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Seismic behavior of geosynthetic encased columns and ordinary stone columns

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ABSTRACT

This study is concerned with evaluating and comparing the behavior of geosynthetic encased stone columns (GECs) and ordinary (conventional) stone columns (OSCs) during and after seismic excitations. For this purpose, well instrumented GECs and OSCs are installed in kaolinite clay beds consolidated in a large steel tank. In order to simulate the seismic behavior of columns supporting an embankment, surcharge loads are applied and the experimental setup is subjected to large-scale shaking table tests. The strains in the encasement are measured by making use of water-proof strain gauges during the course of the experiments. The vertical load capacities of GECs and OSCs after the seismic excitation were measured by a series of stress controlled column load tests. The experimental data at hand suggests that under the action of seismic loads there is a significant strain demand on the encasement confining the GECs. An almost linear relationship between the seismic energy input expressed in terms of IA (Arias Intensity) and reinforcement strain amplitude is observed. GECs in general have exhibited a superior performance both under static and seismic loads when compared to OSCs.

1. Introduction

Ground improvement using ordinary stone columns (OSCs) in soft clayey soils is a cost and time efficient soil remediation technique that has been practiced for decades. OSCs have been used in a wide spectrum of applications for enhancing the foundation soil properties of rigid and flexible structures such as buildings, embankments, and oil storage tanks that are founded on weak clays (e.g., Murugesan and Rajagopal, 2006, 2007, 2010; Gniel and Bouazza, 2010; Ali et al., 2012; Shahu and Reddy, 2014; Almeida et al., 2015). While OSCs have proven themselves to be a viable method, there are inherent shortcomings associated with the use of OSCs in soft soils. Early studies have pointed out that their stability is predominantly based on the available lateral support that is provided by the surrounding soil (Hughes and Withers, 1974; Hughes et al., 1975). When implemented in extremely soft soils ($s_u < 15$ kPa), the columns usually fail in bulging due to lack of lateral support that the weak soil can offer. One way to overcome bulging failure is to encase the granular column materials with a reinforcing geosynthetic and thereby forming a geosynthetic encased column (GEC) which increases column performance by providing lateral confinement (Raithel and Kempfert, 2000; Alexiew et al., 2005).

The engineering behaviors of OSCs and GECs have been studied by means of both laboratory and field experiments, finite elements methods, and analytical models. Most of the laboratory tests reported in the literature deal with physical modeling of columns with small scale models (e.g., Sivakumar et al., 2004; Gniel and Bouazza, 2009; Najjar et al., 2010; Miranda and Da Costa, 2016). Apart from the small scale tests, field testing of encased columns has also been the focus of research endeavor. Yoo and Lee (2012) have conducted full-scale load tests on geogrid-encased columns in soft ground. Hosseinpour et al. (2015) conducted field tests and reported that the presence of encasement around the column enabled the column to support 2.3 times the total applied vertical stress. Numerical models utilizing finite elements and finite difference methods have been developed to model GECs by Yoo (2015) and Yu et al. (2016), respectively. The open-source computational platform OpenSees was used to numerically model GECs by Tang et al. (2015). Castro (2017) demonstrated that the column arrangement had a small influence on the settlement reduction when the area replacement ratio and encasement stiffness to column diameter were kept constant. Hasan and Samadhiya (2017) ran small scale laboratory tests and 3D finite elements analysis utilizing PLAXIS. The results indicated that ultimate load intensity and stiffness of the soft clay increased due to geosynthetic encasement of granular columns. Most of the available experimental data pertains to the engineering behavior of GECs under vertical loading (e.g., Van Impe, 1989; Raithel et al., 2005; Black et al., 2007; Malarvizhi and Ilamparuthi, 2007; Alexiew et al., 2012; Dash and Bora, 2013; Gu et al., 2016; Hong et al., 2016; Debnath and Dey, 2017). To date, there are not many studies on

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the behavior of such columns under shear loading with the notable exceptions of Murugesan and Rajagopal (2009) and Mohapatra et al. (2016). Although there is an abundance of literature on the vertical stress-strain behavior of GECs and OSCs, there are not many studies in the literature on the behavior of GECs and OSCs under the action of dynamic loads. Guler et al. (2014) conducted a finite element analysis to model GECs under the action of seismic input motions and determined that implementation of GECs to support embankments underlain by weak soils greatly reduces the seismically induced settlements.

The aim of this study is to shed light into the seismic behavior of GECs and OSCs supporting earthen embankments underlain by weak clay. 1-g shaking table tests are conducted on OSCs and GECs. In industrial practice it is expected that GECs extend to a layer with a minimum SPT of 20. However in practice, OSCs sometimes extend to a bearing strata but often also remain floating. Therefore some of the OSC's were left floating and are designated as f-OSCs. In order to quantify the seismic behavior and performance of GECs, the settlement behavior of the GECs and strains occurring on GECs' during seismic excitation are quantified. A significant strain demand on the encasements was observed under the action of seismic loads. Post-dynamic-action load capacities of the columns are also studied by a series of stress controlled load tests. A relationship between the seismic input energy and reinforcement strain on GECs is also presented in this study.

