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Bearing capacity of geogrid reinforced sand over encased stone columns in soft clay

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ABSTRACT

Stone columns develop their load carrying capacity from the circumferential confinement provided by the surrounding soils. In very soft soils, the circumferential confinement offered by the surrounding soft soil may not be sufficient to develop the required load carrying capacity. Hence a vertical confinement would yield a better result. The load carrying capacity is further increased with the addition of a sand bed over the stone columns. In the present study, a series of laboratory model tests on an unreinforced sand bed (USB) and a geogrid-reinforced sand bed (GRSB) placed over a group of vertically encased stone columns (VESC) floating in soft clay and their numerical simulations were conducted. Three-dimensional numerical simulations were performed using a finite element package ABAQUS 6.12. In the finite element analysis, geogrid and geotextile were modeled as an elasto-plastic material. As compared to unreinforced clay bed, an 8.45 fold increase in bearing capacity was observed with the provision of a GRSB over VESC. The optimum thickness of USB and GRSB was found to be 0.2 times and 0.15 times the diameter of the footing. A considerable decrease in bulging of columns was also noticed with the provision of a GRSB over VESC. Both the improvement factor and stress concentration ratio of VESC with GRSB showed an increasing trend with an increase in the settlement. It was observed that the optimum length of stone columns and the optimum depth of encasement of the group of floating VESC with GRSB are 6 times and about 3 times the diameter of the column respectively.

1. Introduction

Structures constructed on soft clay experiences either of the two problems namely, excessive settlement and tilting due to shear failure of the soil. One of the common remedial measures is to construct stone columns below the footing. Upon loading, a stone column normally bulges and pushes the surrounding soil radially. The surrounding soil imparts a confining effect to the stone column. As a result of this confinement, the stone column can take vertical loads. Higher the confinement, higher is the load carrying capacity of the column. This confinement may be provided to stone columns by encasing the individual stone columns with geosynthetics. The encasement increases the bearing capacity and the stiffness of soil, prevents squeezing of stones into the surrounding clay, reduces lateral bulging of stone columns and preserves the drainage and frictional properties of stone aggregates (Raithel et al., 2002; Murugesan and Rajagopal, 2006, 2007; Wu and Hong, 2009; Gniel and Bouazza, 2009; Lo et al., 2010; Zhang et al., 2011; Ali et al., 2012; Almeida et al., 2013, 2015; Ghazavi and Afshar, 2013; Hosseinpour et al., 2015; Mohapatra et al., 2016; Gu et al., 2016; Fattah et al., 2016; Geng et al., 2016; Castro, 2017). Moreover, being highly permeable, the stone columns also act as vertical drains and speed up the consolidation process of the surrounding soft clay. The concept of encasement was first proposed by Van Impe in 1989 (Van Impe, 1989). Murugesan and Rajagopal (2010) performed a series of single and group of load tests with or without encasement using a displacement method. Murugesan and Rajagopal (2006) and Lo et al. (2010) presented a numerical method to study the vertically encased stone columns. It is reported that the bearing capacity can be further improved and the settlement can be further reduced by minimizing bulging of the stone columns. Geosynthetic sheets can be conveniently used as horizontal reinforced layers in the granular columns (Madhav et al., 1994; Sharma et al., 2004; Basudhar et al., 2008; Wu and Hong, 2008). A series of model

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tests on a group of floating stone columns were conducted by Wood et al. (2000) to study the effect of long-term drained settlement. Shahu and Reddy (2011) conducted a series of laboratory small scale model tests and their finite element analysis to study the different parameters effecting bearing capacity and settlement of the stone columns. Two-dimensional numerical models were developed based on lumped parameter approach for a single layer and multilayer geosynthetic-reinforced granular bed (Deb et al., 2007, 2008) placed over the stone column-reinforced soft soil. A theoretical approach was developed by Shahu et al. (2000) to analyze the effectiveness of granular mat placed over the stone column-reinforced soft ground. Generally, a cushion of sand bed is placed over the stone columns to distribute the stresses uniformly and to provide a drainage path (Mitchell, 1981). Only a few studies have been reported in the literature indicates that this sand layer, when reinforced with planar geosynthetics, can noticeably improve the bearing capacity of the foundation system (Abdullah and Edil, 2007; Deb et al., 2011). Arulrajah et al. (2009) reported the use of a geogrid-soil platform over the stone columns in the construction of high-speed railway embankments in Malaysia. Han and Gabr (2002) performed a numerical analysis of pile-supported earth platforms and geosynthetic-reinforced earth platform over soft soil. Most of the reported numerical studies are based on the two-dimensional finite element analysis considering geosynthetic sheet as an elastic material and the experiments used stone columns resting over a hard stratum without considering group effect. There are very limited experimental investigations or three-dimensional numerical studies to show the combined effect of geogrid-reinforced sand bed (GRSB) with vertically encased stone columns (VESC). The present study consists of a series of laboratory model tests and their numerical simulations through a three-dimensional finite element analysis. Some parametric studies are also conducted by varying the stiffness of the geogrid, the stiffness of geotextiles, the length of the VESC and the depth of encasement.

2. Laboratory model tests

2.1. Material used

The materials used in the present study were clay, sand, stone aggregates which were mainly collected from the nearby sites of NIT Silchar and geogrid and geotextile which were obtained from a vendor in India. Gradation curves of clay, sand and stone aggregates are shown in Fig. 1. Clay was used as a foundation bed in which stone columns were constructed. Sand was used as a blanket over the stone column reinforced soft clay. Index properties of the clay (ASTM D4318, 2005 and ASTM D2487, 2006) are shown in Table 1. It is intended to carry out the laboratory tests with a soft clay having undrained cohesion, $c_u = 10$ kPa. In order to find out the quantity of water required to attain this strength a series of laboratory UCS tests were conducted on remolded soil samples with different water contents. From the graph between c_u and water content, the water content corresponding to $c_u = 10$ kPa was found out to be 32%. At this water content, the bulk unit weight (γ) was around 17.2 kN/m^3. A water content of 32% was maintained in all the tests.

Stone aggregates with particle size in the range of 2–6 mm were used to prepare the stone columns and their basic properties are listed in Table 2.

The sand blanket (henceforth termed as a sand bed) was made of poorly graded sand passing through 4.75 mm sieve. The sand bed was prepared at 70% relative density for all the tests. Friction angle of sand obtained from standard triaxial CU tests was 42°. Basic properties of sand are shown in Table 2.

Biaxial geogrid, made of high-density polyethylene was used as a reinforcement layer in the sand bed. Properties of the geogrid as per ASTM D6637, 2001 and geotextile as per ASTM D4595, 2011 are presented in Table 3. The geotextile was used for encasement of the stone columns.

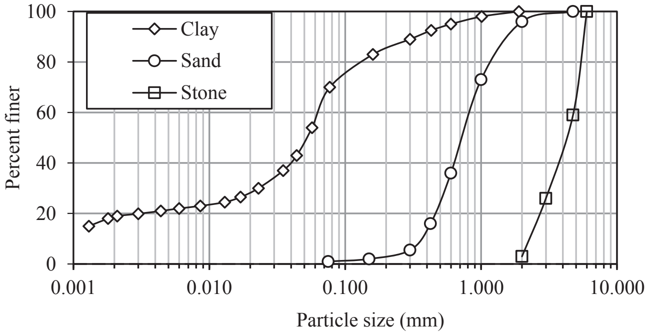

Fig. 1. Particle size distribution curves for clay, sand and stone aggregate.

Table 1
Properties of clay.

Parameter	Value
Liquid limit (%)	43
Plastic limit (%)	22
Plasticity index (%)	21
Specific gravity	2.62
Coefficient of permeability (m/s)	6.77×10^{-10}
Bulk unit weight at 32% water content (kN/m^3)	17.2
In situ vane shear strength (kPa)	10
USCS classification system	CL

2.2. Test setup

To prepare the test setup, a steel tank of plan dimensions 1000 mm × 1000 mm and height 1000 mm as shown in Fig. 2 was used. The four sides and bottom of the tank were made of 6 mm thick mild steel sheet and were braced laterally with mild steel angles on the outer surface to achieve necessary stiffness against bending during the tests. Initially, the inner surface of the tank wall was coated with a thin film of silicon grease and then covered with a smooth polythene sheet to minimize friction between the soil and the tank wall. Proper overlapping of the polythene sheets was made to avoid loss of water through the sides. In order to maintain a constant density and water content for all the tests, the tank was filled with soft clay in layers, each of 100 mm thick. The soft clay layer was prepared from a known weight of dry clay grinded to fine powder and thoroughly mixed with water corresponding to the water content of 32%. The clay lump was then put in the tank and compacted with a square steel rammer of size 150 mm and weight 10 kg to attain a bulk unit weight around 17.2 kN/m^3. The process

Table 2
Properties of sand and stone.

Parameter	Values	
	Stone	Sand
Specific gravity	2.65	2.67
Maximum dry unit weight (kN/m^3)	16.64	17.78
Minimum dry unit weight (kN/m^3)	14.13	14.63
Bulk unit weight for test at 70% relative density (kN/m^3)	15.80	16.70
Internal friction angle at 70% relative density (degree)	46	42
Uniformity coefficient (C_u)	2.51	2.43
Curvature coefficient (C_c)	0.95	0.98
USCS classification	GP	SP

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