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PERFORMANCE OF ENCASED SILICA-MANGANESE SLAG STONE COLUMNS IN SOFT MARINE CLAY

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ABSTRACT

Stone columns are the most suitable and economical ground improvement technique for soft soils. Stone columns accelerate the consolidation process, thereby increase the stiffness of the soil. This increase may not be sufficient because of the less lateral confinement, which leads to excessive bulging. The strength of the composite soil can also be increased further by encasing the column with geotextile. In this paper, model tests were conducted on end-bearing stone columns with geotextile encasement and compared with the unreinforced (plain) stone columns. The stone columns were prepared by placing the silica-manganese slag, sand and were reinforced with geotextile with different encasement lengths of D, 2D, 3D, and 4D (D is the stone column diameter; i.e., 5 cm). The tests demonstrated that the engineering behavior of the soil was improved by introducing the silica-manganese slag (when compared with conventional stone columns) and also with encasement. Bulging can also be reduced by providing encasement beyond the zone of bulging.

Keywords: Bulging; Encasement; Geotextile; Marine clay; Silica-manganese slag; Stone column

1. INTRODUCTION

Due to development of infrastructure in metropolitan cities, suitable sites for construction have been reduced and caused a rise in land prices. Because of this problem, industries are looking for cheaper land for construction. As a result, some sites which were not used earlier due to low strength are now being used for construction. When these soils are loaded, they may experience failure due to excessive settlement. Greenwood (1970) was first to propose load transfer theory, settlement prediction, and estimation of ultimate bearing capacity. Hughes and Withers (1974) found that stone columns fail under compressive loads in general shear, bulging, and sliding. The load-carrying capacity of the columns is acquired via lateral confinement from the surrounding soils (Greenwood, 1970). While the stone columns improve soft soil, sufficient load-carrying capacity may not be achieved because of the less lateral confinement. To overcome this situation, geosynthetic material can be used for encasing stone columns. This is the most popularly used method.

Many researchers have used geosynthetic material as encasement for stone columns to improve soft soils. Murugesan and Rajagopal (2009; 2010), Gniel and Bouazza (2009), Samadhiya et al. (2009), and Hasan and Samadhiya (2016) studied the behavior of geosynthetic/geogrid-encased

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stone columns and found that the stiffness of soft soil can be improved by increasing the encasement length. Malarvizhi and Ilamparuthi (2004) reported that settlement can be reduced by providing the encasement by increasing the stiffness of the stone column. Murugesan and Rajagopal (2009) studied geosynthetic-encased stone column performance and found that the pressure settlement response showed linear behavior.

Malarvizhi and Ilamparuthi (2004; 2007) and Ali et al. (2011) studied the effect of length to diameter ratio (L/D) and found that the load-carrying capacity was increased by increasing the L/D ratio whereas the influence is much less in floating columns (Malarvizhi & Ilamparuthi, 2004). The bearing capacity of composite soil increases with column length, but the increase is not significant when the length exceeds beyond six times the column diameter (Ali et al., 2011). Samadhiya et al. (2009), Murugesan and Rajagopal (2010), Ali et al. (2011), and Hasan and Samadhiya (2016) conducted tests on stone columns of different diameters and concluded that the stiffness of the soil increases with a decrease in the diameter of the column. This is because of the higher confining stresses mobilized on smaller diameter columns. Fattah et al. (2016) studied the behavior of stone columns in embankments and concluded that the Stress Concentration Ratio (SCR; the ratio of the stresses in the column to the surrounding soil) increases gradually with increasing L/D ratio.

Dheerendra Babu et al. (2010) conducted experiments on stone columns reinforced with vertical nails placed along the circumference and found that the circumferential nails enhanced the stone column performance. Furthermore, the behavior of composite ground was improved with the number of nails. They also found that in order to enhance the stone column performance significantly, the depth of embedment of nails required was 3D to 4D. Fattah & Majeed (2012a) studied the behavior of capped stone columns encased with geogrid by the finite element method and found that the capped stone column increased the bearing improvement ratio (q treated/q untreated) and decreased the settlement for all L/D ratios. The bearing improvement ratio also increased with the thickness of the cap, up to 0.4 times the footing diameter.

