Experimental Studies on Groups of Stone Columns with Various Shapes of Geotextile

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Abstract. A wide range of treatments has been proposed to improve soft soils. However, increasing construction costs combined with today's environmental considerations will undoubtedly make the stone column technique a good alternative to the other techniques. In this paper, results obtained from stone columns installed in clay soil are presented and discussed. To do this and because in real conditions stone columns are used in groups, a series of experimental tests were performed on the groups of 3 and 12 stone columns and compared with the single stone columns. The stone columns were reinforced with a vertical encasement, horizontal layers, and a combination of both. It is found that, in a group of stone columns, the use of the combination of vertical encasement and horizontal layers outperformed other shapes. In addition, both group arrangements of stone columns result in more increase in bearing capacity in comparison with the single stone columns. However, the group of 3 stone columns had better efficiency despite its lower replacement area ratio.

1 Introduction

Suitable land for construction has diminished due to the rapid growth of infrastructure worldwide, while unoccupied land often consists of soft soils with a low bearing capacity which has become a major issue. To overcome such a problem, soil modification is needed to improve the mechanical properties of soft soil. Among the various methods for improving the mechanical properties of the ground, the stone column technique is commonly used worldwide. However, stone columns may not work well in very soft soil due to bulging of columns. Encasement materials have been used to minimize bulging of stone columns and improve their performance (Van Impe, 1986). Most experimental studies (Van Impe, 1986; Barksdale and Bachus, 1983; Greenwood, 1970; Vesic, 1972; Madhav and Vitkar, 1978; Aboshi et al., 1979; Debnath and Dey, 2017) have summarized the load settlement behavior of the stone columns. Wood et al. (2000) conducted some model tests in kaolin clay to examine the deformational behavior of a stone column group. In their studies, the spacing, length and diameter of columns were all variables. The increase in the performance of the stone column is strongly related to the tensile strength of the encasement material (Rathod et

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al., 2020). The column in the center of the columns bulged uniformly, however the surrounding columns bulged away from the neighboring columns (McKelvey et al., 2004). Ambily and Gandhi (2007) studied the behavior of the stone column groups using model tests done on the kaolin clay soil in a cylindrical tank and examined the influence of various design parameters. The findings showed that with increasing the column distance, the bearing capacity of stone columns decreases. Black et al. (2007) studied the aspect of settlement performance of single and group columns using a large triaxial cell equipped to test samples. The settlement performance of a group of columns was considered to be highly influenced by inter-column and footing interaction effects.

Several laboratory tests have been performed on horizontal geosynthetics reinforcement layers both inside and above the columns. Madhav (1982) suggested this form of reinforcement for the first time. Ghazavi et al. (2018) performed several experimental tests on stone column groups to find the influence of employing horizontal geotextile on the bearing capacity. It was found that the bearing capacity of a group of stone columns with horizontal reinforcement was greater than that of a group of ordinary stone columns. In this case, the failure mode was a combination of buckling and bulging due to general shear failure. The results of some laboratory tests on the stone column groups showed that the horizontal layers of geotextile and geogrid, respectively were the best reinforcing material for the floating and end-bearing columns (Ali et al., 2014).

Combining the horizontal and vertical reinforcements could be the next possibility for increasing the performance of the stone columns. Hasan and Samadhiya (2017) did this by testing on a single stone column, not on the column group using unit cell model tests. The results showed that the use of this type of reinforcement increases the bearing capacity of stone columns.

In real conditions, stone columns are used in-group however, there is no comprehensive approach for all types of reinforcement materials. On the other hand, most model tests have been conducted in a cylindrical cell and the stone column designs have adopted the unit cell concept. Further, the combination of both vertical and horizontal reinforcement as a group of stone columns has not been studied so far. There is no study either on the benefits of the arrangements of group stone column.

The current paper shows the results of a series of laboratory tests performed on stone columns (both single and group) installed in kaolin clay bed and reinforced with a vertical encasement, horizontal layers, and a combination of both. The study focuses on the two types of arrangement of the group stone columns.

