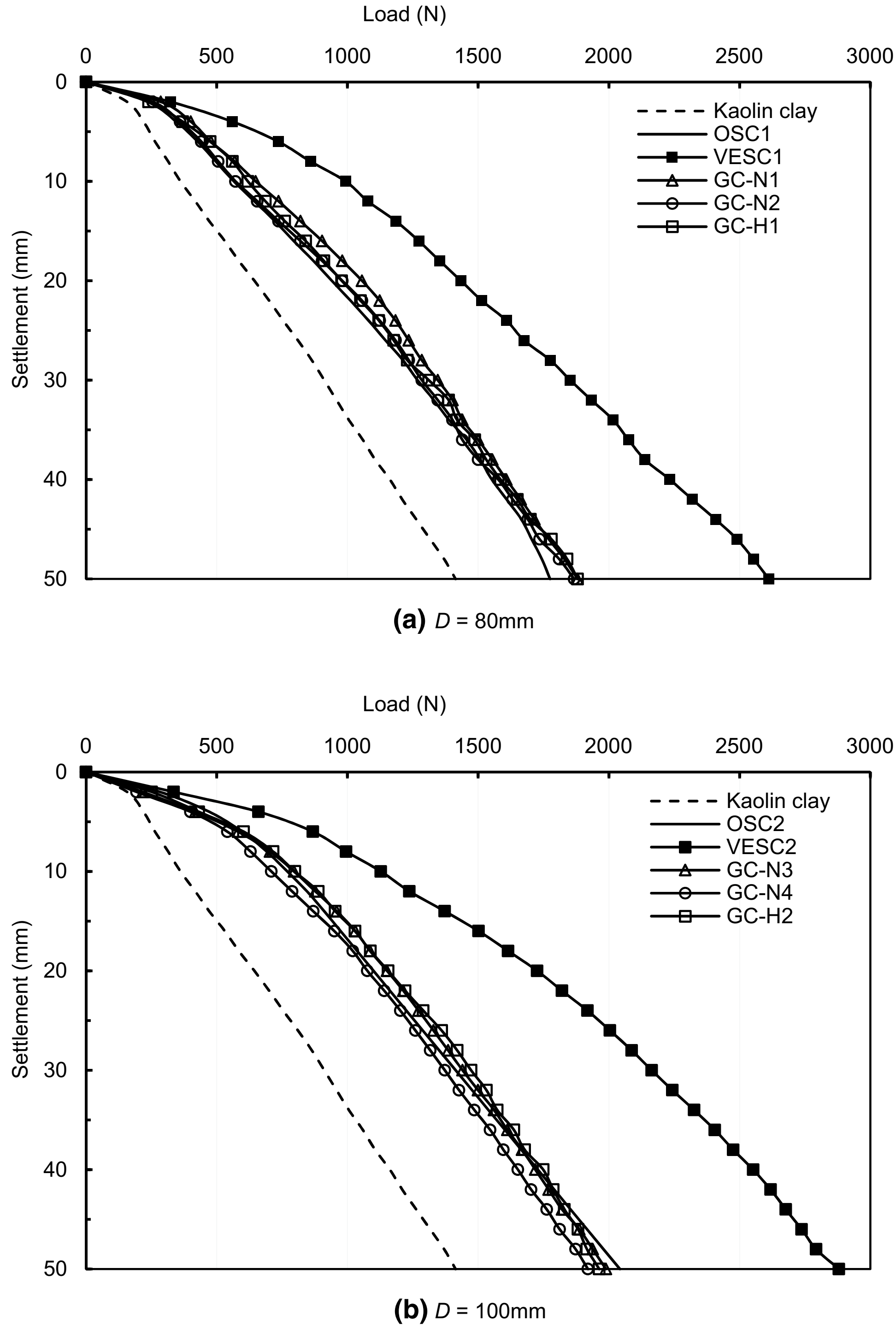
Load–Settlement Behaviour

Figure 7a, b demonstrates the load–settlement behaviour for the columns with the diameter of 80 and 100 mm, respectively, up to the settlement of 50 mm. As seen, OSCs, VESCs and GCs increased the bearing capacity of clay soil. The increase in the bearing capacity for OSC1 ($D = 80$ mm) and OSC2 ($D = 100$ mm) was 25.6% and 44.4%, respectively. Also, using VESC1 and VESC2 led to an increase in bearing capacity by 84.8% and 103.7%, respectively. In the case of using geofoam, GC-N1 ($D = 80$ mm) and GC-N3 ($D = 100$ mm) led to an increase in the bearing capacity of the kaolin clay by 33.0% and 40.7%, respectively. The magnitude of this increase for GC-N2 and GC-H1 ($D = 80$ mm) was 32.1% and 33.0%, while for GC-N4 and GC-H2 ($D = 100$ mm) was 35.8% and 38.9%, respectively.

