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Shaking table tests on geosynthetic encased columns in soft clay

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ABSTRACT

This paper presents the results of an experimental research on the behavior of geosynthetic encased stone columns and ordinary stone columns embedded in soft clay under dynamic base shaking. For this purpose, a novel laminar box is designed and developed to run a total of eight sets of 1-G shaking table tests on four different model soil profiles: Soft clay bed, ordinary stone column installed clay bed, and clay beds with geosynthetic encased columns with two different reinforcement stiffnesses. The geosynthetic encased columns are heavily instrumented with strain rosettes to quantify the reinforcement strains developing under the action of dynamic loads. The responses of the columns are studied through the deformation modes of the encased columns and the magnitude and distribution of reinforcement strains under dynamic loading. The response of the granular inclusion enhanced soft subsoil and embankment soil and the identification of the dynamic soil properties of the entire soil body are also discussed in this article. Finally, to determine the effect of dynamic loading on the vertical load carrying capacity, stress-controlled column load tests are undertaken both on seismically loaded and undisturbed columns.

1. Introduction

Growing demand on infrastructure projects and scarcity of land in urban areas are forcing many embankments to be built on soft soils. When the area of interest is in a seismically active zone, combined effects of soft soil conditions and seismic hazard constitute an unfavorable design scenario where advanced engineering measures should be taken. Conventional piles are often used to mitigate the effects of seismic loading on the structure that are underlain by soft clays. Zhang et al. (2016) has run centrifuge tests on a 4 × 3 pile-raft system embedded in soft kaolin clay bed to study the bending moments occurring on the piles due to seismic loading and the response of the raft under seismic excitation. Banerjee et al. (2014) has examined the seismic effects on piles installed in soft clays by means of centrifuge tests and numerical modeling.

While the literature on seismic behavior and performance of foundation systems with piles is plentiful, geosynthetic encased columns (GECs) received little attention as a countermeasure against seismic loading. Recently, the prospect of utilizing stone columns for enhancing the rocking foundation systems' performance has been investigated by (Liu and Hutchinson, 2018). GECs have proven themselves to be a cost efficient soft soil remediation technique for supporting superstructures with flexible and rigid foundations. Small scale laboratory tests (e.g., Black et al., 2007; Murugesan and Rajagopal, 2010; Ali et al., 2014; Debnath and Dey, 2017; Hasan and Samadhiya, 2017; Miranda et al., 2017; Ghazavi et al., 2018; Mazumder et al., 2018; Chen et al., 2018; Das Amit and Deb, 2018) and field tests (Yoo and Lee, 2012; Almeida Marcio et al., 2015) have demonstrated the benefits of installing GECs to withstand vertical loads.

The available literature on GECs rarely extends beyond the study of GECs subjected to static vertical loads. The exceptions to this are the studies conducted by Murugesan and Rajagopal (2009) and Mohapatra et al. (2016) where model ordinary stone columns (OSCs) and GECs embedded in sand are sheared in large scale direct shear type apparatus. Building on the experimental work on large scale direct shear apparatus, Mohapatra and Rajagopal (2017) have numerically modelled the shear behavior of GECs by making use of a finite difference software. Further, Mohapatra and Rajagopal (2017) have modelled the entirety of an embankment supported by GECs. Guler et al. (2014) have run a series of finite elements analysis utilizing DIANA to investigate the performance of OSCs and GECs under the action of seismic loads. The analysis has shown that GECs prevented excessive settlement of the superstructure. Tai et al. (2017) have studied the time-dependent clogging behavior of a stone column interacting with the surrounding host unit cell soil. Deb and Behera (2017) have mathematically modelled granular column installed soft ground by considering the

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variability of permeability and compressibility parameters consolidation.

In the currently available literature, very limited cases of soft soils tested under simulated seismic excitations is reported. The response and deformation characteristics of GECs under seismic loads is a relevant issue which has not received attention. Moreover, the prospect of improving the seismic performance of soft clay beds with GECs is also not investigated in the available literature. Cengiz and Güler (2018) have run shaking table tests on model OSCs and GECs embedded in soft kaolinite clay beds and established that there is a correlation between the seismic input energy and reinforcement strain.

This study aims to model soft clay beds, with and without column inclusions, subjected to dynamic base shaking. The dynamic excitations applied to the experimental models were sinusoidal acceleration time histories with varying frequencies and peak acceleration values and simulated earthquake accelerograms. A total of nine kaolinite clay beds are consolidated in a novel laminar box assembly which is specifically developed for this experimental research endeavor. The behavior and performance of OSCs and GECs embedded in soft clay beds and response of the column installed clay beds are investigated through a series of 1-G shake table tests.

2. Laminar box

Generally, flexible containers are designed as either passive or active containers for use in 1-G or at N-G (centrifuge) shaking table tests (Turan et al., 2009). Passive type flexible containers or more specifically laminar boxes constitute the vast majority of the cases reported in the literature. Passive laminar boxes are excited by a shake table; active containers are operated by horizontal acting actuators which displace the soil profile. Takahashi et al. (2001) developed an actively controlled laminar box to study the deformation of a pile due to large lateral movement under seismic loading. Prescribed acceleration or displacement time histories could be applied to the laminates of an actively controlled laminar box assembly to study the soil response to specific combinations of dynamic loads. In passively controlled laminar boxes, soil's free field response to input motions can be studied.