2 Experimental program

2.1 Materials

The modelling investigation is concerned with the fundamentals of the mechanics of stone columns so that it would be appropriate to use well-defined materials. It was decided to use kaolin clay soil with the moisture content of 23% corresponding to the soil unconfined compression strength of 30 kPa. To do this a number of unconfined compression strength tests were performed on the kaolin clay soil.

In practice, the columns diameters are made at the diameters of 0.6-1.0 m and the ratio of the column diameter to the diameter of the stone column materials is usually a value between 12 and 40. Thus, stone aggregates with a particles size ranging 2 to 10 mm were used for the formation of the model stone column of size 80 mm diameters. Table 1 and 2 showed the properties of both stone aggregates and the kaolin clay soil, respectively.

Table 1. Properties of kaolin clay and crushed stone aggregates

Parameter	**Stone aggregates**
Maximum dry unit weight (kN/m^3)	16.9
Minimum dry unit weight (kN/m^3)	14.3
Specific gravity (no units)	2.7
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	*GP*

Table 2. Properties of kaolin clay and crushed stone aggregates

Parameter	**Kaolin clay**
Maximum dry unit weight (kN/m^3)	15.5
Minimum dry unit weight (kN/m^3)	-
Optimum moisture content *(%)*	19
Unconfined compression strength (kPa)	30
Specific gravity (no units)	2.6
Liquid limit *(%)*	48
Plastic limit *(%)*	25
Plasticity index *(%)*	23
Bulk unit weight at 23% moisture content (kN/m^3)	19.1
USCS classification symbol	*CL*

From the scaling effect law presented by Iai (1989), three parameters, stone column material unit weight, the diameter of the stone column and the stiffness of the reinforcement material, play a fundamental role in the simulation of the test:

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

where J is the stiffness of the reinforcement, D is the stone column diameter and γ is the unit weight of crushed stone aggregates. Also, m and f represent model and field conditions, respectively. The unit weight of crushed stone aggregates used for both model and field condition was the same. So, it does not affect Eq. 1. The stone column with a diameter of 80 mm was used equivalent to 0.10 of the field conditions. However, since the value of the diameter in Eq. 1 has the power of 2, so to establish equality in Eq. 1, the secant stiffness of the model tests is 0.01 field tests. The stiffness of the reinforcement varies in the range of 1000-4000 kN/m in the field condition (Alexiew et al., 2005). Therefore, the geotextile used in the experiments, according to the above explanations, will have a secant stiffness of 10-40 to observe the effect of scale as in previous studies (Dash and Bora, 2013; Ayadat et al., 2008). The current study has a secant stiffness of 15 kN/m. Table 3 shows other properties of the geotextile.

Table 3. Properties of geotextile

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

* ASTM D 4595 Standard.

2.2 Experimental set up

2.2.1 Equipment

To minimize the boundary effects on the results of the tests, a tank was built in 1200*1200*1000 mm^3 (Fig. 1), including a loading frame, pumping unit and hydraulic jack, which similar to some studies (Murugesan and Rajagopal, 2010; Rezaei et al., 2019a). The rigid steel plate with a thickness of 30 mm and the diameters of 160 mm and 260 mm for the single and the group of floating stone columns, respectively, were used as loading objects so that both the surrounding soil and the stone column were loaded. Also, loading was conducted at a displacement rate of 1 mm/min up to a settlement of 50 mm (Ali et al., 2012; Rezaei et al., 2019b). For controlling the lateral deformation of the column, a minimum ratio of 4 of the column length to column diameter was suggested (Barksdale and Bachus, 1983). Thus, in the present study, the ratio of the column length to the column diameter of the columns was 5.