According to the results, by using OSCs or GCs instead, the bearing capacity would increase. Encasing OSCs via vertical geotextile reinforcement resulted in a further increase in the bearing capacity of kaolin clay soil. It was because geotextile provides additional confinement, which led to more stiffness of the column. Moreover, the comparison between Fig. 7a, b for OSCs showed that by increasing the diameter, the bearing capacity of the clay soil increased by 15.0%. Also, comparing VESC1 with VESC2 showed that upon elevation of the diameter, the bearing capacity rose by 10.3%. Further, the average value of this increase was 4.3% for GCs. The results showed that the increase in the bearing capacity with increasing diameter in VESC is more than twice that of GCs. This is because geotextile has more stiffness, which leads to more confinement than geofoam. Application of VESC1 and VESC2 increased the bearing capacity of the OSC1 and OSC2 by 47.2% and 41.0%, respectively. Therefore, with an increase in the column diameter, the benefit of the encasement decreases. It is because the lateral stresses mobilized in encased stone columns are higher for smaller diameter columns. Based on the experimental study, Ghazavi and Afshar [36] also observed that the encasing the stone columns with geotextile, led to increase in the bearing capacity of the stone column by 38% and 32%, respectively, for $D = 80$ and 100 mm. This showed that encasing the stone columns resulted in more increase in the bearing capacity. Also, the results of the study demonstrated that increasing the column diameter reduced the efficiency of geotextiles as discussed above for the present study.

The effect of the geofoam length was studied for two different lengths. It was seen that with the increase in the length of geofoam from half-length (GC-N2 and GC-N4) to full-length (GC-N1 and GC-N3), the variation of the bearing capacity was negligible. This was because of the deformation mode of OSCs in the form of bulging changes to the small bulging with elastic shortening in both lengths. Therefore, the use of shorter geofoam columns seems sufficient. In other words, from an economic point of view, the use of half-length geofoam column is recommended. As observed in Fig. 7, the performance of the GC-Hs was almost the same as that of GC-Ns. In other words, filling GCs with stone aggregates did not lead to more increase in the bearing capacity. It might be because GC was not a good element for encasing the stone aggregates.

Fig. 7 Variation of load–settlement behaviour of kaolin clay bed, OSCs, VESCs and GCs



Comparison of OSCs and GCs showed that the variations of the bearing capacity of the columns for both diameters were negligible. Therefore, the use of GCs instead of OSC led to almost the same results in the bearing capacity of the kaolin clay. This shows that the stiffness created by the stone aggregates is the same as the stiffness created by the geofoam materials. From another perspective, the geofoam columns are very easy to install and save both cost and time by eliminating compaction operations. Also, there is not any soil distribution in installation in such cases. Also, the lightness of the geofoam makes it easy to work with and reduces the cost of transportation.

By comparing the stress level in a model test using vertical steel bars as reinforcement [18], it should be noted that the stress level in reinforced stone columns with the diameter of 100 mm at the strain of 10% was 95 kPa.

Table 4 Variation of β with AR

Diameter (mm)	80	100
AR%	16	25
GC-N1	1.06	–
GC-N3	–	0.97
GC-N2	1.05	–
GC-N4	–	0.94
GC-H1	1.06	–
GC-H2	–	0.96
VESC1	1.47	–
VESC2	–	1.41

Table 5 Variation of the maximum BCR values with AR

Type of column	AR	
	16	25
GC-N1	1.82	–
GC-N3	–	2.24
GC-N2	1.67	–
GC-N4	–	2.05
GC-H1	1.80	–
GC-H2	–	2.28
VESC1	2.79	–
VESC2	–	3.29

However, in this study, the stress level for GC-N3 and VESC2 was 63 and 92 kPa, respectively, which indicated that increasing the stiffness of the reinforcement has a great effect on the increase in the bearing capacity.

To show the improvement of GCS and VESC over OSC, the parameter of the ratio of the area replacement (AR) is defined which offers the percentage of soil replaced by the column materials and is obtained from dividing the column area to the loaded area. In order to compare the benefits of geofoam material and geotextile encasement with OSC, the dimensionless parameter (β) is defined, which is explained as the ratio of the bearing capacity of the reinforced column (GCs or VESCs) to unreinforced stone column (OSCs). The variations of β with AR for different columns diameters are presented in Table 4. As seen, the variation of the β was almost the same for GCs. Thus, by considering the bearing capacity, the performance of the GCs was similar to that of OSCs. In addition, it was found that the β values for VESCs vary within the range of 1.41–1.47. In this case, the elevation of AR leads to a decrease in β, so it means that increasing the column diameter led to a decrease in the efficiency of the reinforcement. Also, as stated for VESCs, in geofoam columns, the column efficiency decreases with increasing the column diameter.

As seen in Table 5, with the increase in the AR, the stiffness of the column increases and as a result, the bearing capacity of the column increases, which eventually increases the BCR values.

Bearing Capacity Ratio

The bearing capacity ratio (BCR) parameter is explained as the reinforced soil bearing capacity to the unreinforced soil bearing capacity. The BCR is used to evaluate the performance of unreinforced or reinforced columns to show the soil improvement by considering the bearing capacity. Figure 8 displays the BCR variations with the different diameters up to a settlement of 50 mm. It was found that the value of BCR in columns varies in the range of 1.26–2.79 and 1.23–3.29, respectively, for $D = 80$ and 100 mm columns. For $D = 80$ mm, the minimum BCR belongs to OSC1, while for $D = 100$ mm, it belongs to the GC-N4. The maximum BCR, for both diameters, was related to VESC1 and VESC2. In all cases, the BCR value grew with the elevation of the column diameters. Figure 8 also shows that as the loading increases up to initial settlements, the BCR value increases. Then, the value of BCR decreases. It is because the bulging occurred and the columns reached their ultimate resistance. In addition, by continuing the loading process, the bearing capacity has not increased significantly. Hence, the value of BCR either remains constant or decreases. In some studies, such as Rezaei et al. [37], who used steel bars to reinforced stone columns, the BCR varies in the range of 1.33–3.58 and 1.44–3.91, respectively, for $D = 80$ and 100 mm columns. Therefore, by comparing these results with the results of the present study, it could be concluded that by using the higher stiffness of the reinforcement, the increase in the bearing capacity would be greater.

Lateral Deformation of the Columns

After the tests of OSCs and VESCs were over, the plaster slurry was poured into the stone column and allowed to settle for 24 h to harden. After that, the surrounding kaolin clay was removed carefully to obtain the deformation of the column where the bulge depth was visible and the dissipation of the column material did not occur. Figure 9 demonstrates the deformed shapes of OSC and VESC indicating lateral deformation of the columns, respectively, which occurred at 1.2D and 2D depths from the top of the column. Moreover, the samples of 100 mm columns were measured to obtain the lateral bulging, which was 24 mm for OSC and 12 mm for VESC. Thus, OSC bulging was larger than VESC bulging. The bulging in VESC was reduced because of the extra confinement arising from the reinforcement material. The results show that by reinforcing column, the column stiffness increases, so the bulging reduces and the bearing capacity increases. However, since the geofoam column is an elastic material, it returns

