Improvement of Soft Marine Clay with Laterally Reinforced Silica-Manganese Slag Stone Column

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Abstract

Among all the techniques available for ground improvement, stone columns are the most preferred elements used for supporting a wide variety of flexible structures such as road, railway embankments, and oil storage tanks. In this study, several laboratory tests have been conducted to improve the soft marine clay with end bearing stone columns by using Silica-Manganese slag as stone column material. Further, these stone columns were reinforced with circular geotextile discs by placing them laterally within the column. The improvement in load carrying capacity was studied and compared to the clay bed and unreinforced i.e. plain stone column. Circular geotextile discs of two different spacings (D and D/2, where "D" is the diameter of the stone column) with varied reinforcement depths, such as D, 2D, 3D and 4D, were tried. It was found that the soil reinforced with a spacing of D/2 to the embedment length of 3D shows better performance than a spacing of D. It was also observed that the bulging diameter was reduced by incorporation of the geotextile reinforcement and found below the reinforcement.

Keywords: Stone column, Marine clay, Silica-Manganese slag, Geotextile discs

1. Introduction

Many methods are available for improving the ground which include compaction, preloading, dewatering, deep mixing, grouting, etc. In recent years, a rapid advancement in deep densification technique has providing a plethora of economical and practical alternatives for many ground engineering applications in which stone columns have got more popularity and proven to be one of the successful methods. Greenwood [1] is the pioneer in proposing the load transfer theory, estimation of settlement prediction, improvement of the load carrying capacity by stone columns and ultimate bearing capacity, etc. After Greenwood, many researches have reported on stone columns [2-5] and found that the granular piles fail in general shear, bulging and sliding. From the literature, it is very well established that the stone columns build their load carrying capacity from the lateral confinement from the surrounding soils [1, 5-6]. Ayadat et al. [7] have done the analytical work on the behavior of collapsible fills and found that the soil collapse upon wetting and lateral stress decreases due to the loss of confinement. Stone columns in very soft soils may not always give sufficient load carrying capacity because of lack of confinement from the surrounding soft soil and there are chances of squeezing out the soft soil into the aggregate [6]. In such situations, there is a need to increase the confinement by providing geosynthetic material to improve the performance. One form of providing the reinforcement is placing the geosynthetic material within the stone column as horizontal circular discs.

Most of the research work on stone columns with encasement has been done with geosynthetic (geogrids/geotextiles) materials [8-12] and found that the stiffness of the soft soil can be increased. Settlements can also be reduced by increasing the

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stiffness of the reinforcing material [13-14]. Murugesan and Rajagopal [8] studied the behavior of geosynthetic encased stone columns through experiments and found that the load settlement response shows linear behavior unlike the conventional stone columns. Malarvizhi and Ilamparuthi [15] studied the load versus settlement behavior of encased stone columns and found that the stress concentration ratio can be increased with the encasement and can be enhanced by increasing the stiffness of the encasing material. This stress concentration ratio can also be increased with increasing the shear strength of the native soil [16]. Fattah et al. [17] have studied the performance of embankment resting on soft clays with geogrid encasement and observed that the mode of failure changed from local shear to general shear. Soft soils can also be improved by driving the nails through the circumference of the columns and this can be enhanced with the number of nails and the depth of embedment required to get the significant load carrying capacity is 3D to 4D [18].

In addition to the above, some more researchers have been studied who have provided reinforcement in the horizontal direction [11, 19]. Basu et al. [19] studied the effect of fiber placed in between the layers of stone column and found that the increase in length and the amount of fiber content decreases the bulging of column and concluded the depth of maximum bulging from the surface decreases and the total length of bulging is increased. The bulging of the column can be restricted by providing the reinforcement beyond the zone of bulging [10]. Samadhiya et al. [11], Hasan and Samadhiya [12] have also conducted model studies by reinforcing the stone column with geogrid strips placed at different spacings to different embedment lengths and concluded that the load intensity increases with the decrease in vertical spacing between the strips and the strength increases up to a reinforcement length of 3D and further there is no improvement.

Malarvizhi and Ilamparuthi [13, 15], Kausar Ali et al. [20] have carried out experiments on stone columns with varying L/D ratio (length to diameter ratio) and studied the importance of L/D ratio in designing the stone columns. The load carrying capacity of the stone column can be improved with the increase in L/D ratio whereas this influence is very less in case of floating stone columns [13]. Kausar Ali et al. [20] found that this increase in bearing capacity is not significant when the L/D ratio exceeds six. Murugesan and Rajagopal [9], Samadhiya et al. [11], Hasan and Samadhiya [12], Kausar Ali et al. [20], Hasan and Samadhiya [21] studied the effect of stone column diameter and found that the bearing capacity increases with the decrease in diameter of the stone column because of the high confining stresses in small diameter stone columns. Mohanty and Samanta [22] conducted tests on layered soil and the loading is done to the area of stone column only and to the entire unit cell and found that the stiffness increases by increasing the area replacement ratio. Fattah et al. [23] studied the L/D ratio of stone column and concluded that the stress concentration ratio (ratio of the stresses in the column to the surrounding soil) is proportional to the L/D ratio. Ambily and Gandhi [24] studied the single stone column by loading to its area alone and the results indicate that the failure is by bulging and the maximum bulging is at a depth of 0.5D to 1D whereas if the column is loaded for the entire tank wall, the failure did not take place and the load-settlement behavior is linear. Malekpoor and Poorebrahim [25] have conducted experiments on Compacted Lime-Soil (CL-S) column and found that the CL-S columns showed better performance than the conventional stone columns.

