Numerical Analysis of Geosynthetic- Encased Stone Columns under Laterally Loads

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Abstract**—**Out of all methods for ground improvement, stone column became more popular these days due to its simple construction and economic consideration. Installation of stone column especially in loose fine graded soil causes increasing in load bearing capacity and settlement reduction. Encased granular stone columns (EGCs) are commonly subjected to vertical load. However, they may also be subjected to significant amount of shear loading. In this study, three-dimensional finite element (FE) analyses were conducted to estimate the shear load capacity of EGCs in sandy soil. Two types of different cases, stone column and geosynthetic encased stone column were studied at different normal pressures varying from 15 kPa to 75 kPa. Also, the effect of diameter in two cases was considered. A close agreement between the experimental and numerical curves of shear stress - horizontal displacement trend line is observed. The obtained result showed that, by increasing the normal pressure and diameter of stone column, higher shear strength is mobilized by soil; however, in the case of encased stone column, increasing the diameter had more dominated effect in mobilized shear strength.

Keywords**—**Ordinary stone column, validation, encased stone column, laterally load.

I. Introduction

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 and loose sandy soil. Among all the methods, stone columns are more popular because of their ease of installation and cost effectiveness compared to the 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 [1]. The construction of stone column involves partial replacement or lateral compaction of unsuitable or loose subsurface soils with a compacted vertical column of stone aggregate. The presence of the columns creates a composite material which is stiffer and stronger than the original soil [2]. When the stone columns are installed in very soft clays, they may not derive significant load capacity owing to low lateral confinement. McKenna et al. [3] reported cases where the stone column was not restrained by the surrounding soft clay, which led to excessive bulging, and also the soft clay squeezed into the voids of the aggregate. In such situations, the load capacity of the stone column can be improved by imparting additional confinement to the stone column by encasing the individual stone columns using a suitable geosynthetic [4].

By using geotextile, the geosynthetic encasement helps in easier installation of the stone column and increases the load carrying capacity and stiffness [5]. Geosynthetic encasement of stone column also increases the shear load carrying capacity. The higher strength of the EGCs 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 EGCs [6]-[10]. However, these columns may also be subjected to significant shear loading [11]. During earthquakes, stone columns can be subjected to lateral [12] thrusts which may lead to shear failure of ordinary stone columns (OSCs). Murugesan and Rajagopal [13] carried out limited laboratory studies using plane strain condition to understand the behavior of OSCs and EGCs subjected to shear loading. Extensive research has been carried out on various applications of ordinary OSCs without encasement and to assess the effectiveness of these methods in laterally load by using field case histories [14], field tests [15], physical experiments [16]-[17], and numerical simulation [18]. Ayadat and Hanna [2] have reported the benefit of encasing stone columns installed in collapsible soils. Murugesan and Rajagopal [19] evaluated the behaviour of geosynthetic-encased stone columns through numerical analyses, and found that the encased stone columns are stiffer than conventional stone columns, and are less dependent on the strength of the surrounding clay soil to mobilize column load capacity fully. While encased stone columns have been used in practice, there have not been any systematic investigations to understand the behaviour of encased stone columns. Murugesan and Rajagopal [20] evaluated the shear load capacity of non-reinforced and reinforced stone columns by generating lateral soil movements through laboratory tests. Yoo [21] employed three-dimensional FE model of geosynthetic-encased stone columns installed in soft clay and analyzed the effect of factors such as consistency of soft ground, the geosynthetic encasement length and stiffness, and area replacement ratio.

The present paper focuses on understanding the behaviour of OSCs and EGCs under lateral loading by simulation of large direct shear tests. The objective is to study the improvement in lateral resistance of virgin soil due to the installation of OSCs and EGCs. Results of selected experimental tests conducted by Mohapatra and Rajagopal

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[22] were used to validate the numerical model utilised in this study. Based on obtained data by using FE software ABAQUS, three-dimensional model of stone column configured and the shear stress-displacement response of stone column defined in two alternatives cases of using geosynthetic encasement and without geosynthetic, detailed parametric analyses were performed by varying the diameter of the stone column and surcharge for two cases of encasement and without encasement. Three different surcharge (30, 45, and 75 kPa) pressures, two different diameters of stone column (50 and 100 mm), and the behavior of two types of stone column (OSCs and EGCs) were compared with each other in laterally loaded. The material properties selected in the analysis were based on material properties that Mohapatra and Rajagopal [22] had used in their tests and are illustrates in Table I.

TABLE I
MATERIAL PROPERTIES [22]

Parameters	Properties		
	sand	Stone	Geotextile
Modulus of elasticity (kPa)	10,000	100,000	29,000
Poisson s ratio (μ)	0.3	0.3	0.33
Cohesion (kPa)	0	0	-
Peak friction angle (φ)	43	63	-
Critical state friction angle (φ)	34	48	-

II. VALIDATION AND FE STRATEGY

According to experimentally test [22], 50 mm diameter stone columns were installed at the center of the shear box using hollow steel tube. The laboratory model studies on lateral load capacity of granular columns were carried out using a large direct shear box having plan size of 305 mm x 305 mm and a depth of 140 mm. 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. Fig. 1 (a) shows the plan view of the large direct shear box with a single stone column at the center of the shear box [22].

To overcome the limitation of laboratory experiments and to get a complete understanding of the mechanism inside the shear box, the FE software ABAQUS was used for simulation of direct shear test. Figs. 1 (b) and (c) show the meshed and geometry view of OSCs installed at the center of the shear box in numerical modeling. Relatively fine mesh is occupied near the surface while a coarser mesh was used for further distance from the center. Stone column and surrounding soil were modeled as elastic perfectly plastic material by using Mohr-Coulomb model.

Geosynthetic encasement was modelled as geotextile type shell element which behaves as an isotropic linearly elastic material with no failure limit. From the above study, it was concluded that shear load capacity of the EGCs depends on the diameter of the column and overburden pressure acting on the soil. 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.

The boundary conditions were chosen such that the displacement of the horizontal boundary is restricted in all directions, while vertical boundaries are restricted horizontally and free to move in the vertical direction. For stone column-soil contact, the modeling of the interfaces is an important concern. Therefore, one of the main issues is identifying interaction between soil and stone column. Friction plays an important role in the interaction effects between stone column and soil. Friction is an integral part of the contact algorithms of ABAQUS and it is based on a Coulomb formulation where the magnitude of the friction force is proportional to the normal force, but its direction is always opposite to that of the sliding velocity. The Coulomb friction law neglects the elasticity between the particles and a rigid plastic contact behavior is assumed. When a compressive normal pressure (p) applied on the lateral surface of the columns, it can only transfer shear forces along their lateral surfaces. When contact take places, according to the modified Coulomb's friction theory, the relationship between shear force and normal pressure is shown as (1):

$$\tau = f \times p \tag{1}$$

where f is friction coefficient, and p is normal pressure in lateral surface that varied in each level of soil. As reported by Jeong et al. [23] the interface friction coefficient (f) for sand varies from 0.4 to 0.6. Therefore, in this study interface friction coefficient (f) of 0.5 for all the types stone column was adopted. In the present paper, a series of numerical calculations have been performed to investigate the behavior of granule stone columns in sandy soil under shear static loading. Fist, three-dimensional FE, ABAQUS software, analysis was done on OSCs in laboratory scale to validate by some experimental tests [22].

Additionally, analyses were carried out under shear static loading in order to evaluate the effects of ordinary and encasement stone column on the shear bearing capacity of stone column subjected to such loading.