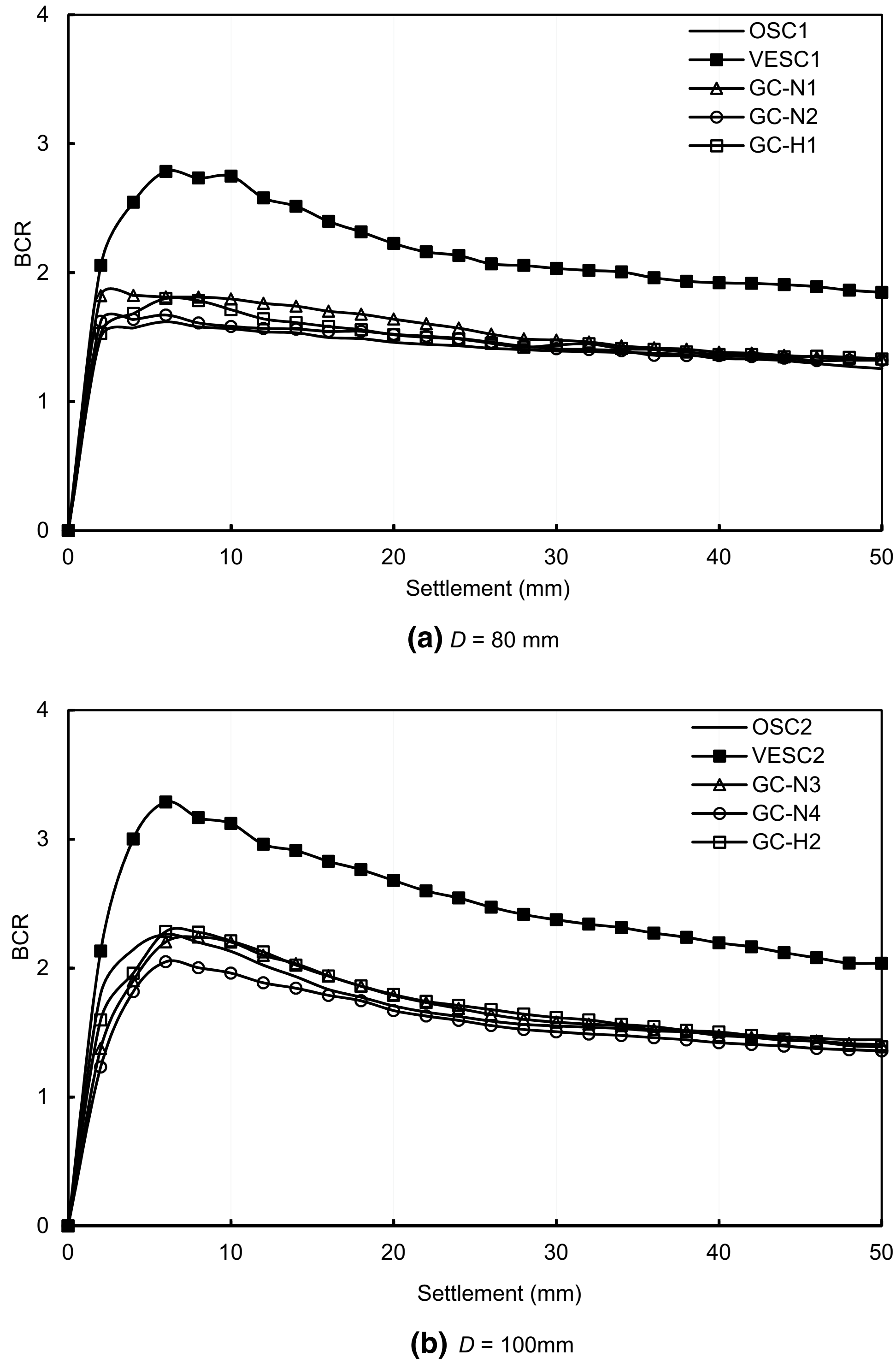


Fig. 8 Variation of bearing capacity ratio (BCR) versus settlement

to its original shape by unloading and it is not possible to measure its deformation by the method mentioned above. Moreover, after removing the geofoam, it was observed that a small bulging with elastic shortening occurred in GC-Ns. Also, in GC-Hs, the walls of the columns were damaged by the crushed stone aggregates.

Conclusions

The present study introduces a new technique for using geofoam as a column material (GC), which shows its efficiency in comparison with other well-established

Fig. 9 Deformation of columns after test: **a** OSC, **b** VESC

techniques such as ordinary stone columns (OSC) and vertical encasement stone columns (VESC). To do this, small-scale experimental tests were conducted on floating columns with a diameter of $D = 80$ and 100 mm in a kaolin clay bed with the length of $5D$. The tests focused on studying a new type of column made from geofoam material (GC). The following outcomes were presented:

- The bearing capacity of GCs is almost equal to the bearing capacity of OSCs. However, this amount is smaller than VESC. This shows that the stiffness created by the stone aggregates is the same as the stiffness created by the geofoam materials.
- In VESCs, the reinforcing stone column with geotextile provides additional confinement. Thus, the bulging reduces and the bearing capacity increases. This indicates that the geotextile encasement increases the stiffness of the column.
- The value of β varies in the range of 0.94–1.06 and 1.41–1.47 for GCs and VESCs, respectively. Therefore, it is concluded that the increase in the area replacement ratio (AR) in the GCs and VESC, leads to a decrease in the benefits of the geofoam and geotextile materials.
- Increasing the geofoam length has a small effect on the bearing capacity of the column. In this case, the deformation mode of the geofoam column in both lengths is small bulging with elastic shortening.
- The geofoam columns could be a good alternative material because they have the same performance with the ordinary stone columns and are very easy to install and save both cost and time.