In spite of applying this technique to the soft soils for improving with stones, there are very limited investigations have been done with the other materials which gave better performance than the conventional stone column material. In this study, an alternate material for the stone aggregates called Silica-Manganese slag is used. This column is reinforced with circular geotextile discs within the column at different spacings for varying embedment lengths and the effect of geotextile reinforcement on load - settlement and bulging behavior were studied.

2. Materials

Highly compressible marine clay collected from Visakhapatnam port, India is used for improving the properties of soil. The properties of marine clay are shown in Table 1.

Table 1 Properties of clay

Property of Marine clay	Value/ Classification
Specific Gravity	2.50
Fines content (Silt+ Clay)	94%
Soil classification (ASTM D-2487)	CH
Liquid limit (W_L)	72 %
Plastic limit (W_P)	36 %
Plasticity Index (I_P)	36 %
Maximum Dry unit weight	14.2 kN/m^3
Optimum Moisture Content (OMC)	29.5%
Shear strength of soil (in kPa) at 54 % water content	15.0

In this study, Silica-Manganese slag is used as the stone column material obtained from Sri Mahalaxmi Smelters (Pvt.) Limited, Vijayanagaram (Dt.), A.P., India which is produced during the process of steel production. It is found that Silica-Manganese slag provides more load carrying capacity as compared to the stone aggregates and this can be attributed to the presence of certain properties which are better, including strength (Table 2). The surface of the slag is also relatively rough (shown in Fig. 1(a)) which may increase the friction between the slag aggregates and helps in increasing the stiffness and causes the increase in the load carrying capacity of the column. Silica-Manganese slag consists of major constituents of CaO and SiO_2 for about 24% and 45% respectively. The stone/slag aggregates passing through 10mm and retained on 4.75mm have been taken for this study and is shown in Fig. 1(a). To check the improvement by replacing the stone column with Silica - Manganese slag, load test for the stone column with stone aggregates was also conducted and the improvements have been studied.

(a) Silica manganese slag

(b) Circular geotextile discs

Fig. 1 Materials used for this study

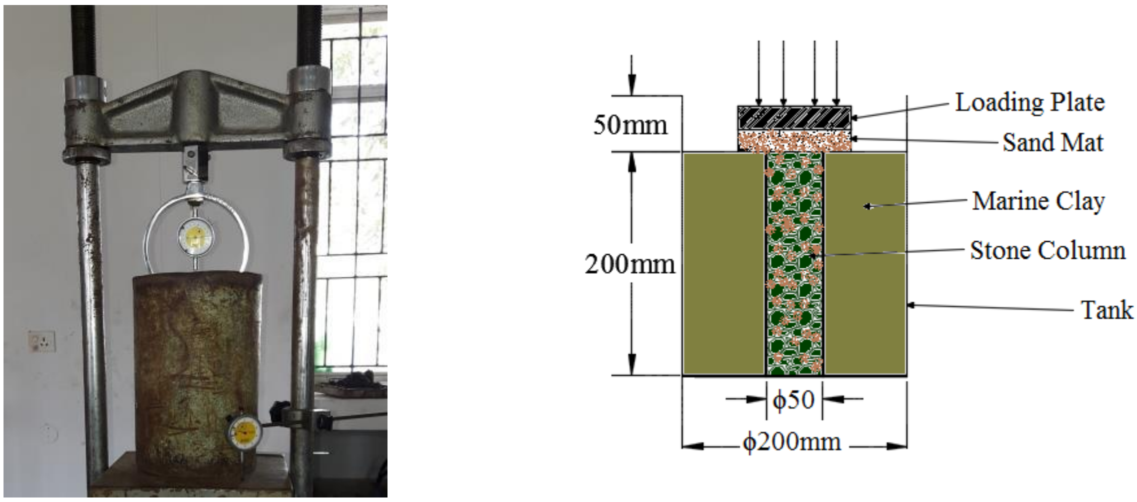
Table 2 Properties of aggregates

Property of Aggregate	Stone Aggregates	Slag Aggregates
Water absorption (%)	0.50	0.49
Unit weight	15.9kN/m^3	16.7kN/m^3
Specific Gravity	2.66	2.79
Aggregate Crushing Value	25 %	22 %
Aggregate Impact Value	22 %	21 %

Non-woven geotextile is used as the lateral reinforcing material. It is collected from Ayyappa Geotextile installers, Vishakhapatnam, India. The tensile strength of the geotextile is 4.5kN/m and the Mass is 100g/m^2. Circular geotextile discs used in this study are shown in Fig. 1(b).

