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Load-settlement response of shallow square footings on geogrid-reinforced sand under cyclic loading

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ABSTRACT

To study the settlement and dynamic response characteristics of shallow square footings on geogrid-reinforced sand under cyclic loading, 7 sets of large scale laboratory tests are performed on a 0.5 m wide square footing resting on unreinforced and geogrid reinforced sand contained in a 3 m × 1.6 m × 2 m (length × width × height) steel tank. Different reinforcing schemes are considered in the tests: one layer of reinforcement at the depth of 0.3B, 0.6B and 0.9B, where *B* is the width of the footing; two and three layers of reinforcement at the depth and spacing both at 0.3B. In one of the two double layered reinforcing systems, the reinforcements are wrapped around at the ends. The footings are loaded to 160 kPa under static loading before applying cyclic loading. The cyclic loadings are applied at 40 kPa amplitude increments. Each loading stage lasts for 10 min at the frequency of 2 Hz, or until failure, whichever occurs first. The settlement of the footing, strain in the reinforcement and acceleration rate in the soil have been monitored during the tests. The results showed that the ultimate bearing capacity of the footings was affected by the number and layout of the reinforcements, and the increment of bearing capacity does not always increase with the number of reinforcement layers. The layout of the reinforcement layers affected the failure mechanisms of the footings. Including more layers of reinforcement could greatly reduce the dynamic response of the foundations under cyclic loading. In terms of bearing capacity improvement, including one layer of reinforcement at the depth of 0.6B was the optimum based on the test results. It is found that fracture of geogrid could occur under cyclic loading if the reinforcement is too shallow, i.e. for the cases with the first layer of reinforcement at 0.3B depth.

1. Introduction

Geosynthetic-reinforced soils has been widely used in the construction of road, foundations, railway embankment, retaining walls and slopes to improve the stability, bearing capacity and stiffness of structures (Wang, 2006; Lambert et al., 2011; Moghaddas Tafreshi et al., 2011; Ahmadi and Hajialilue-Bonab, 2012; Yang et al., 2012, 2016; Bao et al., 2013; Javankhoshdel and Bathurst, 2016; Mehrjardi et al., 2016; Yu et al., 2016; Chen et al., 2018; Esmaeili et al., 2017; Hou et al., 2017; Mohapatra and Rajagopal, 2017; Sun et al., 2017; Jiang et al., 2018; Shadmand et al., 2018). Many researchers have experimentally studied the bearing capacity of footings on reinforced sandy soils (Shin et al., 2002a; b; Basudhar et al., 2007; Ghazavi and Lavasan, 2008; Vinod et al., 2009; Lavasan and Ghazavi, 2012, Huang, 2016a, b; Saha Roy and Deb, 2017; Shahin et al., 2017). Gabr et al. (1998) found that the inclusion of geogrid reinforcement could greatly change the stress distribution in soils below footings, thus increasing the bearing capacity of the foundations. Based on a series of large scale field tests on footings resting on reinforced sand, Adams and Collin (1997) found that the ultimate Bearing Capacity Ratio (*BCR*), which defines the ratio between the bearing capacities of footings on reinforced sand and those on unreinforced sand, could be as high as 2.5, but large settlement is required to reach those values.

There are many factors that could affect the performance of geosynthetic-reinforced foundations, such as soil geosynthetics interface interaction, number of reinforcement layers, reinforcement spacing, depth of the first reinforcement layer etc. Abu-Farsakh et al. (2013) and Gill et al. (2013) performed tests on geogrid reinforced foundations and suggested that, to improve *BCR*, the optimal number of reinforced layers was 3 or 4 layers, and the effective reinforcement depth was 1.25B–2.5B, where *B* is the width of footing. Park et al. (2013) studied the bearing capacity of sand-mat system on soft soils and found that the *BCR* could be increased up to 29.4 times depending on the setup of the sand-mat system, and the initial bearing capacity of the soft ground. Hegde and Sitharam (2017) studied the bearing capacity of 150 mm wide square footings on soils reinforced with geocell, geogrid cell and

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bamboo cell, and found that the improvement of *BCR* is the greatest in bamboo cell reinforced soils. The authors also performed 3D numerical analysis using FLAC^{3D}, and suggested that the geometry and strength of the geocells are the major factors that affect the *BCR*.

Limited study has been performed on the behavior of geosynthetic-reinforced foundations under cyclic loading. Most existing studies are on strip footings or planar-reinforced foundations (Das and Shin, 1996; Das, 1998; Ghazavi and Lavasan, 2008; Moghaddas Tafreshi and Khalaj, 2008; Boushehrian et al., 2011; Moghaddas Tafreshia and Dawson, 2012; Qian et al., 2012). Shin et al. (2002b) investigated the effect of geogrid reinforcement in reducing the settlement of a railroad bed and sub-ballast layer under cyclic loading, and found that including one layer of geogrid at the interface of the subgrade soil and the sub-ballast course is the most effective measure. Moghaddas Tafreshia et al. (2014) stated that "geosynthetic inclusions would be most effective if used in the zone significantly stressed by the loading surface (e.g. footing or tire wheel) which may be over a depth of 1 or 2 width/diameters beneath the footing/tire wheel". Raymond (2002) found that under cyclic loading, reinforcement is more effective when the foundation soil is in a loose condition, especially in reducing plastic settlement. Moghaddas Tafreshi and Dawson (2010a, b) reported that under cyclic loading, for the same mass usage of geotextile, the geocell-reinforcement system is stiffer and more effective than the system with planar reinforcement system in improving the bearing capacity and reducing footing settlement.