III. RESULT AND DISCUSSION

In this section, the influence of different parameters on the performance of the stone column is studied through 3D numerical analyses. Modeling and laboratory test [22] on OSCs were terminated upon reaching 40 mm horizontal displacement of the bottom shear box because at this displacement both the peak and the critical state shear resistance were mobilized. Also, the case in which a single EGCs was installed at the centre of the shear box was terminated at 40 mm horizontal displacement so as to mobilize tensile resistance of the geosynthetic encasement. Tests

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involving OGCs and EGCs were terminated at 40 mm horizontal displacement in order to avoid boundary effects. The soil samples were sheared at a uniform strain rate of 1 mm/min.

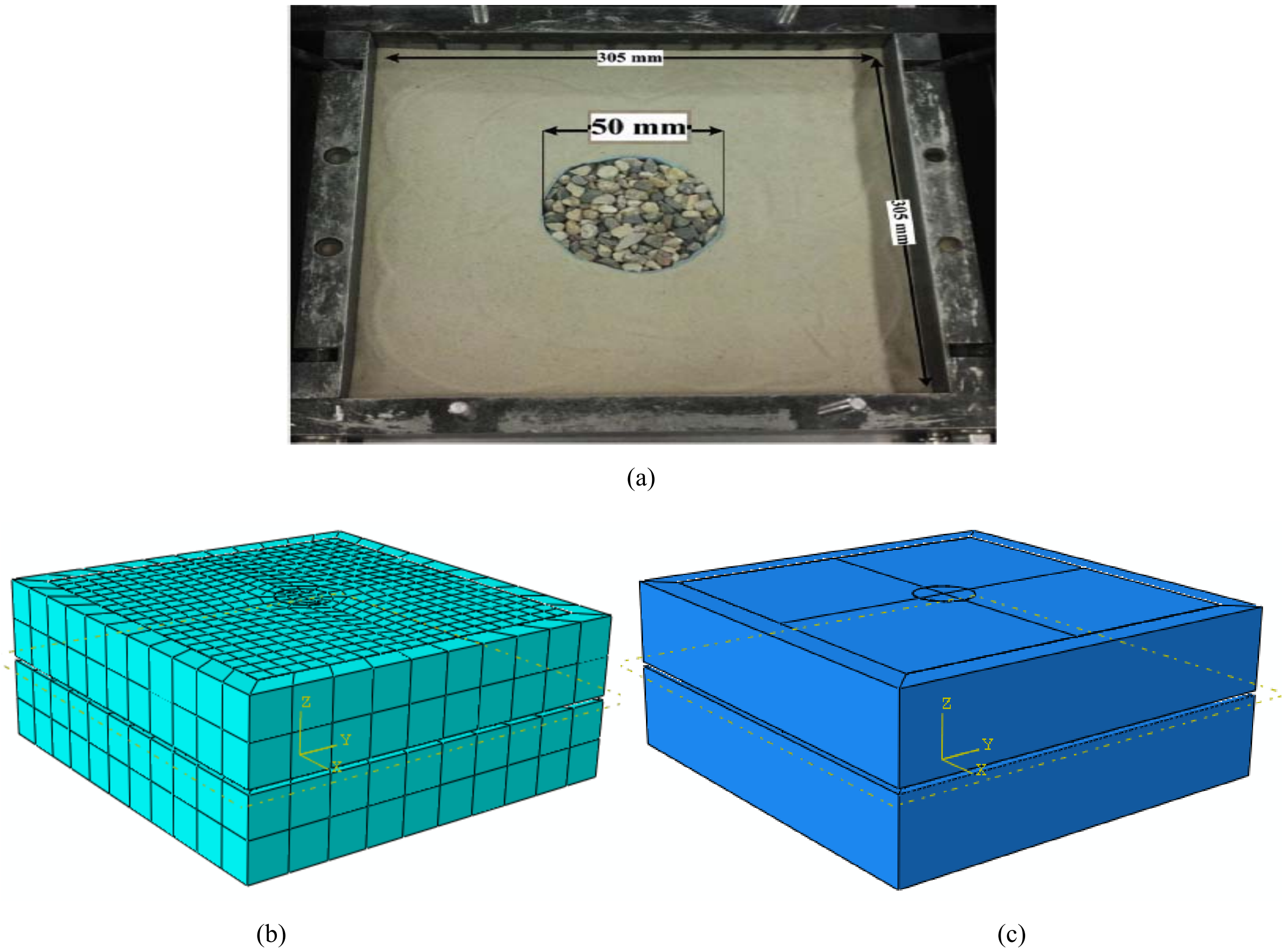

Fig. 1 Schematic of single stone column used in the (a) experimental test [22] (b) meshed and (c) geometry of numerical modeling

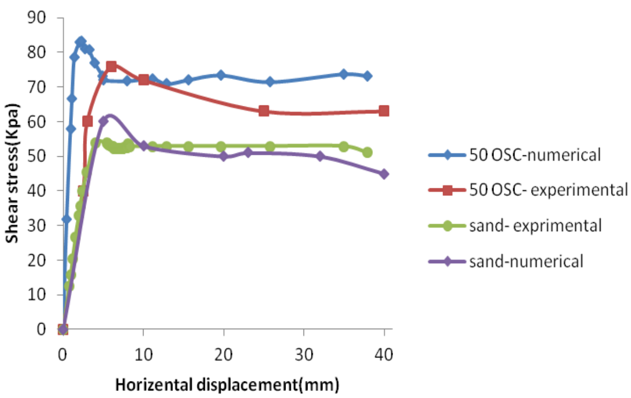

Fig. 2 Comparison of numerical and experimental results of shear stress versus horizontal displacement in the case of OSCs

In Fig. 2, from the direct shear test (experimental [22] 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. From the laboratory experiments [22], it was observed that due to the installation of OSCs, increase in shear resistance is achieved. Comparison of experimental [22] and numerical shear stress–horizontal displacement curves is shown in Fig. 2, it can be seen that the general trends of FE method are similar to those of the experimental tests for sandy soil and soil with non reinforced stone column with 50 mm diameter.

In Fig. 3, it was observed that due to the installation of OSCs, 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 geotextile showed considerable increase in the shear resistance due to the confinement effect from the encasement. Fig. 3 shows the results of geotextile encased granular column at a normal pressure of 75 kPa. On encasing the column, higher shear stresses are mobilized as compared to the corresponding OGCs, also results show that increasing the diameter of the granular columns, higher shear resistances are mobilized because the percent area occupied by the granular column is higher in the plane of shear. This behaviour can be clearly observed for both 50 mm and 100 mm diameter columns. In the case of OGCs, the soil specimen had undergone considerable strain softening whereas for EGCs minimal strain softening occurred and in a few cases strain hardening was pronounced at higher strain levels. The numerical models were performed at three different normal pressures. Figs. 3-5 show that by decreasing the normal pressure form 75 kPa to 30 kPa, lower shear strength is mobilized by soil treated with ordinary and encasement granular columns of 100 and 50 mm diameter. Also higher peak shear stresses observed for Encasement cases are illustrated in Figs. 3-5. An increase in shear strength due to encased granular columns can be described by the apparent cohesion due to the effects of geotextile confinement. The geotextile straining during the shear displacement produces higher confining pressures within the granular columns leading to this additional shear strength.

It can be seen that after the peak, strain softening takes place in the case of OSCs and shear strength remained constant thereafter. In the case of EGCs after the peak, very little strain softening is observed compared to OGCs and shear resistance becomes almost equal to the peak value at 40 mm displacement. It can be seen that the encasement has also increased the shear modulus of the soil mass. Also results show increasing the diameter of the stone column has negligible effect in peak shear stress in the case of OSCs rather than the case of EGCs.

Figs. 6 and 7 show the peak shear stress with increasing the diameter of the stone column in case of OGCs and EGCs at different normal pressures. As it was shown in Figs. 6 and 7, in constant surcharge by increasing the diameter of the stone column in the case of OGCs, little changes were observed in shear resistance, however in the case of EGCs by increasing the diameter of the stone column the more changes in shear resistance obtained. Thus, in the case of EGCs, the increasing the diameter has more dominant effect.

Figs. 8 and 9 show the variation of shear strength at 40 mm displacement versus diameter for both OGCs and EGCs at different normal pressures. In the case of OGCs, the strength behavior is similar to that observed at peak stress but in lower normal pressure stress the rate of increasing of shear strength decreased. Also, in the case of EGCs, a steady increase in shear stress beyond the peak is observed with an increased diameter due to mobilization of additional confinement from tensile forces in geosynthetic encasement.

IV. Conclusion

The present work quantifies the response of OSCs and geosynthetic encasement stone column subjected to shear loading using numerical methods. One small scale tests on single stone column were simulated numerically in order to verify the accuracy of the modeling. The results from the parametric studies are presented to quantify the effect of stone column diameter and surcharge on shear stress-horizontal displacement response of stone column in two case of encasement and ordinary column, based on the results obtained from this study, the following conclusions are made:

- The shear stress is found to increase upon reinforcing the sand with OSCs due to the higher shear resistance of the combined soil-granular column system;
- In both cases of encasement and OSCs, generally peak shear stress increases with an increase in normal pressure and diameters;
- The geosynthetic-encased stone columns exhibit a stiffer and stronger response. These encased columns show negligible strain-softening response. By contrast, the OSCs exhibited a softer response, with significant strain-softening;
- By increasing the diameter of the stone column, the performance of encasement stone column in shear resistance is superior to that of small diameter; moreover, increasing the diameter had not considerable effect in the case of ordinary column.

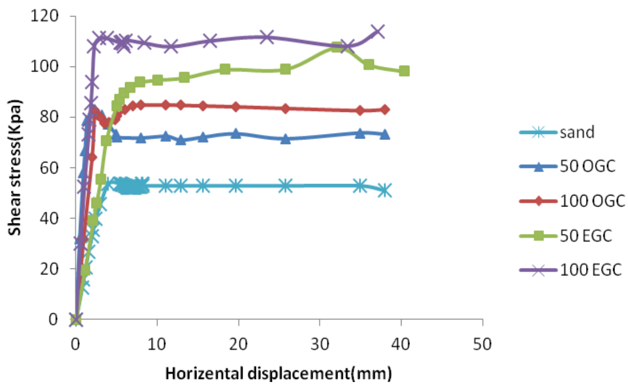

Fig. 3 Shear stress versus horizontal displacement for two cases of OSCs and EGCs (75 kPa surcharge)

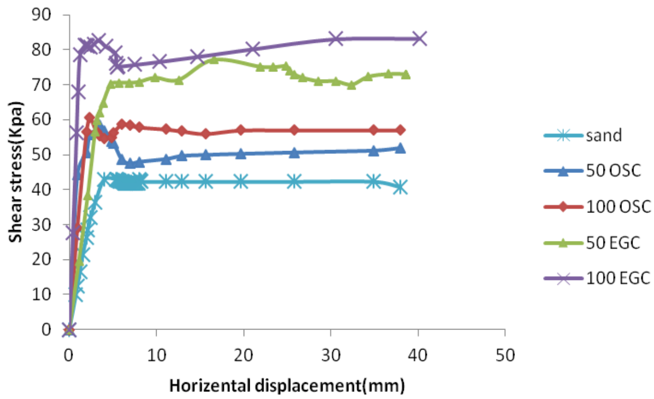

Fig. 4 Shear stress versus horizontal displacement for two cases of OSCs and EGCs (45 kPa surcharge)

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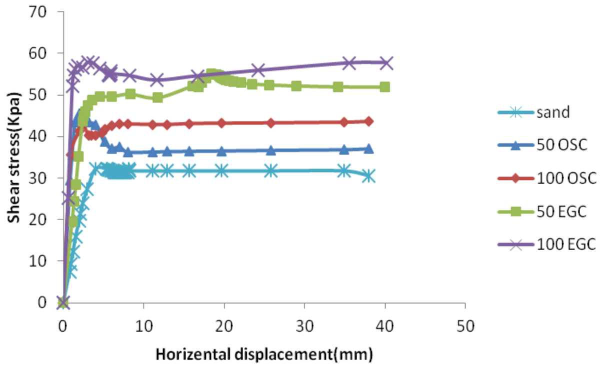

Fig. 5 Shear stress versus horizontal displacement for two cases of OSCs and EGCs (30 kPa surcharge)

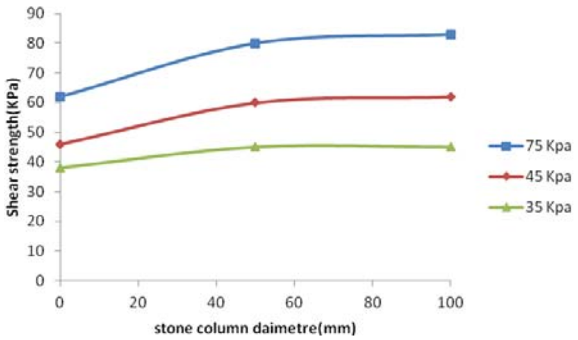

Fig. 6 Peak shear strength versus stone diameter in the case of OSCs

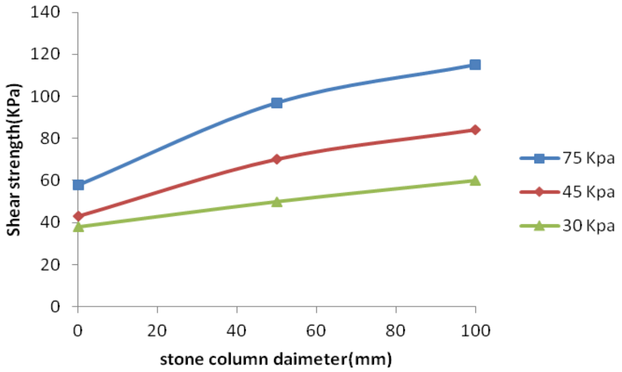

Fig. 7 Peak shear strength versus stone diameter in the case of EGCs

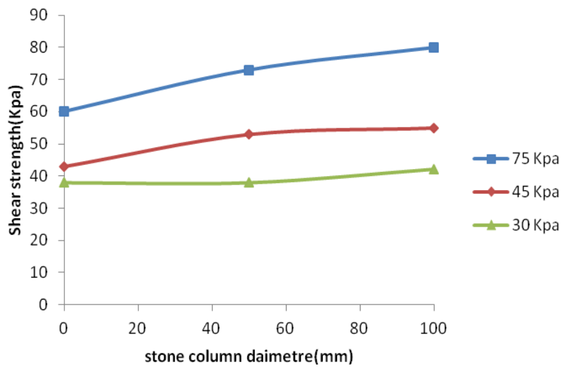

Fig. 8 Shear strength mobilized at 40 mm shear displacement versus stone diameter in the case of OSCs

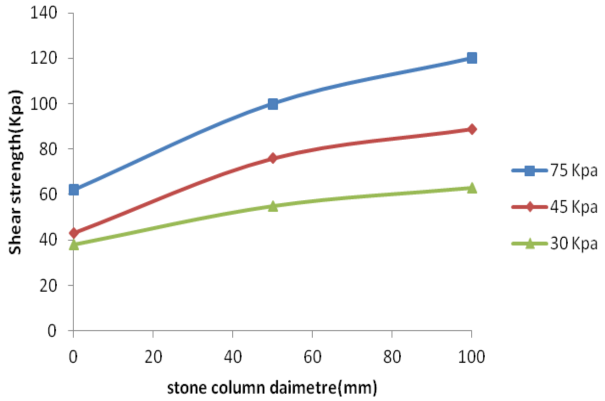

Fig. 9 Shear strength mobilized at 40 mm shear displacement versus stone diameter in the case of EGCs

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