Well graded clean river sand sieved through 4.75mm sieve which is collected from Nagavali River, Srikakulam is used as a sand blanket.

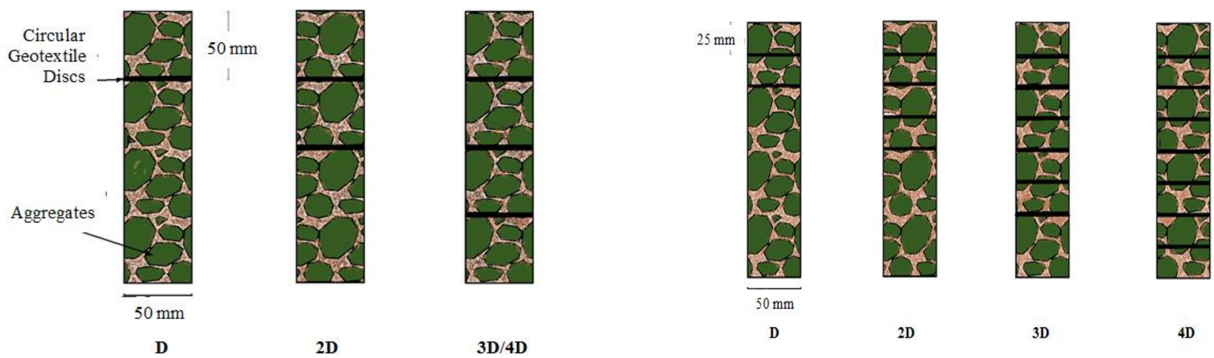
3. Results and Discussion



(a) Loading frame setup (b) Schematic view of loading frame

Fig. 2 Loading frame

An experimental program has been carried out on the individual clay bed, plain stone column of stone aggregates and slag and reinforced stone columns of Silica - Manganese slag. The stone columns have been constructed with 50mm diameter and 200mm length in a cylindrical tank of 200mm length and 200mm diameter. The stone column dimensions are selected so as to maintain a minimum L/D ratio of four which is required for developing a full limiting axial stress on the column [26]. Fig. 2(a) shows the test setup for the loading frame and 2(b) shows the schematic view of loading frame used for this study. The diameter of the stone column and tank are selected in such a way that the distance between the column to the inner surface of the tank does not overlap the failure zone (extends to 1.5D) [27] (shown in Fig. 2(b)).



(a) 50mm spacing (b) 25mm spacing

Fig. 3 Mode of placing of circular geotextile discs within the stone columns

When the soft soil improved with the stone columns is loaded, the column deforms laterally into the soft soil and bulging occurs at the top portion of the column. To prevent the bulging of the column, lateral reinforcement has been provided inside the stone column by placing the geotextile discs of 50mm as column diameter. In this study, the reinforcement is provided at two different spacings of D and D/2 and is placed for different embedment lengths of D, 2D, 3D and 4D measured from the surface of the clay bed and the mode of placing of circular geotextile discs is shown in Fig. 3 (a) and Fig. 3 (b).

3.1. *Preparation of clay bed*

Marine clay was dried, pulverized and mixed with required quantity of water to achieve the required water content (54%). Several vane shear tests have been conducted on a cylindrical specimen and the water content required to get the desired shear strength of 15kPa was selected. Before placing the soil into the tank, the inner surface is cleaned and coated with grease to decrease the friction between the tank and soil. Water is mixed to the soil thoroughly to make it into a consistent paste and is filled in the tank for 50mm layers up to the desired depth of 200mm by compacting each layer with wooden hammer so that there will be no air voids. To maintain the constant density of the clay bed, the inner surface of the tank was marked at 5cm intervals and the weight of the soil required for the desired density of each layer was calculated. This soil was mixed with water to make it into a paste and was compacted with wooden hammer till the marking. To maintain the constant water content, the soil samples were collected at different depths during the construction of clay bed and the water contents were determined and they were found to be almost uniform with ±1%. The clay bed was prepared afresh for each test to install the stone column. This bed is kept for 24 hours for moisture equalization by covering it with wet gunny bag.

3.2. Construction of unreinforced stone column

For constructing the unreinforced stone column, a PVC pipe of 1mm thick and 50mm diameter (equal to the stone column diameter) was properly placed at the center of the tank. Before placing the pipe, outer surface of the pipe and the inner surface of the cylinder are greased to decrease the friction between the pipe/tank and the soil. Around the PVC pipe, clay bed is prepared for the required depth of 200mm with 50mm layers by compacting each layer with wooden hammer so that there will be no air voids within the soil. To avoid the absorption of moisture, water is sprinkled on the aggregates before placing into the column. The aggregates are placed in the pipe in 50mm thick layers by compacting with the steel rod of 15mm diameter and 900 gram weight from a depth of 100mm by giving 10 blows per layer to maintain the uniform density. Construction of each layer was done by simultaneously lifting the pipe to a height of 45mm to maintain the overlap between the pipe and the column. Compacted densities of the stone aggregates and Silica - Manganese slag are 15.9kN/m^3 and 16.7kN/m^3, respectively. This method of displacement is more representative of the bottom feed method which is commonly used at sites [28]. After completion of construction of stone column, this setup is covered with wet gunny beg and kept it for 24 hours for moisture equalization and to improve the proper bonding between the soil and the aggregates. This method of construction of stone column was adopted by many researchers [15, 20].