Considering that the stress distribution and influence depth of square footings are different from those of strip footings, the reaction of reinforced soils subjected to cyclic rectangular loading could be different. This paper studies the effect of reinforcement depth, number of reinforcement layers and the depth of the first reinforcement layer on the behavior of shallow square footings under cyclic loading using a series of large-scale laboratory model tests. A 0.5 m wide square footing resting on geogrid reinforced dense sand in a 3 m long, 2 m deep and 1.6 m wide steel box was tested using an MTS electro-hydraulic servo loading system. Unreinforced sand and sand reinforced with one, two and three layers of reinforcements were tested. Reinforcement layers were placed at the depth of 0.3B, 0.6B and 0.9B below the sand surface. Stage cyclic loading was applied to the footing. Each loading stage lasted for 10 min (or till failure, whichever occurs first) at the frequency of 2 Hz. The settlement of the footings, strain in the reinforcement layers and acceleration rates of the soils at different depths were monitored to investigate the response of the foundations under different reinforcing schemes.

2. Experiment

2.1. Materials used in the tests

River sand obtained from a local river bank in Liuzhou, Guangxi Province was used in the tests. The particle size distribution of the sand is shown in Fig. 1. According to the Unified Soil Classification System, the soil can be classified as well-graded sand (SW). The specific gravity of the sand was 2.65. The sand had a moisture content of 6.87% at its natural condition when tested. During the tests, the sand was compacted to an average bulk density of 18.1 kN/m^3. The friction angle of the dry sand was 39°.

A commercially available geogrid (aperture size 40 mm × 40 mm) was used for reinforcement in the experiment. Typical tensile behavior of the geogrid is shown in Fig. 2. The ultimate tensile strength of the geogrid was about 31.4 kN/m, at the failure strain of about 11.4%.

2.2. Experiment setup

The experiment setup comprises an MTS electro-hydraulic servo loading system, sand box, monitoring and data acquisition system as shown in Fig. 3. The loading capacity of the MTS loading system is 250 kN. As recommended by Liu (2012), sinusoidal wave type of cycle loading was used to simulate traffic load. The function of the cyclic loading (P) is described as:

$$P = P_0 + P_A \sin(2\pi f t) \quad (1)$$

where P_0 is the mean value, P_A is the amplitude, and f is the frequency of the cyclic loading respectively.

The inner dimension of the sand box was 3 m long, 1.6 m wide and 2 m high. Steel channel sections and angle sections were used to strength the walls and corners for the box. The side walls were made of 6 mm thick steel plate. The front wall was made of a 20 mm thick tempered glass panel for observation purpose. The experimental setup is shown in Fig. 3. A 30 mm thick 50 cm wide steel plate was used to model a rigid square footing (Engineering Geology Handbook Compilation Committee, 2007).

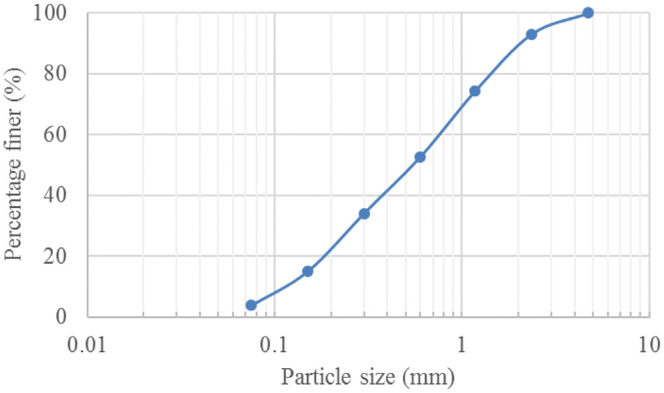

Fig. 1. Particle size distribution of the river sand used in the tests.

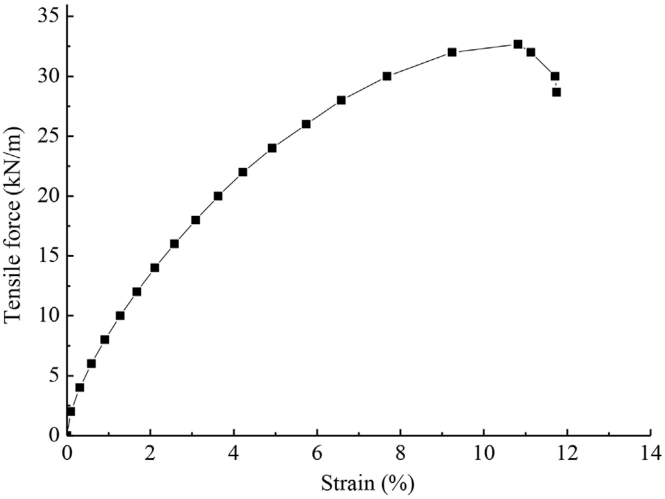

Fig. 2. Tensile behavior of a typical geogrid sample.

2.3. Measuring and data acquisition system

The settlement of the footing was monitored using the displacement transducer built in the MTS loading system. Flexible displacement meters were installed on the geogrid at 0B, 0.3B 0.5B and 1.0B away from the centerline of the footings. Dynamic accelerometers were used to monitor the dynamic response of the foundation soil. A typical layout of the instrumentation used in the tests is shown in Fig. 4.

2.4. Experimental scheme

Seven sets of tests were performed on footings resting on: