Experimental and numerical modelling of geosynthetic encased stone columns subjected to shear loading

Sunil Ranjan Mohapatra [i)] and K. Rajagopal [ii)]

i) PhD Student, Department of Civil Engineering, Indian Institute of Technology, Madras, Chennai, 600036, India.
ii) Professor, Department of Civil Engineering, Indian Institute of Technology, Madras, Chennai, 600036, India.

ABSTRACT

This paper presents the experimental and numerical study for analyzing the shear load capacity of geosynthetic encased stone columns (GESC). Past studies on GESC have mainly focused on the vertical load capacity. However, they may also be subjected to significant amount of shear loading for instance, near the toe of high embankments and retaining walls. The shear load capacity of the GESC depends on the diameter of the column, over burden pressure acting on the soil and strength properties of geosynthetic etc. In order to analyze the shear load capacity of GESC, laboratory tests were performed using a large shear box with GESC. The experimental results were compared with those obtained by 3-dimensional numerical modelling using FLAC^{3D} software. The results showed that the geosynthetic encasement provides an additional confinement to the aggregates which leads to improvement in the performance of GESC.

Keywords: Stone column, geosynthetic, FLAC^{3D}, shear loading, large shear box, soft clay

1 INTRODUCTION

Soft clay soils provide great challenge for geotechnical engineers due to their low bearing capacity and high compressibility. Various ground improvement methods like lime treatment, cement stabilization, deep soil mixing and use of stone columns have been in practice for improvement of soft clay soils. Among all the methods stone columns are more popular because of their ease of installation and cost effectiveness compared to other methods. Stone column is a better option where chemical treatment is not feasible due to environmental regulation or where soil is inert to chemical reaction. Stone columns not only improve the bearing capacity of soft clay soils but also provide a preferential drainage path, due to which consolidation of soft clay can be achieved in a short period of time (Babu et al. 2013) reflecting in reduction of the post construction settlements. These columns mobilize their strength from the lateral confinement provided by the surrounding soil (Hughes and Withers, 1974; IS 15284-Part1-2003). The load carrying capacity of the columns in soft clay soils (c_u< 15 kPa) is very low. Even the formation of stone column in such soils is a major concern due to the low confinement from the surrounding soil. In such cases, the geosynthetic encasement helps in easier installation of the stone column and increases the load carrying capacity and stiffness (Murugesan and Rajagopal 2006). Geosynthetic encasement of stone column also increases the shear load carrying capacity. The higher strength of the geosynthetic encased stone columns (GESC) under such shear loading will help in increasing the factor of safety against global slope failures.

Past studies have mainly focused in understanding the vertical load capacity on GESC (Gniel and Bouazza 2009, 2010; Murugesan and Rajagopal 2007; Ali et al. 2012; Khabbazian et al. 2010; Zhang et al. 2012). However, these columns may also be subjected to significant shear loading for instance near the toe of high embankments (Almeida et al. 2014) and retaining walls etc. During earthquakes, stone columns can be subjected to lateral thrusts (Raju 2001) which may lead to shear failure of ordinary stone columns (OSC). Murugesan and Rajagopal (2008) carried out limited laboratory studies using plane strain condition to understand the behavior of OSC and GESC subjected to shear loading. They reported significant improvement in shear load carrying capacity of stone column due to presence of encasement. The variation of diameter and group effect was not considered for the above study. Hence, detailed studies pertaining to understand the behavior of stone column subjected to shear loading forms the focus of this paper.

In the current research work, behaviour of OSC and GESC were analyzed using laboratory tests and 3-dimensional numerical simulations. The laboratory tests were performed on single stone column of 50 mm and 100 mm diameter placed at the center of the shear box. Tests were performed at different normal pressures varying from 15 kPa to 75 kPa, which corresponds to 1 m to 5 m height of embankment loading in real field condition. The numerical simulations of the stone columns subjected to shear loading were performed using FLAC^{3D} (Fast Lagrangian Analysis of Continua in 3 Dimensions) software.

From the above study it was concluded that shear load capacity of the GSEC depends on the diameter of the column, overburden pressure acting on the soil, strength properties of geosynthetics etc. Apart from the passive resistance provided by the stone column, geosynthetic encasement provides an additional confinement to the aggregates which leads to improvement in its performance.

2 LABORATORY MODEL TESTS

Stone columns were subjected to shear loading in a fully automated large direct shear box (ASTM D3080, 2004) having plan area of 305 mm × 305 mm. Stone column and surrounding soil inside the shear box was maintained at a constant height of 140 mm. The lateral movement of the top box was constrained whereas the bottom box was allowed to move horizontally on roller supports. The shear force developed between the two boxes was measured with an electronic load cell and LVDT was used for measuring the horizontal displacements. Uniform normal pressure was applied on the soil specimen using a pneumatic bladder. A constant strain rate of 1mm/min was adopted for the experimental program. Fig.1 shows a schematic diagram of the large direct shear box.

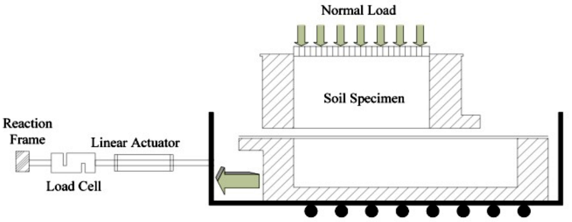

Fig.1. A schematic of large shear box showing major components.

2.1 Materials

Uniformly graded, air dried sand having peak and critical state friction angles of 43° and 34° was used to prepare the soil bed. Sand was compacted to a dry density of 1.66 g/cc corresponding to 72% relative density.

Poorly graded aggregates were used for preparation of stone columns. 50 mm diameter stone columns were made with aggregates passing through 4.75 mm and retained on 2 mm sieve, whereas 100 mm diameter stone column were made with aggregates passing through 9.5 mm and retained on 2 mm sieve. Peak and critical state friction angles of aggregates measured from large direct shear box are 63° and 48° respectively. In order to maintain the ratio of column diameter to maximum aggregate size, two different sizes of aggregates were used. Fig. 2 shows the particle size distribution of sand and aggregates.

Woven geotextile was used as an encasement for stone columns. Geotextiles were cut to the required dimensions and were glued using quickset epoxy adhesive to form a tubular structure. Ultimate tensile strength of woven geotextile (ASTM D4595, 1986) was found to be 34 kN/m corresponding to a strain level of 37 %.

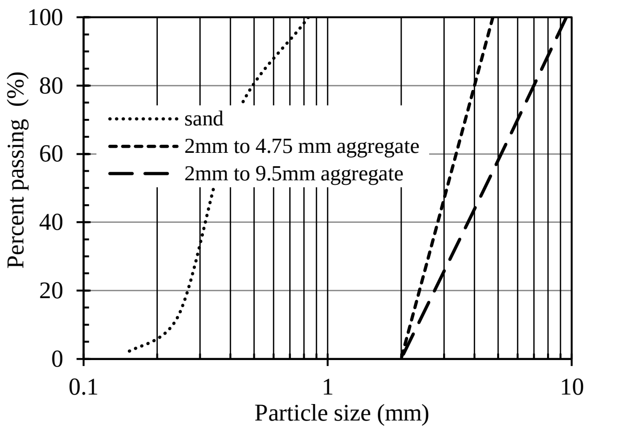

Fig.2. Grain size distribution of sand and aggregates.

2.2 Experimental Procedure

50 mm and 100 mm diameter stone columns were installed at the center of the shear box using hollow steel tube. Initially the steel tube was placed at the required position and sand was compacted around it using needle vibrator. After compaction of sand pre-measured quantity of aggregates was charged into the steel tube and was compacted in three equal layers using an 8 mm diameter tamping rod. After ensuring proper compaction of aggregates to a height of 140 mm, steel tube was withdrawn carefully. In case of encased stone column, encasement tube was first wrapped around the steel tube before placing it inside the shear box and procedure similar to that of OSC was adopted. Fig. 3 shows the schematic diagram of testing plan configuration with a single stone column at the center of the shear box.

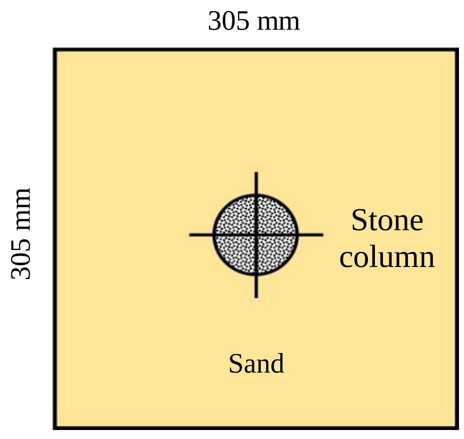

Fig. 3. Schematic diagram of single stone column at the center of shear box.

3 NUMERICAL MODELLING

To overcome the limitation of laboratory experiments and to get a complete understanding of the mechanism inside the shear box numerical model was developed using FLAC^{3D} (Version 3.1). Stone column and surrounding soil were modelled as elastic perfectly plastic material using Mohr-Coulomb model. Geosynthetic encasement was modelled as geogrid type shell element which behaves as an isotropic, linearly elastic material with no failure limit. Fig. 4 shows the plan view of OSC installed at the center of the shear box. The material properties for sand, stone column and geosynthetic are given in Table-1.

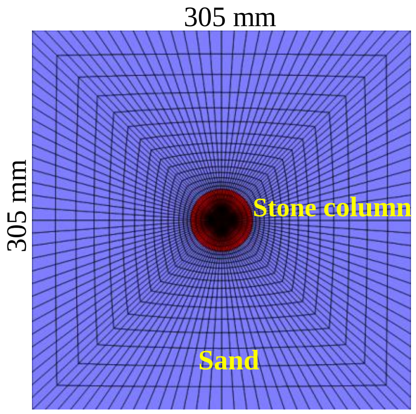

Fig. 4. Plan view of ordinary stone column installed at the center of shear box.

Table 1. Parameters used for numerical simulation.

Parameter	Stone column	Sand	Geosynthetic
Constitutive Model	Mohr-Coulomb		Linear elastic
Young's Modulus (kPa)	100,000	10,000	29,000
Poisson's Ratio	0.3	0.3	0.33
Peak friction angle (°)	63	43	--
Critical state friction angle (°)	48	34	--
Dilation angle (°)	18	12	--

Large friction angle of sand and aggregates are the artifact of large direct shear box (Christopher et al. 2008). Apparent cohesion developed during the testing procedure is accommodated in the numerical modelling to have a better correlation of experimental and numerical results.

4 RESULTS AND DISCUSSION

From the direct shear test (experimental and numerical) it was observed that the shear resistance of virgin soil increases due to the installation of stone column. Stone column and the surrounding soil behave as a composite, which mobilizes higher shear resistance when subjected to shear loading.

4.1 Effect of installation of OSC and GESC

From the laboratory experiments (Fig. 5) it was observed that due to the installation of OSC, increase in shear resistance is achieved. Stone columns having 100 mm diameter mobilizes higher shear resistance as compared to 50 mm diameter on account of higher area replacement ratio. Whereas stone columns encased with geosynthetics showed considerable increase in the shear resistance due to the confinement effect from the encasement. From the numerical analysis, similar trend was observed as shown in Fig. 6. Comparing the results of laboratory experiments and numerical modelling, significant deviation in peak shear stress values are observed but at large horizontal displacement better correlations are observed between them. As the interaction between shear box and soil was not modelled, this difference in peak shear stress value is reasonable. Numerical modelling is used to understand the failure mechanisms of the stone column with and without encasement. An increase in σ_x value was observed above the shear plane (center of top box) in case of 50 mm diameter stone column at 75 kPa confining pressure (Fig. 7). From the figure it can be seen that σ_x values for GESC is equal to that of OSC up to 9 mm horizontal displacement. From 9 mm to 21 mm, value of σ_x reduces slightly due to bending of GESC and after 21 mm a steady increase was observed. Encased stone column behave as a semi-rigid pile, which provide passive resistance due to which higher shear stress are be mobilized compared to OSC.

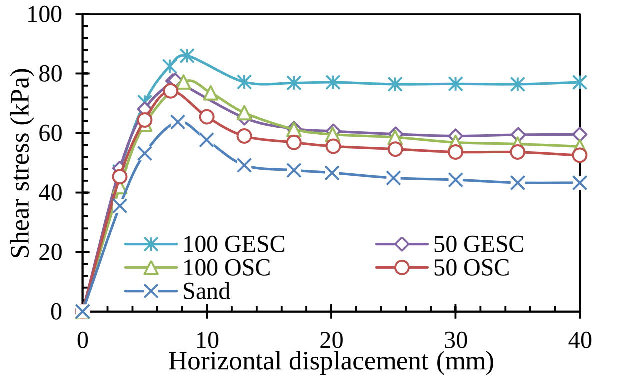

Fig. 5. Shear stress vs. displacement (σ_n =75 kPa).

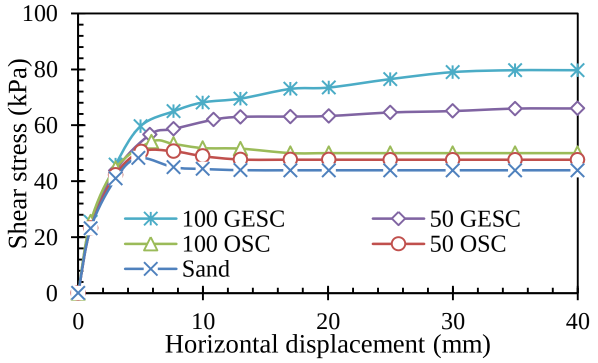

Fig. 6. Shear stress vs. displacement (σ_n =75 kPa).

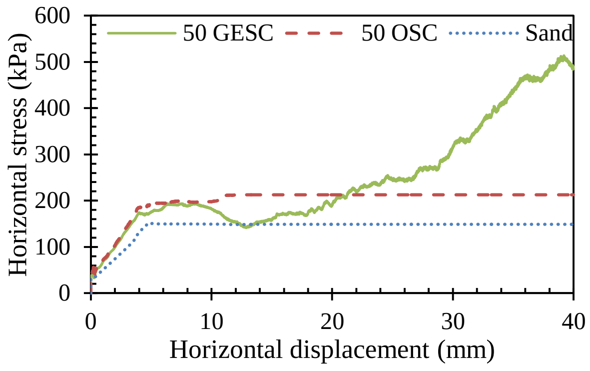

Fig. 7. Horizontal stress (σ_x) developed above the shear plane.

Along with the passive resistance, mobilization of hoop tension in the geosynthetic encasement provides an additional confinement to the aggregates which increases the measured shear stress value significantly.

5 CONCLUSIONS

The present work quantifies the response of geosynthetic-encased stone columns subjected to shear loading using both experimental and numerical methods. As the interaction between the direct shear box and the soil is not modelled in numerical analysis, the peak shear stress from numerical analysis was found to deviate from the experimental value. However, at large displacements the results obtained from both the techniques showed good correlation. Numerical modelling aided to understand the failure mechanisms of the stone columns.

The major conclusions drawn from the present work are as following:

1) The shear resistance of the virgin soil increases due to installation of OSC.
2) For GESC at large horizontal displacements there was an increase in the post peak shear resistance.
3) In case of OSC post peak shear resistance remain constant due to failure of stone columns.
4) In encased columns, the geotextile reinforcement prevents the shear failure of stone columns.
5) With the increase in area replacement ratio, the shear resistance increases in both ordinary and encased stone columns.
6) Additional confinement is mobilized inside the stone column due to geosynthetic encasement.

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REFERENCES

1) Ali, K., Shahu, J.T. and Sharma, K.G. (2012): Model tests on geosynthetic-reinforced stone columns: a comparative study, *Geosynthetics International*, 19(4), 292-305.
2) Almeida, M.S.S., Hosseinpour, I., Riccio, M. and Alexiew, D. (2014): Behaviour of Geotextile-Encased Granular Columns Supporting Test Embankment on Soft Deposit, *Journal of Geotechnical and Geoenvironmental Engineering*. 141(3), 04014116.
3) ASTM Standard D3080 (2004): Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions. *American Society for Testing and Materials*. ASTM International.
4) ASTM Standard D4595 (1986): Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method. *American Society for Testing and Materials*. ASTM International.
5) Babu, M.R.D., Nayak, S. and Shivashankar, R. (2013): A Critical Review of Construction, Analysis and Behaviour of Stone Columns, *Geotech. Geol. Engg.*, 31,1-22.
6) Christopher, A.B., Benson, C.H. and Edil, T.B. (2008): Comparison of shear strength of sand backfills measured in small-scale and large-scale direct shear tests, *Can. Geotech. Journal*, 45(9), 1224-1236.
7) FLAC 3D (2006): Fast Lagrangian analysis of continua in 3 dimensions, Version 3.1, Itasca consulting group, Inc., Minnesota.
8) Gniel, J. and Bouazza, A. (2009): Improvement of soft soils using geogrid encased stone columns, *Geotextiles and Geomembranes*, 27, 167-175.
9) Gniel, J. and Bouazza, A. (2010): Construction of geogrid encased stone columns: A new proposal based on laboratory testing, *Geotextiles and Geomembranes*, 28, 108-118.
10) Hughes, J.M.O. and Withers, N.J. (1974): Reinforcing of soft cohesive soils with stone columns, *Ground Eng*, 7(3), 42-49.
11) IS 15284-Part1 (2003): *Indian standard*-Design and construction for ground improvement-Guidelines. Part-1 Stone columns.
12) Khabbazian, M., Kaliakin V.N. and Meehan, C.L. (2010): Numerical study of the effect of geosynthetic encasement on the behaviour of granular columns, *Geosynthetics International*, 17(3), 132-143.
13) Murugesan, S. and Rajagopal K. (2006): Geosynthetic-encased stone columns: Numerical evaluation. *Geotextiles and Geomembranes*, 24(6), 349-358.
14) Murugesan, S. and Rajagopal, K. (2007): Model Tests on Geosynthtic Encased Stone Columns, *Geosynthetics International*, 24(6), 349-358.
15) Murugesan, S. and Rajagopal, K. (2008): Shear load tests on stone columns with and without geosynthetic encasement, *Geotech. Test. Journal*, 32(1), 35-44.
16) Raju, V.S. (2001): Rehabilitation of Earthquake Damaged Berths at Kandla Port, *Proceedings of the International Conference on Ocean Engineering*, IIT Madras, Chennai, India, K55-K70.
17) Yoo, C. and Lee, D. (2012): Performance of geogrid-encased stone columns in soft ground: full-scale load tests. *Geosynthetics International*, 19(6), 480-490.
18) Zhang, Y., Chan, D. and Wang, Y. (2012): Consolidation of composite foundation improved by geosynthetic-encased stone columns, *Geotextiles and Geomembranes*, 32, 10-17.