3.3. Construction of reinforced stone columns

Reinforced stone columns have been constructed by placing the circular geotextile discs of 50mm diameter for two different spacings of D and D/2 for embedment lengths of D, 2D, 3D and 4D. The procedure for construction of reinforced stone column was the same as for the unreinforced stone columns; whereas the geotextile discs were placed at the specified places (D or D/2). After completion of construction of a stone column, this setup is covered with wet gunny bag and kept for 24 hours for equalization of moisture and to improve the proper bonding between the soil and the aggregates. During the process of construction for 2.5cm spacing (D/2), the geotextile is placed at 2.5cm intervals, but the blows were given after every 5cm interval to maintain the uniform density.

3.4. Testing of clay bed/stone columns

Tests on clay bed/stone columns have been conducted in a conventional loading frame by applying the load through 12mm thick and 10cm diameter (2D) steel circular plate which is representing an area replacement ratio of 25% [29]. These tests are strain-controlled with a rate of settlement of 0.24mm/min and the load was observed for every 1mm settlement till the maximum settlement is 20mm. Schematic diagram of the clay bed and the column foundation with loading frame is shown in Fig. 2(b).

4. Model test results

The stone columns of silica-manganese slag are reinforced with geotextile with circular geotextile discs at spacings of 5cm and 2.5cm for embedment lengths of D, 2D, 3D, 4D. The load tests have been conducted on clay bed and stone columns and the improvement of soil properties by reinforcing with the stone columns have been studied with respect to the clay bed. The load carrying capacity was determined by drawing the double tangent to the Load – Settlement curve.

The results indicating that by modifying the clay bed, a clear improvement in load carrying capacity was observed to be about 57% and 71% with stone aggregates and silica-manganese slag, respectively. The results also indicated that the silica-manganese slag gives 9% better load carrying capacity compared to stone aggregates as column material. This improvement may be due to the densification of the soil bed by inclusion of the Silica-manganese slag of higher stiffness than stone aggregates. This accepts the observations of Malarvizhi and Ilamparuthi [13] that the load carrying capacity increases by increasing the stiffness of the column material. The increase in load carrying capacity is arguably due to the increased friction between the rough surfaces (shown in Fig. 1(a)) of the slag aggregates.

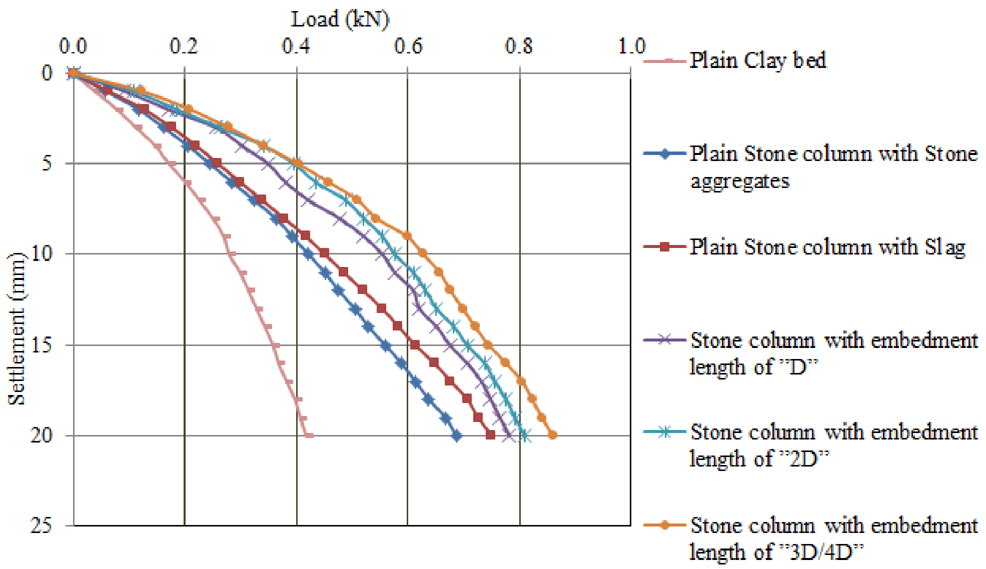


Fig. 4 Effect of reinforcement placed at a spacing of 5cm on load-settlement behavior for varying embedment lengths

