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Technical note

Bearing capacity of horizontally layered geosynthetic reinforced stone columns

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ABSTRACT

In very soft soils, the bearing capacity of stone columns may not improve significantly due to very low confinement of the surrounding soil. Therefore, they may be reinforced with geosynthetics by using vertical encasement or horizontal layers. Very limited studies exist on horizontally reinforced stone columns (HRSCs). In this research, some large body laboratory tests have been performed on horizontally reinforced stone columns with diameters of 60, 80, and 100 mm and groups of stone columns with 60 mm diameter. Results show that the bearing capacity of stone columns increases by using horizontally reinforcing layers. Also, they reduce lateral bulging of stone columns by their frictional and interlocking effects with stone column aggregates. Finally, numerical analyses were carried out to study main affecting parameters on the bearing capacity of HRSCs. Numerical analysis results show that the bearing capacity increases considerably with increasing the number of horizontal layers and decreasing space between layers.

1. Introduction

Stone columns are often used as a proper ground improvement method to improve bearing capacity and reduce settlement of superstructures. In addition, because of high permeability of stone column material, consolidation rate in fine soils increases and liquefaction potential in liquefiable soil may also be reduced.

The bearing capacity of long ordinary stone columns (OSCs) with occurance of bulging failure at upper parts of the column mainly depends on confinement offered by surrounding soft soil. In very soft soils, OSCs may not offer significant load capacity due to very low lateral confinement (Nazari Afshar and Ghazavi, 2014). Thus, it is necessary to provide additional confinement by vertical encasing with geosynthetics (VESC) or using horizontal geosynthetic reinforcement layers (HRSC), as seen in Fig. 1.

Vertical encasing with geosynthetics was initially proposed by Van Impe (1989) and has been studied extensively using analytical solutions (Raithel et al., 2002; Wu et al., 2009; Pulko et al., 2011; Wu and Hong, 2014; Zhang and Zhao, 2015), experiments (Gniel and Bouazza, 2009, 2010; Wu and Hong, 2009; Murugesan and Rajagopal, 2010; Ghazavi and Nazari Afshar, 2013; Ali et al., 2012, 2014; Yoo et al., 2015; Miranda and Da Costa, 2016; Hong et al., 2016; Gu et al., 2016; Fattah et al., 2016; Ou Yang et al., 2017; Mehrannia et al., 2017; Debnath and Dey, 2017; Cengiz and Guler, 2018), and numerical methods (Murugesan and Rajagopal, 2006; Khabbazian et al., 2010; Lo et al., 2010; Keykhosropur et al., 2012; Elsawy, 2013; Almeida et al., 2013; Choobbasti and Pichka, 2014; Hosseinpour et al., 2014; Rajesh, 2016; Geng et al., 2016; Gu et al., 2017a, 2017b; Debnath and Dey, 2017). Most of analytical and numerical studies used unit cell concept that assumed infinitely wide loaded area with end-bearing stone columns having constant diameter and spacing, where the stone column and the surrounding soil were treated in axisymmetric conditions (Pulko et al., 2011) and some of studies considered real 3D geometry of single or group of encased stone columns (Keykhosropur et al., 2012; Khabbazian et al., 2010; Geng et al., 2016; Gu et al., 2017a, 2017b; Debnath and Dey, 2017).

Another alternative for reinforcing stone columns is the use of horizontal geosynthetic layers studied by Madhav (1982), Sharma et al. (2004), Ayadat et al. (2008), Wu and Hong (2008), Nguyen et al. (2013) and Prasad and Satyanarayana (2016). Also, Latha and Murthy (2007), Ali et al. (2012, 2014), and Hosseinpour et al. (2014) studied the behavior of HRSCs and compared them with VESCs.

For the first time, Madhav (1982) have performed small-scale in situ tests on HRSCs. Sharma et al. (2004), Ayadat et al. (2008) and Prasad and Satyanarayana (2016) performed a series of tests on single HRSCs with 60, 23 and 50 mm diameters, respectively and found that the load-carrying capacity of HRSCs increases with increasing the number of the horizontal reinforcing strips and decreasing the spaces between them.

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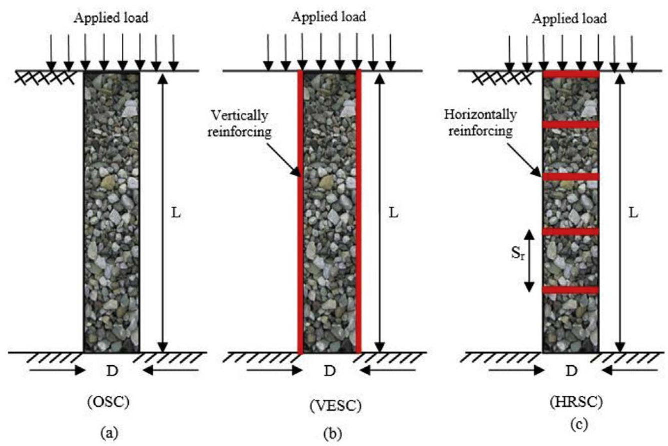

Fig. 1. Schematics of: (a) OSC; (b) VESC; (c) HRSC.