Samadhiya et al. (2009) and Hasan and Samadhiya (2016) studied the lateral reinforcement of geogrid strips by varying the vertical spacing and concluded that the load intensity was increased by decreasing the spacing. The strength of granular pile was increased by increasing the length of reinforcement to a depth of three times the diameter and no further increment was observed. Basu et al. (2016) worked with fiber-reinforced stone columns and found that the diameter of bulging can be decreased by increase the length and the fiber content. The depth of maximum bulging from the surface also decreased, but the total length of bulging was increased. Prasad and Satyanarayana (2016) studied the behavior of geotextile-reinforced stone columns by placing the reinforcement laterally at different spacings and found that the load-carrying capacity increased with the decrease in spacing.

Ambily and Gandhi (2004) carried out experimental studies by loading stone columns on their area alone and found that the failure occurred in the form of bulging of the stone column at a depth of about 0.5D to 1.0D below the surface. When the load was applied to the tank wall, the load/settlement behavior was linear and the failure did not take place. Fattah & Majeed (2012b) studied the geogrid-encased floating stone columns and found that the maximum lateral displacement occurred at an effective encasement length ratio (length of geogrid encasement along the stone column/total stone column length) of 0.6. Gniel & Bouazza (2009) carried out experiments on geogrid-encased stone columns and found that maximum bulging occurred at a depth of 2D. This could be reduced by providing encasement beyond the zone of bulging. Damoerin et al. (2015) carried out a series of tests to increase the shear strength of the soil by improving the cement column and found that this increased the shear strength of the soil. Fattah and Majeed (2009) studied the behavior of encased floating stone columns and found that the bearing improvement ratio increased by increasing the area replacement ratio for both ordinary and encased stone columns.

Fattah et al. (2010) carried out tests on stone columns by varying the SCR and found that the stiffness was increased with an increase in stiffness of the treated soil. Malarvizhi and Ilamparuthi (2007), and Murugesan and Rajagopal (2010) studied the stone column behavior and concluded that the SCR increased by inclusion of the encasing material and also with the stiffness of the encasing material.

Ambily and Gandhi (2007) carried out tests on stone columns by varying the spacing between the columns and shear strength of the soil for both single and group columns. They found that the stiffness improvement factor (the ratio of stiffness of treated soil to untreated soil) depends on the angle of internal friction between the stones and the spacing between the columns, independent of the shear strength of the soil. They also found that the settlement increased and the load-carrying capacity decreased with an increase in spacing up to an L/D ratio of 3 (beyond this, the change was negligible). For stone columns reinforced to L = 2D the improvement ratio was very high and the settlement reduction ratio was very low (Fattah et al., 2016).

From the literature review, it is clear that many researchers have studied soft soil improvement by using different types of stone aggregates. However, there has been limited research on the replacement of stone aggregates with other materials. In this study an alternate material (Silica-Manganese slag) was used as the column material and the sand was replaced within the voids between the aggregates. This column was further encased with geotextile material with different encasement lengths, and the bulging and load versus settlement behavior was studied.

2. MATERIALS AND METHODS

2.1. Materials

Marine clay of high compressibility was selected for this study, and was collected from Visakhapatnam port, India. The marine clay used in this study is shown in Figure 1a and the properties are shown in Table 1.

Table 1 Properties of marine clay

Property of Marine clay	Value/ Classification
Fines content (Silt+ Clay)	94%
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%
Soil classification (Indian Standard Classification)	CH
Shear strength of soil (in kPa) at 54 % water content	15.0
Specific Gravity	2.50

In this study, stone column material was replaced with Silica-Manganese slag, as it has better properties compared to stone chips (shown in Table 2), in order to enhance the strength properties. The slag is a by-product from the steel industry, consisting of SiO_2 and CaO in proportions of about 45% and 24%, respectively. It was collected from Sri Mahalakshmi Smelters (Pvt.) Limited, Vijayanagaram (Dt.), India. The Silica-Manganese slag used in this study is shown in Figure 1b. The aggregates (stone/slag) passing through 10mm and retained on 4.75 mm were taken for this study. The aggregate size was selected as per the guidelines given by Nayak (1983). Table 2 shows the properties of Stone aggregates and silica-manganese Slag.

Table 2 Properties of aggregates

Property	Stone Aggregates	Slag
Water absorption (%)	0.50	0.49
Specific Gravity	2.66	2.79
Unit weight of compacted slag (kN/m^3)	15.9	16.7

The results of the silica-manganese slag stone columns were compared with the results of the plain stone column, which was prepared with stone chips. These stone chips were stone aggregates collected from a quarry near Rajam, India.

Clean river sand (collected from Nagavali River, Srikakulam (Dt.), India) was used in this study. This sand was used to fill the air voids within the aggregates and also used to cover the clay bed with a 20 mm-thick layer.

Non-woven geotextile was used as the reinforcement for encasing the stone column (shown in Figure 1c). It was collected from Ayyappa Geotextiles installers, Vishakhapatnam, India. This geotextile sheet was stitched into the shape of a bag and was used for the encasement of the stone column. The mass of the geotextile was 100 g/m^2 and the tensile strength was 4.5 kN/m.

(a) Marine Clay (b) silica-manganese Slag (c) Geotextile encasement

Figure 1 Materials used in this study

2.2. Experimental Study

The experimental program was carried out on a clay bed, a plain stone column (PSC) with stone chips, slag, slag and sand, and a series of reinforced stone columns with slag and sand. For the stone column reinforced with slag and sand, reinforcement was provided using geotextile with different encasement lengths of D, 2D, 3D, 4D. When selecting the coarse aggregate material (i.e., stones and slag), the aggregate varied in size between 4.75 mm and 10 mm. For the stone column reinforced with slag (60%) and sand (40%), the proportions were selected in such a way that the air voids in between the aggregates were replaced by the sand. The experiments were carried out using a steel tank of 200 mm in height and 200 mm in diameter. The length of the stone column was 200 mm and the diameter was 50 mm, to represent a minimum L/D ratio of four required to develop the full limiting axial stress on the stone column (Greenwood & Kirsch, 1983). Load was applied via a 100 mm steel disc (2D) representing the unit cell area. The lateral dimensions were selected in such a way that the failure zone (extending to 1.5D) did not overlap with the distance between the column and the inner surface of the tank (Meyerhof and Sastry, 1978). A schematic diagram of the loading frame with a typical stone column diagram is shown in Figure 2, and the mode of application of reinforcement is shown in Figure 3.

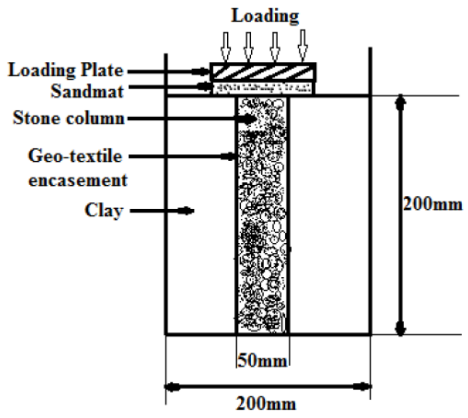

Figure 2 Schematic diagram of loading frame

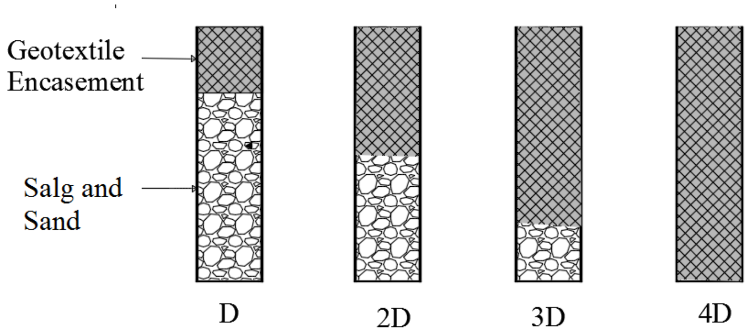

Figure 3 Schematic diagram of mode of application of reinforcement
(Length of encasement is represented in terms of diameter)

2.2.1. Clay bed preparation

The soil sample was air-dried, pulverized, and thoroughly mixed by adding the required amount of water (giving a water content of 54%) to make a consistent paste. The water content required was determined by performing vane shear tests on cylindrical specimens to get the desired shear strength of 15 kPa. Before placing the soil into the tank, the inner surface was cleaned and coated with grease to decrease the friction between the tank and soil. The clay paste was then put into the tank in 50 mm layers up to the required depth of 200 mm, and was compacted with a wooden hammer so that there were no air voids within the soil. This clay bed was then kept for 24 hours to allow for moisture equalization, by covering with a wet gunny bag.

2.2.2. Construction of plain stone column (with stone chips/slag/slag and sand)

Each plain stone column was constructed with stone chips, slag, and slag and sand individually. Before constructing the stone column, the tank wall was greased to decrease the friction. A PVC pipe of 50 mm external diameter and 1mm thickness was cleaned and the outer surface was greased to decrease the friction. This pipe was then placed at the center of the tank and a clay bed was prepared around this pipe to a depth of 200 mm with layers of 50 mm, compacted with a wooden hammer to ensure that there were no air voids. To avoid the absorption of moisture, water was sprinkled on the aggregates before placing them into the column. Each layer of the stone column was cast in layers of 5 cm in height by compacting the stones/slag/slag and sand with a 0.9 kg circular steel tamper of 15 mm diameter. This was done by giving 10 blows from a height of 100 mm to achieve a uniform density. The corresponding unit weight of the stone chips was 15.9 kN/m^3 and that of the slag was 16.7 kN/m^3. The stone column was constructed by simultaneously withdrawing the casing pipe along the length of the column to prevent any neck formation due to lateral thrust of surrounding soil. During the process of construction from one layer to the next, the PVC pipe was lifted to a height of 45 mm so that there was an overlap of 5 mm between the top of the layer and the bottom of the pipe (some studies have carried out the construction by simultaneously preparing the clay bed and stone column, e.g., Sharma et al., 2004). The current study focused on the construction of a stone column after preparation of the clay bed as this is more representative of the bottom-feed method and is a commonly-used technique in practice (Black et al., 2007). After construction of the column, the tank was covered with a wet gunny bag for 24 hours to maintain the moisture equilibrium and improve the bonding between the column material and the soil. This method of installation has been followed in many previous studies (i.e., Malarvizhi & Ilamparuthi, 2007; Ali et al., 2011).

2.2.3. Construction of geotextile-encased stone column

To construct the fully-encased (4D) stone column, the PVC pipe was encased and placed in the tank by marking at the center of the tank properly. The stone column was then constructed as for the plain stone column. For other partially-encased columns, the procedure for construction of the bottom (unreinforced) part was similar to that of the plain stone column. After the construction of the plain column portion, the pipe was removed, the pipe was encased with the geotextile and placed in position, and construction was continued up to the surface. After the construction of the column, this tank was covered with a wet gunny bag for 24 hours to maintain the moisture equilibrium and improve the bonding between the soil and the column material.

2.2.4. Testing of clay bed/stone column

After construction of the clay bed/stone column, a 20 mm-thick sand blanket was placed on the surface. Load was applied uniformly through a 12 mm-thick steel plate of 100 mm diameter (representing an area replacement ratio of 25%) at a rate of displacement of 0.24 mm/min.

2.3. Post-Test Analysis

After completion of the load tests, the stone/slag chips and sand were carefully removed and Plaster of Paris was placed in the cavity by making it to a paste in order to capture the deformed shape after hardening. The hardened Plaster of Paris was released by removing the surrounding clay and the deformed shapes of the columns were studied.

3. RESULTS AND DISCUSSION

Load tests were conducted on the improved soil and the results were compared with those of the unimproved clay bed. Figure 4 shows the load-deformation behavior of the clay bed and the series of stone columns. The load and deformations have been read from the load-settlement curve using a double tangent method.