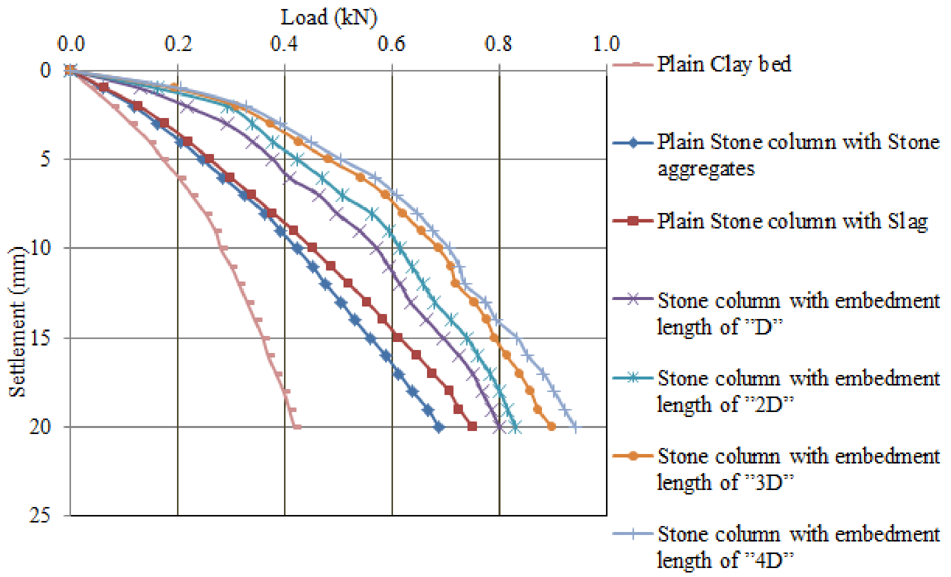


Fig. 5 Effect of reinforcement placed at a spacing of 2.5cm on load-settlement behavior for varying embedment lengths

Fig. 4 shows the load versus settlement behavior of individual clay bed, unreinforced and reinforced stone columns of different embedment lengths for lateral spacing of 50mm. It is observed that the load carrying capacity of the stone column was increased by reinforcing the stone column with circular geotextile discs. The increase in load carrying capacities of the stone columns reinforced with geotextile for a spacing of 50mm are about 6%, 10% and 17% for reinforcement lengths of D, 2D, 3D/4D compared to the unreinforced silica-manganese slag stone column. This increase is about 82%, 89% and 100% compared to the clay bed. This increase in load carrying capacity has resulted because of the increase in frictional forces in the geotextile. In turn, these frictional forces are responsible for the decrease in bulging and subsequently they lead to the transfer of loads to the bottom of the column. Fig. 5 shows the graph for lateral spacing of 25mm. The increase in load carrying capacities reinforced with geotextile with a spacing of 25mm are about 8%, 17%, 23% and 27% for reinforcement lengths of D, 2D, 3D and 4D compared to the unreinforced silica-manganese slag stone column. This increase is about 86%, 100%, 111% and 118% compared to the clay bed. The results showed that the load carrying capacity increases with the depth of embedment of stone column. However, 85% of the load carrying capacity is reached when it is reinforced with an embedment length of 3D when compared to the length of 4D. From these results, reinforcing the stone column with the top 3/4th length of column is the most suitable configuration with spacing of D/2. The load carrying capacity of the stone column reinforced with 50mm spacing for an embedment length of 3D/4D is about 17%. This attainment is reached with 25mm spacing for an embedment length of 2D. Stone columns with geotextile spacing of 25mm showed higher load carrying capacity because of the increased mobilization of the frictional forces, which became possible by decreasing the spacing between the geotextile discs.

4.1. Bearing capacity ratio

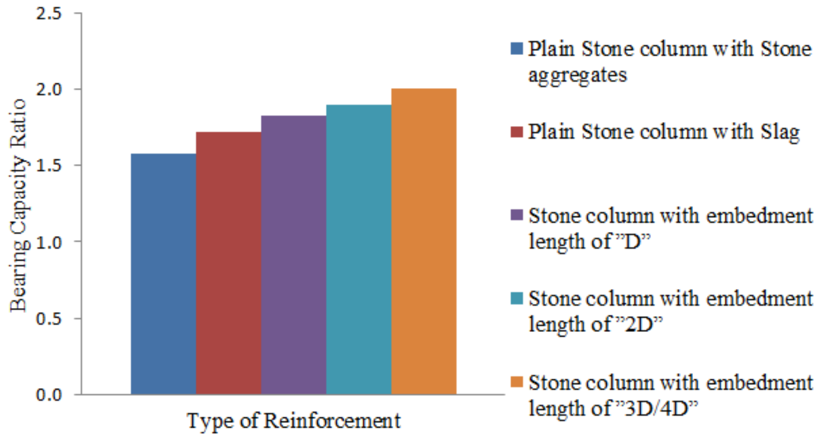


Fig. 6 Variation of BCR for unreinforced and reinforced stone columns with geotextile spacing of D

