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Experimental and numerical investigations of the behaviour of footing on geosynthetic reinforced fill slope under cyclic loading

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A B S T R A C T

This paper investigates the cyclic loading responses of a strip footing supported by a geosynthetic reinforced fill embankment. A series of large-scale model footing tests were conducted first to investigate the accumulation of permanent footing displacement and residual vertical soil stress over large number of load cycles. The embankment fill was a heavily compacted silty sand and the reinforcement was a flexible geogrid, so that the model test configurations were representative of actual field conditions. Both permanent displacement and residual stress accumulated asymptotically with load cycles and majority of the build-up occurred over the first few hundred cycles. The potential effect of load interruptions was part of the study. Depending on how cyclic load interruption was implemented, it may or may not induce a trailing effect on subsequent cyclic loading responses. To have more in-depth understanding, these footing tests were also investigated numerically based on a soil model that can capture the unload-reload stress-strain loop over large number of load cycles. Reasonably good agreement between experimental observations and numerical predictions was also achieved.

1. Introduction

Footings may need to be constructed on or near the crest of a fill slope. In addition to dead load, it is often subjected to live loads of different types such as cyclic loading. Bridge abutment constructed on embankment slope subjected to traffic loading condition is one of the common examples of such type of footings. These days, there is an extensive interest of using reinforcing elements embedded in the soil mass to improve the performance of the slope when subjected to cyclic loading. In practice, the design of a footing on a reinforced fill slope is often based on approximations that consider an "equivalent" monotonic load and the use of a large factor of safety. Main reason behind this practice is the lack of knowledge on progressive accumulation of displacement behaviour under cyclic loading conditions. It is pertinent to emphasise that, for this type of problems, the fill is generally densely compacted, and a large number of load cycles has to be considered.

Experimental studies on the behaviour of model footing on geosynthetic reinforced level ground (Boushehrian et al., 2011; Correia and Zornberg, 2018; Das and Shin, 1994; Mehrjardi and Khazaei, 2017; Puri et al., 1993; Sawwaf and Nazir, 2010; Yeo et al., 1993) or fill slope (Islam, 2013; Islam and Gnanendran, 2013; Sawwaf and Nazir, 2012) under cyclic loading conditions are available in the literature. However, utilising the findings of these experimental studies to predict the performance of reinforced slope subjected to large number of load cycles under field conditions present severe challenges. Furthermore, in practical cases, footings under cyclic loading (such as bridge abutments) experience load interruptions. These load interruptions may or may not affect subsequent accumulation of footing displacement and residual soil stress. Nevertheless, at the time of conducting this research, the authors were not aware of any study which addressed the effect of load interruptions during the cyclic loading period, but this aspect is pertinent to a footing in practical conditions.

A number of analytical and numerical studies (Ahmadi and Eskandari, 2014; Ahmadi et al., 2016; Alamshahi and Hataf, 2009; Ghazavi and Lavasan, 2008; Harikumar et al., 2016; Hegde and Sitharam, 2015; Latha and Rajagopal, 2007; Lee and Manjunath, 2000; Sawwaf, 2007; Selvadurai, 2009; Thanapalasingam and Gnanendran, 2008) on the behaviour of footings on reinforced fill are available in the literature but these studies are restricted to static loading conditions. Published literature on numerical studies on the response of a footing on well-compacted unreinforced and reinforced soil under cyclic loading is very limited and the modelling approaches adopted are also unclear in the publications (Biabani et al., 2016; Boushehrian et al., 2011; Tafreshi et al., 2011). A numerical study of a model circular footing on an unreinforced silica sand under cyclic loading condition was performed by Tafreshi et al. (2011) using the finite difference

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software *FLAC3D*. The Mohr-Coulomb (MC) material model was used for the soil elements. The stress-strain responses obtained from simulations were compared with the experimental data for first few loading cycles. However, the behaviour of permanent footing displacement was not reported in this study. The MC material model in *FLAC* is a strength model in the sense that the MC function is taken to be both the failure surface and the yield surface for perfect plasticity formulation, and pre-failure stiffness is characterised by Young's modulus. Therefore, it was not clear how the accumulation of permanent footing displacement with load cycles was captured. Boushehrian et al. (2011) performed a numerical study on the displacement behaviour of a model footing on unreinforced and geogrid-anchored reinforced sand under cyclic loading conditions using *PLAXIS3D*, an off-the-shelf finite element analysis software. The built-in hardening soil model was used to represent the behaviour of soil elements for which the input parameters were selected to provide a reasonable match with the test data. However, this model did not have any feature to capture the permanent strain accumulation in an unloading-reloading cycle. As reported in this study, the computed accumulation of permanent displacement with load cycles was expected to be due to the effect of stress re-distributions and thus changes of stiffness of the soil with stress state. The analyses were performed for only a small number of loading cycles (about 20). Biabani et al. (2016) investigated the displacement behaviour of a railway slipper on a geocell reinforced granular sub-ballast material under cyclic loading conditions using the finite element software ABAQUS. The Drucker-Prager strength model was used for the sub-ballast, whereas a linear elasto-plastic material model was adopted for the geocell element for which the elastic properties were obtained from laboratory experiments. Interface elements were also used in the contact surface between geocell and granular material for which the properties were obtained from direct shear test results. The results from the analyses were compared with the experimental data. However, the Drucker-Prager material model is a strength model (similar to the MC model but with the intermediate principal stress included in the failure and yield surface function) and again it was not clear how the accumulation of permanent strain was captured. Furthermore, none of the numerical studies found in the literature considered the involvement of a slope in the soil mass.