The load-carrying capacities of the plain stone column with stone chips, slag, slag and sand, and for the reinforced stone columns with encasement lengths of D, 2D, 3D and 4D, were increased by 57%, 71%, 89%, 104%, 121%, 132%, and 150%, respectively, compared to the capacity of the plain clay bed. The load carrying capacity of the soft clay was improved by providing the stone column and also by increasing the reinforcement length. This is because of the increase in stiffness of the column by offering high resistance to bulging by mobilizing the hoop stresses. These results show better performance compared with other studies aimed at improving the performance of the soft soils with different methods, such as by using circumferential nails by Dheerendra Babu (2010) or by using horizontal strips by Ali (2011).

The load-carrying capacity of the stone chips was increased by 9% by replacing them with slag. This improvement may be due to the increased density of the silica-manganese slag compared to the stone chips, or may be due to the increased friction between the rough surface of the slag aggregates.

The load carrying capacity of the plain stone column with slag and sand was increased by 8%, 17%, 23%, and 32% by reinforcing the columns with encasement length of D, 2D, 3D, and 4D, respectively.

From the load-settlement curve, settlement of 7.5 mm was found for the clay bed, decreasing to 7.0 mm, 7.0 mm, 6.8 mm, 6.5 mm, 6.0 mm, 4.5 mm, and 4.0 mm for plain stone columns with stones, slag, and slag and sand, and for reinforced stone columns with encasement lengths of D, 2D, 3D, and 4D, respectively.

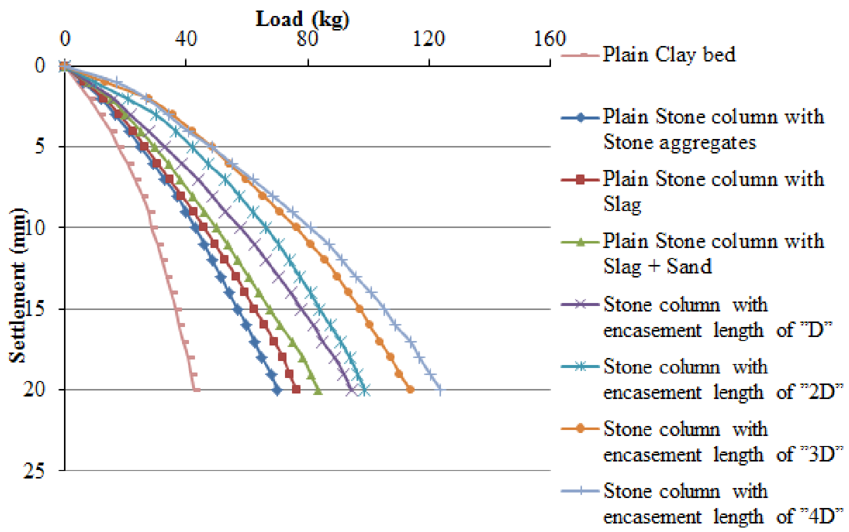

Figure 4 Load-Settlement curves

3.1. Effect of Reinforcement on Bearing Capacity Ratio

The bearing capacity ratio (BCR; the ratio of load-carrying capacity of treated soil to the untreated soil) is a measure of the degree of improvement in the soil. BCR increased by improving the soil with a plain stone column and reached a value of 1.9. This value was further increased by introducing reinforcement and also by increasing the reinforcement length, reaching a maximum of 2.5 at a reinforcement length of 4D. Figure 5 shows the variation in BCR with varied depths of encasement. Figure 5 shows the variation of BCR with varied depths of encasement (H).