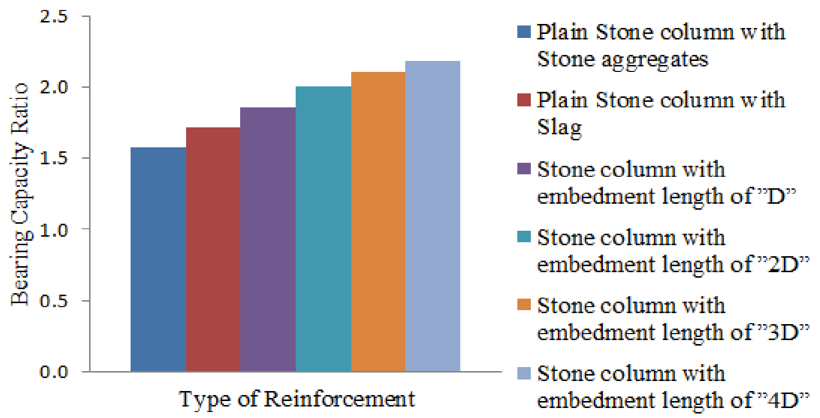


Fig. 7 Variation of BCR for unreinforced and reinforced stone columns with geotextile spacing of D/2

In this study, the variation of bearing capacity ratio (BCR), which is a ratio of load carrying capacity of treated soil to the untreated soil and is a measure of degree of improvement in the soil, has been studied. Fig. 6 and 7 show the variation of BCR values for stone columns of unreinforced and reinforced stone column. Results indicate that the BCR values are increased by providing the stone columns and also with the reinforcement. Further the BCR increases with decreasing the spacing between the geotextile.

5. Analysis of Bulging

After the load tests were completed, aggregates were picked out and thick plaster of paris paste was poured in to the cavity and kept it for 24 hours. The hardened plaster of paris was removed after removing the surrounding soil and the deformation properties were studied. The deformations of the stone columns were measured at every 2.5cm interval and graph was plotted between the depths versus bulging of the column. Fig. 8 and 9 shows deformed shapes of the stone columns and Fig. 10 and 11 shows the laterally deformed bulging curves of different columns for different reinforcement lengths at spacings of 5cm and 2.5cm respectively. For unreinforced column with stone aggregate, the maximum bulging of 12mm was found at the center of the column. This bulging is reduced for the stone column of slag to 11mm and is further reduced with reinforced columns. This may be due to the increased friction between the slag aggregates with rough surfaces (shown in Fig. 1(a)). The maximum bulging of 11mm, 11 mm, 10mm and 6mm were observed for unreinforced stone column with slag, reinforced stone columns for different reinforcement lengths of D, 2D and 3D/4D respectively for stone columns with spacings of 5.0cm. Whereas for 2.5cm spacing, the bugging is reduced and reached to 11mm, 10 mm, 9.5mm, 5mm and 4.5mm for unreinforced and different reinforcement lengths of D, 2D, 3D and 4D, respectively. This reduction in bulging happened due to the increased mobilization of shear resistance only by decreasing the spacing between the circular discs. For both the spacings of 5.0mm and 2.5mm, the load carrying capacity increased with embedment length when confining stresses increased. Maximum bulging was found at the center of the column for unreinforced and fully reinforced columns, whereas the maximum bulging was very much reduced by placing the full reinforcement compared to the unreinforced column. For the other reinforcement lengths, the maximum bulging was found near/just below the end of the reinforcement (shown in Fig. 8, 9, 10 and 11).

Fig. 8 Deformed shapes of stone columns (for Stone aggregate, Unreinforced stone column with Slag, Reinforced stone columns with spacing of 5.0cm for different embedment lengths of D, 2D and 3D/4D respectively)

Fig. 9 Deformed shapes of stone columns (for Stone aggregate, Unreinforced stone column with Slag, Reinforced stone columns with spacing of 2.5cm for different embedment lengths of D, 2D, 3D and 4D respectively)