Wu and Hong (2008) developed an analytical method by using a normalized relation between the volumetric and axial soil strains to analyze the expansion of HRSCs. Nguyen et al. (2013) studied interactions between soil and geotextile layers by triaxial tests on sand columns, with 50 mm diameter, reinforced with horizontal layers of nonwoven geotextile. They studied strain and stress patterns generated on reinforcing geotextile sheets. They found that the peak of mobilized tensile force occurs at the center of the reinforcing sheets and reduces to approximately zero at the stone column periphery. Latha and Murthy (2007) used three reinforcing method, viz. horizontal layers, vertical encasement, and randomly distributed discrete fibers for a sand column with 38 mm diameter and 76 mm height in triaxial device. They compared stress–strain behavior of sand columns reinforced with horizontal layers and vertical encasement with the equal area of reinforcement material. Ali et al. (2012, 2014) performed tests on single stone columns with diameters 50 mm and group of stone columns with diameter of 30 mm for comparing the behavior of VESCs with HRSCs with various lengths for reinforced parts of columns. They found that the best result was achieved when the top half of the stone column length is reinforced with 0.5D spacing between layers, where D is the column diameter. Hosseinpour et al. (2014) conducted a numerical study to compare VESCs with HRSCs. Their analyses show that the best configuration for HRSCs is using reinforcing layers in 0.25D intervals along the full length of the column. Furthermore, by using the same amount of geosynthetic material, horizontally oriented reinforcement layers can be more effective than the vertical encasement.

As mentioned, the behavior of VESCs has been paid attention in the literature. However, there are very limited studies on HRSCs. In addition, most of previous experimental studies on HRSCs used triaxial test device with a constant confinement pressure, or very small scale model tests. Such tests have scale effects and the results may not simply apply to real scale stone columns. This paper presents results and findings of some large body experimental loading tests carried out on single and group of stone columns with various diameters reinforced with horizontal sheets. The main objective of this research is to investigate the effectiveness of horizontal reinforcement layers with various materials for stone columns with various diameters and then extending the findings of tests to large real stone columns by performing numerical analyses.

2. Experimental investigation

2.1. Material properties

Clay, crushed stone, two types of geotextile and one type of geogrid have been used as materials in this research. According to the Unified Soil Classification System, clay and stone materials were classified as CL and GP, respectively. Other properties of the stone column and clay bed materials are listed in Table 1.

Table 1
Properties of soil materials.

Stone column (GP)		Surrounding clay (CL)	
Parameters	Value	Parameters	Value
Specific gravity	2.7	Specific gravity	2.7
Maximum dry unit weight	16.6 kN/m^3	Liquid limit (%)	33
Minimum dry unit weight	14.9 kN/m^3	Plastic limit (%)	20
Bulk unit weight for test at 68% relative density	16 kN/m^3	Plasticity index (%)	13
		Optimum moisture content (%)	18
Internal friction angle (φ) at 68% relative density	46°	Maximum dry unit weight	16.8 kN/m^3
		Unit weight at 28% water content	19 kN/m^3
Uniformity coefficient (C_u)	2.16	Undrained shear strength	15 kPa
Curvature coefficient (C_c)	1.15	Compression Index	0.17
Modulus of elasticity (kPa)	40000	Modulus of elasticity (kPa)	900
Poisson's ratio	0.3	Poisson's ratio	0.45
Dilation angle	16°		

The selection of reinforcement material properties is an important task in laboratory model tests with respect to the scale effect concept and similarity analysis rules. According to similarity analysis rules, the value of the non-dimensional parameters for small scale model tests and large scale site stone columns must be the same as illustrated in Eq. (1):

$$\left(\frac{J_m}{\gamma_m D_m^2}\right) = \left(\frac{J_f}{\gamma_f D_f^{22}}\right) \tag{1}$$

where J is the reinforcement stiffness, D is the column diameter and γ is the stone column material unit weight and characters m and f denote the model and field conditions, respectively. Since the material unit weight of the model and field condition are very similar, it is concluded that the tensile stiffness of reinforcing material should be reduced by power two of the ratio of model size to prototype size. Reinforcement tensile stiffness for practical applications varies between 1000 and 4000 kN/m (Ghazavi and Nazari Afshar, 2013). Therefore, in the current research work for stone columns with 60, 80, and 100 mm diameters, two types of nonwoven polypropylene geotextile (GT1 and GT2 with secant stiffness of 16.36 kN/m and 35 kN/m, respectively) and one type of biaxial polyester geogrid (GG with secant stiffness of 250 kN/m and aperture size of 5*5 mm) were used as reinforcing material.

2.2. Experimental setup and test procedure

The test setup consists of a large steel tank with plan dimensions of 120 cm × 120 cm and 90 cm height. The plan dimension of tank was selected such that results of test would not be affected by boundaries of the tank. The loading mechanism is a displacement control system with a servomotor and related drive controls. More information about the test setup was described by Ghazavi and Nazari Afshar (2013). The test procedure involves application of the vertical monotonic load and determination of load-displacement behavior of the clay treated with stone column. After installation of the stone column, the vertical load was applied using a plate located in the center of the column and clay bed. The load was applied on the plate with a constant displacement rate of 1 mm/min.

2.3. Tests schedule

Totally 22 tests were performed on single stone columns and three tests were carried out on groups of stone columns (Table 2). Two