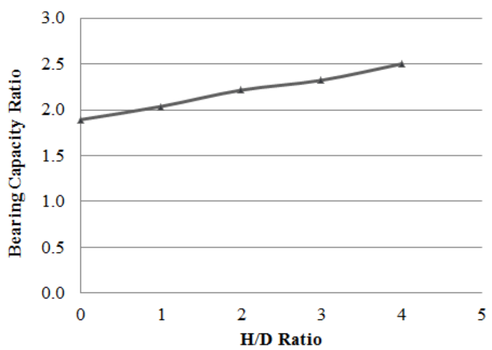

Figure 5 Variation of bearing capacity ratio with depth of encasement

3.2. Bulging Analysis

The maximum bulging for a plain stone column with stone chips is 12 mm. This was decreased to 11 mm and 9 mm by using stone columns with slag and slag and sand, respectively. These values were further decreased to 7 mm, 4 mm, 3.5 mm, and 2 mm by reinforcing the stone columns with encasement lengths of D, 2D, 3D, and 4D, respectively.

For both the plain and fully-reinforced stone columns, the maximum bulging was observed at half the length of the stone column. However, for partially-reinforced stone columns, the maximum bulging was observed at depth just below the end (or junction) of the reinforcement length. For the fully-reinforced stone column the bulging was very much decreased, and the maximum bulging was found at the middle of the stone column. Compared to the upper half, the bulging of the bottom half portion was less, due to the greater hoop stresses near the top, and decreased with depth. Figure 6 shows the deformed shapes of the stone columns and Figure 7 shows the deformations of the different stone columns.

Figure 6 Bulging of stone columns (PSC with stone chips, slag, slag and sand; stone column of slag and sand reinforced with encasement lengths of D, 2D, 3D, and 4D, respectively)

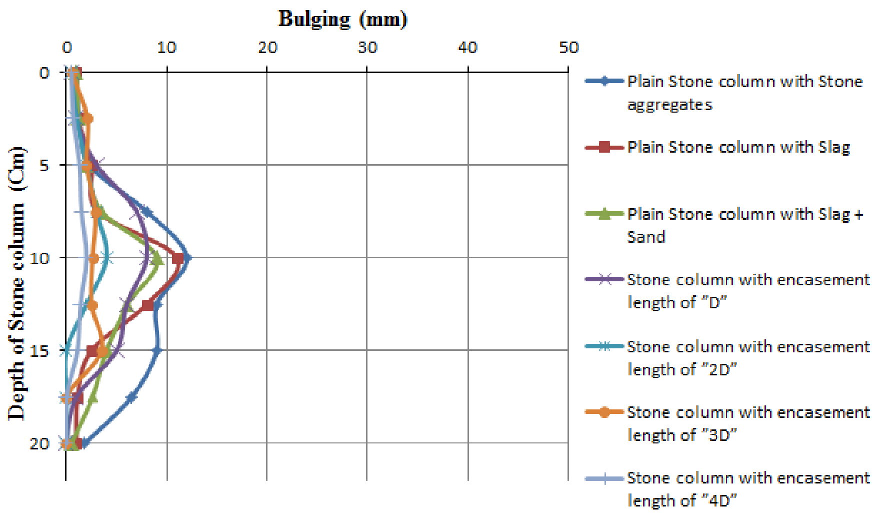

Figure 7 Deformations of stone columns

4. CONCLUSION

Experimental studies were conducted on stone columns by replacing the column material with silica-manganese slag, and the columns were reinforced with geotextile for various encasement lengths. The following conclusions were made: (1) Silica-manganese slag is a potential alternative for improvement of soft soil as it has a better load-carrying capacities than conventional stone columns (about 9%) because of the superior properties of the slag over the stone chips; (2) The load-carrying capacity of the stone column was increased by introducing the encasement, due to mobilization of the hoop stresses which resist bulging. These hoop stresses help to transfer the load to the bottom of the stone column, and thus the bearing capacity increases. The load-carrying capacity also increased by increasing the encasement length of the column; (3) Bulging was reduced by providing reinforcement to the columns. The maximum bulging occurred at the center of the column for both the plain and fully-reinforced columns. For the other reinforcement lengths, bulging was found just below the encasement depth. This indicates that the reinforcement transfers the bulging to the greater depths; (4) The bulging can be decreased by providing reinforcement beyond the zone of bulging (i.e., beyond an encasement length of 2D) due to the increase in confinement on the stone column where the bulging is occurring.

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