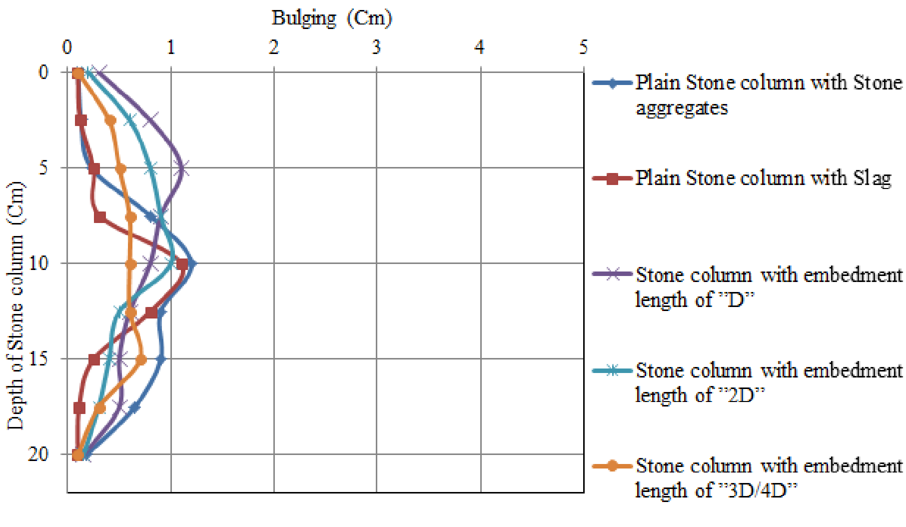


Fig. 10 Deformation of stone columns with depth for geotextile spacing of 5.0cm

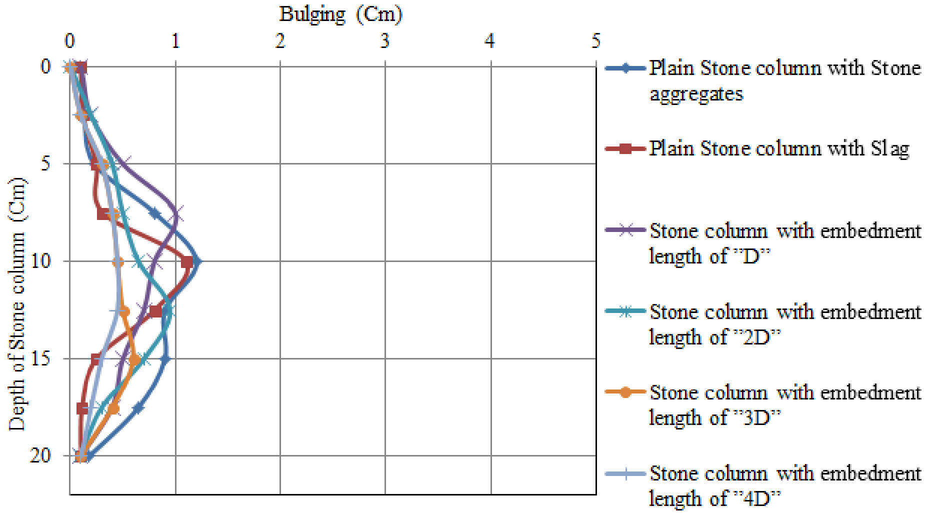


Fig. 11 Deformation of stone columns with depth for geotextile spacing of 2.5cm

6. Conclusions

The present study delineates the experimental work carried out on the soft marine clays improved with silica manganese slag stone columns reinforced with the lateral geotextile discs and the following conclusions were made:

(1) Silica-manganese slag as stone column material is the best solution to improve the load carrying capacity of the soil. This increase is about 9% as compared to the stone aggregates from quarry due to the increase in stiffness of the column material and may also be due to the increasing friction between the slag aggregates.

(2) Laterally reinforced geotextile discs increased the load carrying capacity of the stone columns due to the frictional mobilization in the geotextile discs. This mobilization of friction resists the bulging of stone column and transfers the loads to the bottom of the column and thus the load carrying capacity increases.

(3) Load carrying capacity of the stone column is indirectly proportional to the spacing between the reinforced discs. The load carrying capacity increased with decreasing the spacing between the geotextile discs because of the increased frictional mobilization.

(4) For both the spacings (D and D/2), the load carrying capacity increased with the embedment length. This increased embedment length increases the confining stresses and helps in restricting the bulging. This increment was considerably effective up to an embedment length of 3D.

(5) Fully reinforced stone column gave a stiffer response compared to the unreinforced column because of the prevention of the bulging by a geotextile. The encasement length also results in decreasing the settlement for a given load. For the unreinforced and fully reinforced stone columns, maximum bulging was found at the center of the stone column. Whereas, for the other reinforced cases, it was near/just below the embedment length.

References

[1] D. A. Greenwood, "Mechanical improvement of soils below ground surface," in Conference on Ground Engineering, Institution of Civil Engineers, 1970, pp. 11-22.

[2] J. M. O. Hugher and N. J. Withers, "Reinforcing of soft cohesive soils with stone columns," Ground engineering, vol. 7, pp. 42-49, 1974.

[3] M. R. Madhav and P. P. Vitkar, "Strip footing on weak clay stabilized with a granular trench or pile," Canadian Geotechnical Journal, vol. 15, pp. 605-609, 1978.