2. Description of the experiment

2.1. Materials

The kaolinite clay that is used to form the clay bed is a commercially available kaolinite with a specific gravity (G_s) of 2.62, and plastic and liquid limits of 26% and 49%, respectively. The clay slurry was prepared at a water content of 75% which is approximately 1.5 times the liquid limit of the material. The ratio of undrained shear strength to consolidation pressure (c_u/σ_c) of the clay material obtained from small scale laboratory experiments was 0.2. When the clay is consolidated with an overburden pressure of 25 kPa, the resulting clay had a coefficient of permeability of 1.98×10^{-8} cm/s. While forming the GECs and OSCs, poorly graded sand and gravel materials were used as infill. The engineering properties of column infill materials are given in Table 1. The internal angle of friction of the infill materials are determined by large scale direct shear tests. Parameters such as the coefficient of uniformity is determined by making use of sieve analysis.

Three different geotextiles were used to encase the GECs. The first geotextile is a commercially available spun-bonded non-woven geotextile namely, TencatePolyfelt TS 10 (designated as GT1). The second and third geotextiles are Sefitec PP 50 and Stabilenka 100 which shall henceforth be designated as GT2 and GT3, respectively. The tensile strength tests of these samples are conducted on 200 mm wide samples in accordance with DIN EN ISO 10319 and relevant data is tabulated in Table 2. GT2 and GT3 have been provided by Huesker Synthetic GmbH in cylindrical form and GT1 is locally tailored with a longitudinal seam to achieve a cylindrical shape. All of the encasements had a diameter of 168 mm. The diameters of the model columns were selected so that the model columns will be representative of a field prototype with a diameter of 400 mm, equating the scale ratio roughly to 1: 2.5. Thus, the scaling factor (model/prototype) for the encasement tensile modulus has to be 6.25. Since the model reinforcement moduli (stiffnesses) for GT2 and GT3 are 400 and 1000 kN/m, the prototype equivalent of GT2 and GT3 are 2500 and 6000 kN/m. These values of reinforcement modulus fall well with the field practice.

Table 1
Engineering properties of infill materials.

Property	D_{10} [mm]	D_{30} [mm]	D_{60} [mm]	c_u	e_{max}	e_{min}	ϕ[°]
Sand	0.47	1.1	2	4.25	0.62	0.3	37
Gravel	5	6.1	7.9	1.58	0.94	0.43	44

Table 2
Tensile stiffness parameters of the geotextiles used.

Strain (%)	Tensile force (kN/m)			Secant modulus		
	GT1	GT2	GT3	GT1	GT2	GT3
2	0.72	7.6	21.6	36	380	1050
3	0.9	12.2	31.5	30	400	1050
5	1.25	21	60	25	420	1200
10	1.8	44	115	18	440	1150

GT1 is a non-woven geotextile with a very low tensile stiffness. GT1 served basically only as a bearing medium (carrier material) for the strain gauges rather than being a reinforcement. Gu et al. (2016) used a collar type sensor, namely, hoop displacement gauge for measurements of radial distortions of ordinary stone columns. In the absence of such equipment, a very low modulus geotextile was used to be able to observe ordinary stone columns' behavior under the action of seismic loads.

2.2. Preparation of the experimental model

In order to model the seismic behavior of an embankment on columns, a rigid steel box with inner dimensions of 0.52 m (width) by 2.5 m (length) was used. The height of the box was 2.2 m and the seismic excitations were applied to the box in the long direction. A sketch of the test setup is illustrated in Fig. 1. The setup provides space for 4 unit cells in which columns can be installed. The surcharge plates on top of the individual unit cells mimic the embankment load. In order to reduce the boundary friction, the inner periphery of the test box was covered with a layer of grease and a single layer of plastic sheet was applied over the greased surfaces. Ling et al. (2012) placed EPS blocks to minimize wave refraction from physical model boundaries. Similarly, in the current experiments, 150 mm thick EPS block layers were placed on the two longitudinal ends to prevent the seismic waves from reflecting back from the boundaries. Lombardi et al. (2015) has also demonstrated that including EPS blocks in the boundaries of a rigid box created absorbing boundary conditions and prevented generation and reflection of body waves from the boundaries.

At the base of the box, a 25 cm thick compacted sand layer is installed which is intended to provide a firm bearing stratum below the clay bed. The clay slurry is placed in a non-woven geotextile (500 g/m^2) wrap and the top portion of the geotextile is folded onto itself and sealed by silicone in order to prevent clay slurry from leaking out in the early stages of consolidation. The overburden pressure is applied to the top of the clay bed by making use of four pneumatic pistons. The piston rods applied a vertical pressure with the help of the 550 mm by 510 mm steel loading plates to consolidate the clay. The steel plates are placed on the geotextile wrap that housed the clay slurry and are perforated to allow for the water to drain freely. Water was allowed to drain towards the sides, where the thick nonwoven geotextile transmitted the water to the surface by its transmissivity. Drainage was also allowed through the perforations on the loading plates upwards.

A total of three 1.5 m deep clay beds were prepared within the scope of this study. The undrained shear strength profile of the clay beds are given in Table 3. The clay beds were consolidated under an overburden pressure of 25 kPa and upon completion of consolidation; GECs and OSCs were installed in the clay bed by displacement method. A stainless steel pipe having an inner diameter of 168 mm was pushed into the clay bed by making use of a one-meter-stroke pneumatic piston. The bottom end of the pipe was closed with a flat shoe which was left inside the clay bed, at the base of the installed column. The pipe was pushed through a guide so that the pipe was inserted inside the clay bed vertically. While