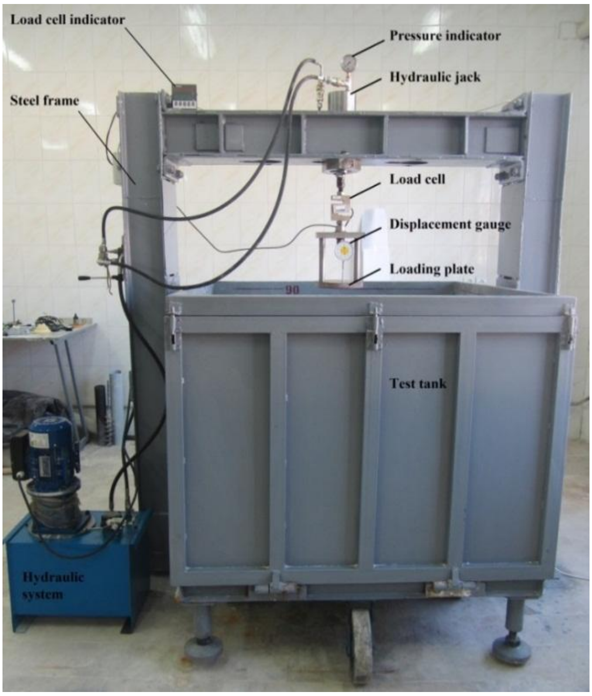


Fig. 1. Test tank

2.2.2 Preparation of clay bed and stone column

The kaolin clay soil at a moisture content of 23% was filled into the tank and compacted in 18 equal layers up to a height of 900 mm. For each layer, to compact the clay with the bulk unit of 19.1 kN/m^3, a 2 kg tamper was dropped on the soil surface through a height of 200 mm (Debnath and Dey, 2017). Also, a coat of oil was smeared on the tank before being filled with wet clay. The oil was intended to decrease the friction between the clay and the tank walls. The replacement method has been used for constructing the stone columns (Fig. 2). This technique was extended in the experimental tests and would cause less disturbance to the soils (Ambily and Gandhi, 2007; Hamidi and Lajevardi, 2018). More information about the preparation of the stone columns and test setup was described by Bazzazian Bonab et al. (2020 and 2021).

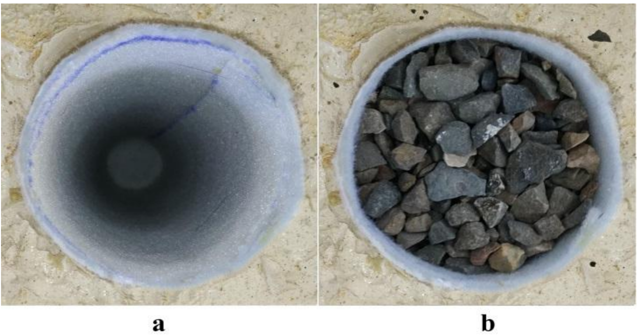


Fig. 2. (a) Placing the geotextile (b) Filling with crushed stone aggregates

2.3 Test conducted

The behavior of the stone column with and without reinforcement in kaolin clay soil was captured by applying a vertical load on the rigid loading plate. To evaluate the load-settlement behavior of stone columns with the column diameter of D = 80 mm, 14 load tests (9 tests for a group of stone columns and 5 tests for single stone columns) were performed on the kaolin clay bed (Table 4).

Table 4. Details of tests conducted

Test type	Loading plate diameter	Test description	Group arrangement
Single	160 mm	Kaolin clay	-
		OSC	-
		VESC	-
		HRSC	-
		VHESC	-
Group	260 mm	Kaolin clay	-
		OSC	3 and 12
		VESC	3 and 12
		HRSC	3 and 12
		VHESC	3 and 12

OSC: Ordinary stone column
VESC: Vertical encasement stone column
HRSC: Horizontal reinforcement stone column
VHESC: Combined vertical-horizontal encasement stone column

For both single and group of stone columns, the tests were performed on an unreinforced kaolin clay bed, OSC, VESC, HRSC, and VHESC (Fig. 3) by applying vertical load on the rigid loading plate. For VESCs, full-length vertical geotextile encasements, and for HESCs, horizontal geotextile layers with equal spacing of column diameter were used (S = D), where S is the spaces of the horizontal geotextile layers and D denotes the stone column diameter. Note that VHESC consists of a combination of HRSC and VESC. It means that full-length vertical geotextile encasement was used within the 6 layers of horizontal geotextile (S = D). Two groups of 3 and 12 stone columns (Fig. 4), with a triangular configuration, were considered with the distance between them being twice as large as the diameter (160 mm).