[4] H. Aboshi, E. Ichimoto, K. Harada, and M. Emoki, "The compozer, a method to improve characteristics of soft clays by inclusion of large diameter sand columns," in International conference on soil reinforcement, Paris, 1979, pp. 211-216.
[5] J. M. O. Hughes, N. J. Withers, and D. A. Greenwood, "A field trial of the reinforcing effect of a stone column in soil," Geotechnique, vol. 25, pp. 31-44, 1975.
[6] J. M. McKenna, W. A. Eyre, and D. R. Wolstenholme, "Performance of an embankment supported by stone columns in soft ground," Geotechnique, vol. 25, pp. 51-59, 1975.
[7] T. Ayadat, A. Hanna, and M. Etezad, "Failure process of stone columns in collapsible soils," International Journal of Engineering, Transactions B: Applications, vol. 21, pp. 135-142, 2008.
[8] S. Murugesan and K. Rajagopal, "Experimental and numerical investigations on the behaviour of geosynthetic encased stone columns," in Indian Geotechnical Conference, 2009, pp. 480-484.
[9] S. Murugesan and K. Rajagopal, "Studies on the behavior of single and group of geosynthetic encased stone columns," Journal of Geotechnical and Geoenvironmental Engineering, vol. 136, pp. 129-139, 2010.
[10] J. Gniel and A. Bouazza, "Improvement of soft soils using geogrid encased stone columns," Geotextiles and Geomembranes, vol. 27, pp. 167-175, 2009.
[11] N. Samadhiya, P. Maheshwari, A. Zsaki, P. Basu, and A. Kundu, "Strengthening of clay by geogrid reinforced granular pile," International Journal of Geotechnical Engineering, vol. 3, pp. 377-386, 2009.
[12] M. Hasan and N. K. Samadhiya, "Soft soils improvement by granular piles reinforced with horizontal geogrid strips," International Journal of Geotechnical Engineering, vol. 12, pp. 101-108, 2018.
[13] S. N. Malarvizhi and K. Ilamparuthi, "Load versus settlement of clay bed stabilized with stone and reinforced stone columns," in Proceedings of GeoAsia–2004, Seoul, Korea, 2004, pp. 322-329.
[14] N. Hataf and N. Nabipour, "Experimental investigation on bearing capacity of geosynthetic encapsulated stone columns," in 18th International Conference *on Soil Mechanics and Geotechnical Engineering*, Paris, 2013, pp. 2493-2496.
[15] S. N. Malarvizhi and K. Ilamparuthi, "Comparative study on the behavior of encased stone column and conventional stone column," Soils and Foundations, vol. 47, pp. 873-885, 2007.
[16] M. Y. Fattah, K. T. Shlash, and M. J. M. Al-Waily, "Stress concentration ratio of model stone columns in soft clays," Geotechnical Testing Journal, vol. 34, pp. 50-60, 2011.
[17] M. Y. Fattah, H. A. Mohammed, and H. A. Hassan, "Load transfer and arching analysis in reinforced embankment," Proceedings of the Institution of Civil Engineers-Structures and Buildings, vol. 169, pp. 797-808, 2016.
[18] M. R. D. Babu, R. Shivashankar, S. Nayak, and J. A. Majeed, "Load settlement behavior of stone columns with circumferential nails," in Indian Geotechnical Conference, India, 2010, pp. 579-582.
[19] P. Basu, N. K. Samadhiya, and S. S. De Dalal, "An experimental study on random fiber mixed granular pile," International Journal of Geotechnical Engineering, vol. 12, pp. 1-12, 2018.
[20] K. Ali, J. T. Shahu, and K. G. Sharma, "An experimental study of stone columns in soft soils," in Indian Geotechnical Conference, India, 2011, pp. 375-378.
[21] M. Hasan and N. K. Samadhiya, "Experimental and numerical analysis of geosynthetic-reinforced floating granular piles in soft clays," International Journal of Geosynthetics and Ground Engineering, vol. 2, pp. 1-13, 2016.
[22] P. Mohanty and M. Samanta, "Experimental and numerical studies on response of the stone column in layered soil," International Journal of Geosynthetics and Ground Engineering, vol. 1, pp. 1-14, 2015.
[23] M. Y. Fattah, B. S. Zabar, and H. A. Hassan, "Experimental analysis of embankment on ordinary and encased stone columns," International Journal of Geomechanics, vol. 16, pp. 1-13, 2016.
[24] A. P. Ambily and S. R. Gandhi, "Behavior of stone columns based on experimental and FEM analysis," Journal of geotechnical and geoenvironmental engineering, vol. 133, pp. 405-415, 2007.
[25] M. R. Malekpoor and G. R. Poorebrahim, "Behavior of compacted lime-soil columns," International Journal of Engineering-Transactions B: Applications, vol. 27, pp. 315-324, 2014.
[26] D. A. Greenwood and K. Kirsch, "Specialist ground treatment by vibratory and dynamic methods," in Piling and ground treatment, 1984, pp. 17-45.
[27] G. G. Meyerhof and V. V. R. N. Sastry, "Bearing capacity of piles in layered soils," Canadian geotechnical journal, vol. 15, pp. 171-182, 1978.
[28] J. A. Black, V. Sivakumar, M. R. Madhav, and G. A. Hamill, "Reinforced stone columns in weak deposits: laboratory model study," Journal of Geotechnical and Geoenvironmental Engineering, vol. 133, pp. 1154-1161, 2007.
[29] Indian standard code of practice for design and construction for ground improvement - guidelines. Part 1: Stone columns, IS 15284 (Part-1), 2003.