Author Contributions SBB designed and performed the experiments, derived the models and analysed the data. SHL conceived the presented idea and developed the theory and supervised the findings of this work. HRS encouraged the other authors to investigate a novelty of the work. SMM contributed to the final version of the manuscript. SBB and SHL wrote the manuscript with input from all authors. All authors discussed the results and contributed to the final manuscript.

Compliance with Ethical Standards

Conflict of interest The corresponding author, on behalf of other authors, states that there is no conflict of interest.

References

1. Barksdale RD, Bachus RC (1983) Design and construction of stone columns. Report No. FHWA/RD-83/026, Office of Engineering and Highway Operations Research and Development, Federal Highway Administration, Washington, DC
2. Greenwood DA (1970) Mechanical improvement of soils below ground surfaces. In: Proceedings of conference on ground engineering. Institute of Civil Engineers, London, pp 11–22
3. Vesic AS (1972) Expansion of cavities in infinite soil mass. J Soil Mech Found Div 98(SM3):265–290
4. Madhav MR, Vitkar PP (1978) Strip footing on weak clay stabilized with a granular trench or pile. Can Geotech J 15(4):605–609. https://doi.org/10.1139/t78-066
5. Aboshi H, Ichimoto E, Harada K, Emoki M (1979) The composer—a method to improve the characteristics of soft clays by inclusion of large diameter sand columns. In: Proceedings international conference on soil reinforcement, Paris, pp 211–216
6. Shivashankar R, Babu MRD, Nayak S (2011) Performance of stone columns with circumferential nails. Proc Inst Civil Eng 164(2):97–106. https://doi.org/10.1680/grim.2011.164.2.97
7. Van Impe WF (1986) Improving of the bearing capacity of weak hydraulic fills by means of geotextiles. In: Proceedings of the 3rd international conference on geotextiles, Vienna, pp 1411–1416
8. Murugesan S, Rajagopal K (2007) Model tests on geosynthetic-encased stone columns. Geosynth Int 14(6):346–354. https://doi.org/10.1680/gein.2007.14.6.346
9. Chen JF, Wang XT, Xue JF, Zeng Y, Feng SHZ (2018) Uniaxial compression behavior of geotextile encased stone columns. Geotext Geomembr 46(3):227–283. https://doi.org/10.1016/j.geotexmem.2018.01.003
10. Gniel J, Bouazza A (2009) Improvement of soft soils using geogrid encased stone columns. Geotext Geomembr 27(3):167–175. https://doi.org/10.1016/j.geotexmem.2008.11.001
11. Murugesan S, Rajagopal K (2010) Studies on the behavior of single and group of geosynthetic encased stone columns. J Geotech Geoenviron Eng 136(1):129–139. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000187
12. Dash SK, Bora MC (2013) Influence of geosynthetic encasement on the performance of stone columns floating in soft clay. Can Geotech J 50:754–765. https://doi.org/10.1139/cgj-2012-0437
13. Lajevardi SH, Enami S, Hamidi M, Shamsi HR (2018) Experimental study of single and groups of stone columns encased by geotextile. J Sci Technol. https://doi.org/10.22060/CEEJ.2018.12789.5269
14. Lajevardi SH, Shamsi HR, Hamidi M, Enami S (2018) Numerical and experimental studies on single stone columns. Soil Mech Found Eng 55:340–345. https://doi.org/10.1007/s11204-018-9546-9
15. Malarvizhi SN, Ilamparuthi K (2007) Comparative study on the behaviour of encased stone column and conventional stone column. Soils Found 47:873–885. https://doi.org/10.3208/sandf.47.873
16. Shivashankar R, Babu MRD, Nayak S, Manjunath R (2010) Stone columns with vertical circumferential nails: laboratory model study. Geotech Geol Eng 28(5):695–706. https://doi.org/10.1007/s10706-010-9329-1
17. Shivashankar R, Babu MRD, Nayak S (2011) Performance of stone columns with circumferential nails. Proc Inst Civ Eng Ground Improv 164(2):97–106. https://doi.org/10.1680/grim.2011.164.2.97
18. Rezaei MM, Lajevardi SH, Saba H et al (2019) Laboratory study on single stone columns reinforced with steel bars and discs. Int J Geosynth Ground Eng. https://doi.org/10.1007/s40891-019-0154-1