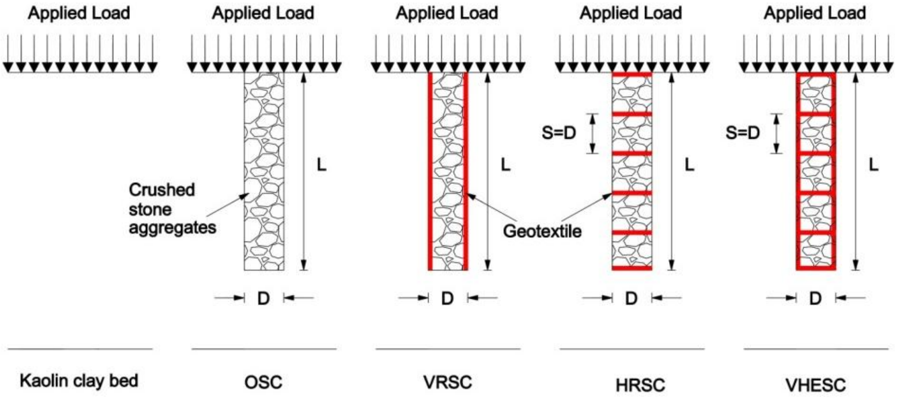


Fig. 3. Schematics of different type of stone columns

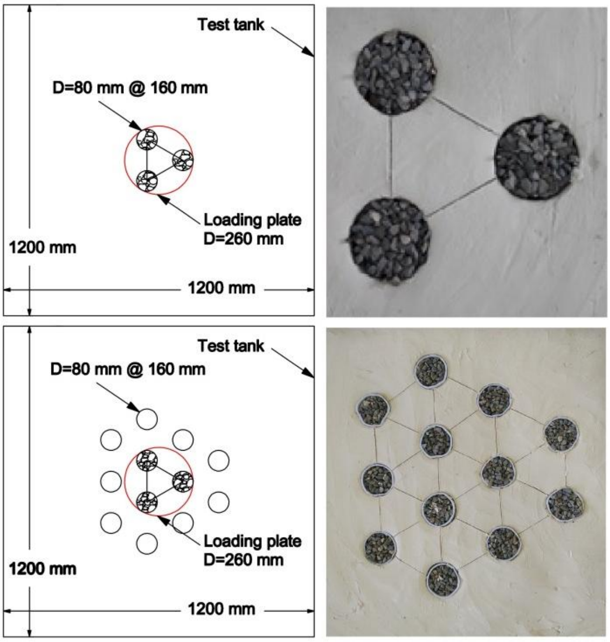


Fig. 4. (a) Plan view of a group of stone columns

3 Results and discussion

3.1 Single stone columns

Fig. 5 shows the load-settlement behavior of single stone columns with a diameter of 80 mm with and without reinforcement up to the settlement of 50 mm. The results show that by reinforcing the kaolin clay bed with OSCs, the bearing capacity increased. Also, using geotextile as reinforcement led to a further increase in the bearing capacity. It is seen that OSCs, VESCs, HRSCs, and VHESCs enhanced the bearing capacity of kaolin clay bed. The magnitude of this increase for OSC, VESC, HRSC, and VHESC was 25.6%, 84.8%, 50.4%, and 103.7%, respectively.

In VESCs, encasing the stone columns with geotextile creates extra horizontal restriction and decreases the stone column bulging. In HRSCs, shear stress mobilization of the geotextile layers and crushed stone materials leads to restrictions between the stone column materials and horizontal layers of geotextile. However, it is seen that the performance of the VESCs seems to be better than that of HRSCs. Also, VHESCs have better performance than the other types. In VESCs, the horizontal restriction due to encasement is greater. However, in HRSCs, small columns are created among the horizontal layers, which leads to an increase in the bearing capacity. From another perspective, placing horizontal layers of geotextile seems easier.