For the purposes of conducting this study, a passive type laminar box is developed and shaking table tests are conducted under 1-G conditions. The laminar box is square in plan with inner clearances of 900 × 900 mm. The height of the samples that can be accommodated in the laminar box is 1932 mm. A 300 mm deep rigid base cavity underlay the laminates. The laminar box consists of 16 individually supported laminate which are made up of aluminum sigma profiles. A vertical clearance of 2 mm is provided between the laminates. The sigma profiles used are rectangular in cross-section with a width and height of 50 and 100 mm, respectively. The laminar box design makes use of the hollow space at the center of the sigma profiles and smooth guide rods are placed throughout the sigma profiles in the direction of shaking. Teflon riders are fitted in the ends of the aluminum profiles so that there is minimum resistance to horizontal movement. Laminar box commissioned as such, enables purely horizontal laminate movements without causing any rocking or twisting with respect to vertical axis and diminishes the possibility of cantilever deformations and toppling of the laminar box. A sketch of a singular laminate is given in Fig. 1. Since the sigma profiles have hollow cross-sections, significant reduction in mass is achieved while retaining the flexural rigidity of the laminates which provides unyielding boundaries for the housed soil specimen. The resulting laminates have an assembly to soil mass ratio of about 7.5% which ensures that the inertia effects of the laminates are within tolerable limits to study the 1D response of the soil.

The laminar box assembly has a surcharge unit powered by four pneumatic pistons. The downwards force output from the pistons are applied to the top of the clay slurry with four 445 × 445 mm steel plates. The surcharge unit is used to consolidate the clay slurry. In order to push the casings into the clay bed, a casing pipe driving unit specially developed for the laminar box assembly is used. The casing driving unit is comprised of a one-meter-stroke pneumatic piston and casing is pushed through a guide collar to ensure the verticality of the resulting column inclusions. The laminar box is illustrated in Fig. 2.

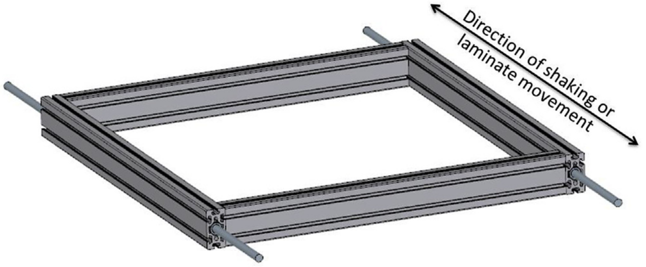

Fig. 1. Sketch of a singular lamina.

3. Materials

The soft clay beds were formed by using commercially available kaolinite clay with a specific gravity (G_s) of 2.62, and Liquid and Plastic Limits of 49% and 26%, respectively. The kaolinite clay slurry is prepared at a water content of 75%, which corresponds to 1.5 times the liquid limit of the material. Similar choice of water content for clay slurry has been reported by many studies (e.g., Murugesan and Rajagopal, 2010; Frikha et al., 2013). A poorly graded gravel was used as column infill material and in the formation of a 150 mm thick firm bearing layer located in the rigid base cavity. Due to the settlement of clay, top four laminates were devoid of any material at the end of the consolidation phase. With the intention of modeling an embankment fill, poorly graded sand was infilled into the void space provided by settlement of the clay. Relevant engineering parameters of sand and gravel are given in Table 1.

Two geotextiles were used in the making of 136-mm-diameter model GECs. The geotextiles used were Sefitec PP 50 and Stabilenka 100 which shall henceforth be named as GTX1 and GTX2, respectively. The wide width tensile strength test data provided by Huesker Synthetic GmbH for these geotextiles are given in Table 2. Since there is no commercially available geosynthetic encapsulation with a diameter of 136 mm, both geotextiles were stitched professionally by the producer and delivered to Karl Terzaghi Soil Mechanics Laboratory at Bogazici University. The bottom ends of the geotextiles were closed off with a circular geotextile cap.

It is intended to model prototype GECs of 340 mm diameter with model GECs of 136 mm diameter in which case the scale ratio becomes 1:2.5 (model/prototype). Since the scaling factor for the encasement tensile modulus is related with the square of the scale ratio (Hong et al., 2016), corresponding prototype encasement tensile modulus is 6.25 times that of the model encasements. Model reinforcement moduli (stiffnesses, J) for GTX1 and GTX2 are 400 and 1000 kN/m, the prototype equivalent of GTX1 and GTX2 are 2500 and 6000 kN/m. These values of reinforcement modulus are representative of middle and high strength reinforcement sleeves that are typically used in field applications.

4. Methodology

4.1. Clay slurry preparation, placement, and consolidation

Meymand (1998) used a specially constructed continuous progressive cavity mixer/pump to mix and pump the clay slurry into the testing assembly. In the present study, a simpler sample preparation and placement technique was adopted. Large stainless-steel drums were connected to a crane scale and suspended from an indoor crane. For every batch of clay slurry produced, 150 kg of tap water was filled