19. Ayothiraman R, Soumya S (2015) Model tests on the use of tyre chips as aggregate in stone columns. Proc Inst Civ Eng Ground Improv 168(3):187–193. https://doi.org/10.1680/grim.13.00006
20. Shariatmadari N, Zeinali SM, Mirzaeifar H, Keramati M (2018) Evaluating the effect of using shredded waste tire in the stone columns as an improvement technique. Constr Build Mater 176:700–709. https://doi.org/10.1016/j.conbuildmat.2018.05.090
21. Saravanan PS (2013) Study on sintered flyash aggregate as columnar inclusions on soft clay. Int J Eng Technol Res 1(1):38–44
22. Marto A, Hasan M, Hyodo M, Makhtar AM (2014) Shear strength parameters and consolidation of clay reinforced with single and group bottom ash columns. Arab J Sci Eng 39:2641–2654. https://doi.org/10.1007/s13369-013-0933-2
23. Rashad AM (2018) Lightweight expanded clay aggregate as a building material—an overview. Constr Build Mater 170:757–775. https://doi.org/10.1016/j.conbuildmat.2018.03.009
24. Dave TN, Rotte VM (2018) Proceedings of GeoShanghai 2018 international conference: ground improvement and geosynthetics. Springer Singapore. https://doi.org/10.1007/978-981-13-0122-3_11
25. Beinbrech G, Hillmann R (1997) EPS in road construction—current situation in Germany. Geotext Geomembr 15:39–57. https://doi.org/10.1016/s0266-1144(97)00006-x
26. Lal BRR, Padade AH, Mandal JN (2014) Numerical simulation of EPS geofoam as compressible inclusions in fly ash backfill retaining walls. In: Proceedings of the ground improvement and geosynthetics, Shanghai, pp 526–535. https://doi.org/10.1061/9780784413401.052
27. Bartlett SF, Lingwall BN, Vaslestad J (2015) Methods of protecting buried pipelines and culverts in transportation infrastructure using EPS geofoam. Geotext Geomembr 43:450–461. https://doi.org/10.1016/j.geotexmem.2015.04.019
28. Leo CJ, Kumruzzaman M, Wong H, Yin JH (2008) Behavior of EPS geofoam in true triaxial compression tests. Geotext Geomembr 26:175–180. https://doi.org/10.1016/j.geotexmem.2007.10.005
29. Chun B-S, Lim H-S, Shin Y-W (2001) Application of constitutive model to predict the behavior of EPS-geofoam. KSCE J Civ Eng 5:175–183. https://doi.org/10.1007/bf02829073
30. Abdelrahman GE, El Kamash WH (2014) Behavior improvement of raft foundation on port-said soft clay utilizing geofoam. Geotech Spec Publ. https://doi.org/10.1061/9780784413401.055
31. Selvakumar S, Soundara B (2018) The performance of EPS geofoam columns: an introduction. In: Proceedings of the 11th int. conf. on geosynthetics, Seoul, pp 47–53
32. Wood DM, Hu W, Nash DFT (2000) Group effects in stone column foundation: model tests. Geotechnique 50(6):689–698. https://doi.org/10.1680/geot.2000.50.6.689
33. Iai S (1989) Similitude for shaking table tests on soil-structure fluid models in 1g gravitational field. Soils Found 29(1):105–118. https://doi.org/10.3208/sandf1972.29.105
34. Alexiew D, Brokemper D, Lothspeich S (2005) Geotextile encased columns (GEC): load capacity, geotextile selection and pre-design graphs. Geotech Spec Publ. https://doi.org/10.1061/40777(156)12

35. Afshar JN, Ghazavi M (2012) Experimental studies on bearing capacity of geosynthetic reinforced stone columns. Arab J Sci Eng 39:1559–1571. https://doi.org/10.1007/s13369-013-0709-8
36. Ghazavi M, Afshar JN (2013) Bearing capacity of geosynthetic encased stone columns. Geotext Geomembr 38:26–36. https://doi.org/10.1016/j.geotexmem.2013.04.003
37. Rezaei MM, Lajevardi SH, Ghalandarzadeh A, Zeighami E (2019) Experimental and numerical studies on load-carrying capacity of single floating aggregate piers reinforced with vertical steel bars. https://doi.org/10.22060/CEEJ.2019.15640.5991
38. Hamidi M, Lajevardi SH (2018) Experimental study on the load-carrying capacity of single stone columns. Int J Geosynth Ground Eng. https://doi.org/10.1007/s40891-018-0142-x
39. Debnath P, Dey AK (2017) Bearing capacity of geogrid reinforced sand over encased stone columns in soft clay. Geotext Geomembr 45(6):653–664. https://doi.org/10.1016/j.geotexmem.2017.08.006