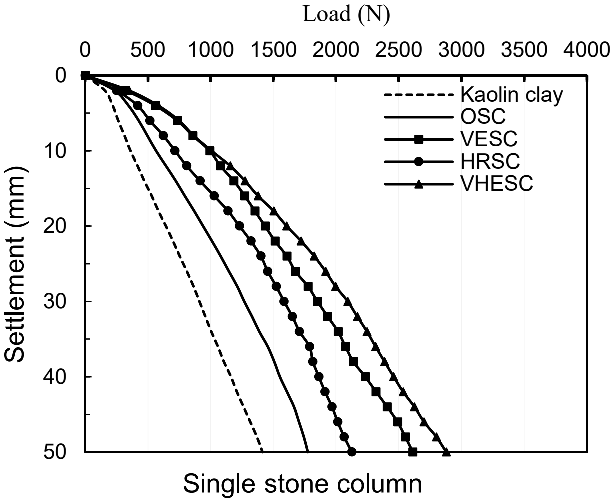
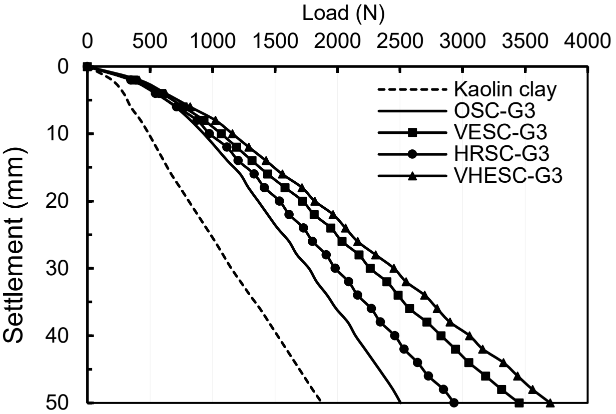


Fig. 5. Variation of load-settlement of single stone columns

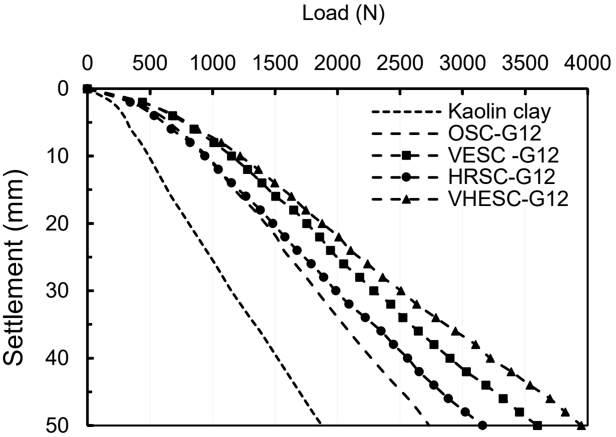
3.2 Groups of stone column

As seen in Fig. 6, groups of 3 and 12 stone columns increased the bearing capacity of the kaolin clay bed. In the groups of 3 stone columns (Fig. 6a), the value of this increase for the groups of OSCs, VESCs, HRSCs, and VHESCs was 33.5%, 84.1%, 56.4%, and 97.3%, respectively. Further, the use of groups of 12 stone columns (Fig. 6b) led to a further increase in the bearing capacity by 45.7%, 91.8%, 68.6%, and 110.6%, respectively, for the groups of OSCs, VESCs, HRSCs, and VHESCs.

In the column groups, the boundary condition provided additional confinement to the column, preventing radial failure. This constrained boundary enabled columns to expand laterally without failing. Where present, the mesh encasement acted to reinforce the column by transmitting surcharge loads to mesh hoop forces, reducing radial expansion, and lowering vertical strain (increasing column stiffness). In other words, column groups acted as block.



(a) Group of 3 stone columns



(b) Group of 12 stone columns

Fig. 6. Variation of load-settlement of the group of stone columns

3.3 Effect of the arrangements of groups of stone columns

A comparison between the arrangements of groups of stone columns indicated that the increase of the number of the columns from 3 to 12 led to enhanced bearing capacity by 9.1%, 4.2%, 7.8%, and 6.7% (Fig. 6), respectively for a group of OSCs, VESCs, HRSCs, and VHESCs. The results indicate that in the group of stone columns, by increasing the number of columns, the growth in bearing capacity is evident which may be attributed to the increase in the stiffness and frictional resistance of the columns. However, the effectiveness of the column number is limited to a critical level, beyond which the extra number of column will not be of much benefit to the overall bearing capacity of the soil.

3.4 Efficiency of the group of stone columns

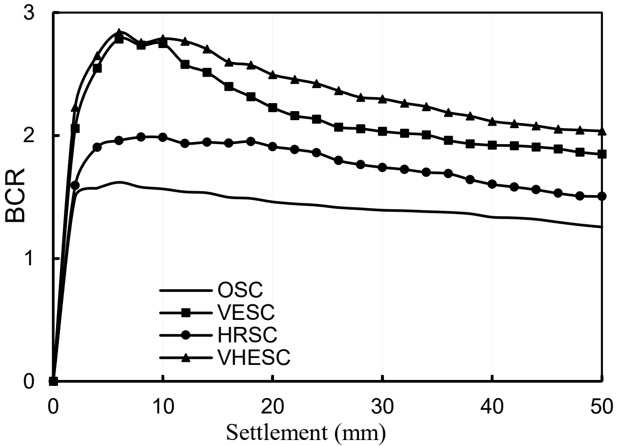
The efficiency of the group of stone columns is defined as the ultimate bearing capacity of the group of stone columns, to the ultimate bearing capacity of a soft single stone column multiplied by the number of the group columns (Lajevardi et al., 2018a). Table 5 reports the efficiency of the groups of 3 and 12 stone columns. As seen, the efficiency of the stone column group with 3 columns is better than that of 12 columns. The reason for this is that according to Fig .4, the loading plate was 260 mm for all groups; so, columns farther from the loading surface have less impact on increasing the bearing capacity. Thus, using a group of 3 stone columns seems very appropriate.

Table 5. Efficiency of group of stone columns

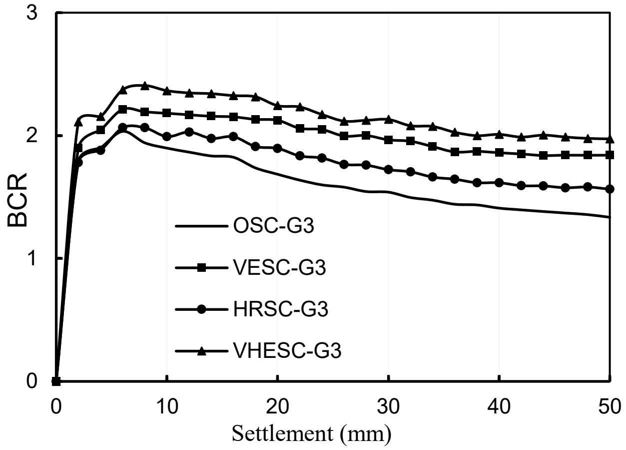
Stone column	Loading plate diameter	Efficiency%	
		3 columns	**12 columns**
OSC	260 mm	47.0	12.8
VESC	260 mm	44.0	11.5
HRSC	260 mm	46.0	12.4
VHESC	260 mm	42.8	11.4

3.5 Bearing capacity ratio

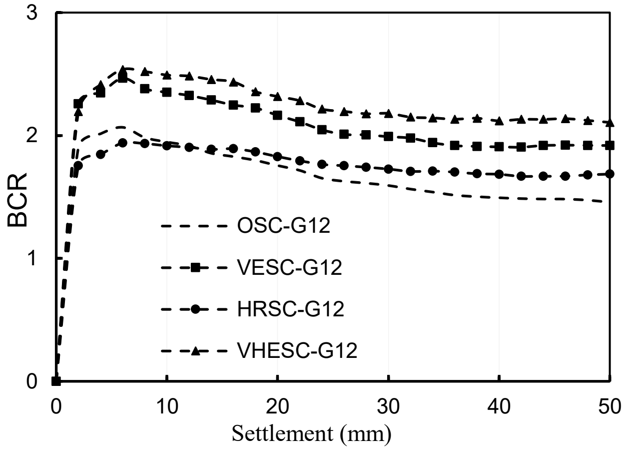
The bearing capacity ratio (BCR) parameter is explained as the reinforced soil bearing capacity to the soil bearing capacity. The BCR is used to evaluate the performance of unreinforced or reinforced columns to show the soil improvement by considering the bearing capacity (Ghazavi and Nazari Afshar 2013). Fig. 7 displays the BCR variations with the settlement for single and group stone columns with a diameter of 80 mm. It was found that the BCR value varies within the range of 1.26-2.84, 1.34-2.41, and 1.46-2.54 for a single, group of 3 stone columns, and group of 12 stone columns, respectively. In the single stone columns, the minimum BCR belonged to OSCs and the maximum BCR was related to VHESC. For the group of a stone column, the minimum BCR belonged to groups of 3 OSCs and the maximum BCR was related to groups of 12 VHESC.



(a) Single stone column



(b) 3 Groups of stone column



(c) 12 Groups of stone column

Fig. 7. Variation of bearing capacity ratio (BCR) versus settlement for VESCs, HRSCs and VHESCs

The BCR values increased in all cases by reinforcing the stone columns. The reason is that the lateral confinement created by geotextile causing diminished bulging. It is shown that, for the group of stone columns, with increasing the loading up to settlement of 8 mm, the BCR value increased. Thereafter, the BCR value decreased. It is because the bulging occurred and the columns reached to their ultimate resistance. Also, by continuing the loading process, the bearing capacity has not increased significantly. Hence, the value of BCR either remains constant or decreases.

3.6 Reinforcement ratio

Reinforcement ratio (RR) is an important parameter to show the influence of the reinforcement on the bearing capacity of the stone column and obtains from dividing the bearing capacity of the reinforced stone column to the ordinary stone column (Lajevardi et al., 2018b). The ratio of the area replacement (RAR) is an important parameter that offers the percentage of soil replaced by the stone aggregate (Castro, 2017) and obtains from dividing the column area to the loaded area. The variations of RR with RAR for two groups of stone columns were presented in Table 6.

Table 6. Variation of RR with RAR

Group arrangement **RAR%**	**3 columns** **28.4**	**12 columns** **113.6**
VESC	1.38	1.32
HRSC	1.17	1.16
VHESC	1.49	1.47

It is seen that for VESCs, HRSCs, and VHESCs the average value of RR varied within the range of 1.35, 1.16, and 1.48, respectively. Thus, reinforcing the stone columns with both vertical and horizontal geotextiles (VHESCs) led to a further increase in bearing capacity. Also, the RR value decreased with increasing the RAR. In other words, by increasing the number of stone columns, from 3 columns to 12 columns, the performance of reinforcement diminished. Thus, the use of a group of 3 columns is recommended as they have less geotextile usage.

4 Conclusions

The laboratory studies have focused on the behavior of single and groups of columns installed in a kaolin clay bed. In all cases, the introduction of stone columns was found to reduce the settlement and improve the bearing capacity compared to the untreated soil. The degree of performance of the column group was found to be dependent upon the area ratio and column configuration. From the various studies, key observations have been summarised as follows:
1- Failure modes of stone column groups are different from those of an isolated stone column, where the columns can interact and restrain the expansion of the neighboring columns. In stone column groups, the central column deforms or bulges uniformly, whereas the edge column bulges away from the neighboring columns
2- In a group of stone columns, using the combination of vertical encasement and horizontal layers (VHESCs) has higher performance in comparison with the other shapes. In this case, the combination of vertical and horizontal geotextiles increases the stiffness and ultimately increase the bearing capacity.
3- It was observed that even with high replacement area ratio, the group of 3 columns with respect to economic issues can outperform the group of 12 columns.
4- The deformational behavior of stone columns as a group of stone columns exhibit bulging, punching, shearing and bending while in single stone columns bulging failure usually occurs at the top of the stone columns for VESCs and in HRSCs, limited bulging occurs between the horizontal layers.
5-The BCR value depends on the number of columns used. Also, BCR value decreases after the column reach its ultimate resistance and eventually remain constant or decreases.
6- Although the use of horizontal reinforcement does not lead to better results compared to other types, it is much easier to install horizontal reinforcement at any depth in the column.

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