An appropriate material model for soil, which can capture the unloading-reloading stress-strain behaviour, is necessary to predict the accumulation of permanent deformation with load cycles (N). A number of such material models for soil (Byrne et al., 2004; Dafalias, 1986; Lashkari and Golchin, 2014; Li, 2002) are available in the literature. However, these models were calibrated for a very small number of N focusing on liquefaction behaviour of loose to medium dense sand. Also, the input parameters for these models were difficult to determine. For a densely compacted sandy soil, with a slow rate of strain accumulation with N, the effect of cyclic loading is only important when a large number of load cycles has to be considered. For such type of problems, an alternative modelling approach originated mainly from pavement engineering is to consider the unloading-reloading responses as elastic. Analysis based on such an approach cannot trace the accumulation of deformation with N. The accumulation of permanent strain or deformation with N, expressed as a multiplier of the resilient strain, is separately established by empirical correlations that may take into account the effect of stress level, stress amplitude and frequency, density and moisture content of the soil etc. Therefore, this is fundamentally an equivalent monotonic approach that factor in a number of empirical correlations.

The investigations of this paper are presented in two sections. The first section discusses the experimental investigation of the behaviour of a large-scale model footing on a flexible geogrid reinforced sandy fill slope under cyclic loading conditions. The behaviours of permanent footing displacement, footing tilting and residual vertical soil stress at different depths of the soil mass under cyclic loading conditions are investigated. The effect of any load interruptions on displacement and stress behaviour is also investigated in this section. In the second section, attempts are made to predict the responses of the model studies using a numerical analysis developed by Alam et al. (2017).

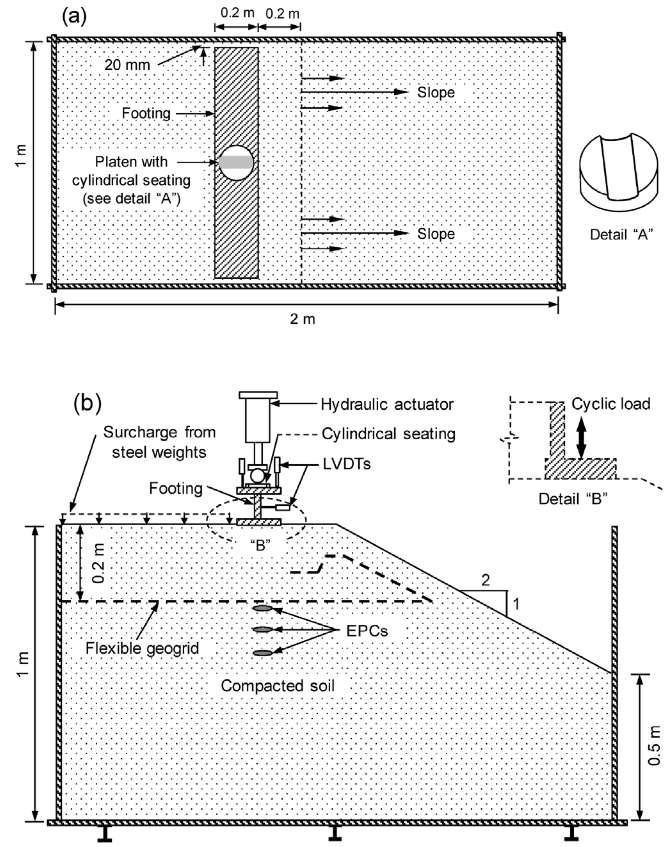

Fig. 1. Model footing testing arrangement; (a) plan view and (b) elevation.

2. Large-scale model footing testing

In order to investigate the footing displacement and soil stress behaviours, a series of large-scale laboratory experiments of a model footing on flexible geogid reinforced dense sandy soil was conducted. The testing arrangement is presented in Fig. 1 which comprised of a rectangular box, a footing, a flexible polyester geogrid reinforcement, a hydraulic actuator, a load cell, displacement transducers, pressure cells and a data acquisition (DAQ) system. The steel made rectangular box had a dimension of 2 m (length) × 1 m (width) × 1 m (height). The side walls of the box were stiffened with channels to ensure that no lateral deformations occurred due to earth pressure induced by the application of loading. The side walls were also galvanised to minimise the friction between sand and the walls. The footing was a 0.2 m wide I-beam for the application of axial loading. The length of the footing was 0.96 m which provided 20 mm clearance with the side walls as shown in Fig. 1(a) and therefore the testing condition was essentially plane-strain. The model footing represents, approximately, the central portion of a strip footing. The axial loading from the actuator was applied without inducing any moment via a spherical rotational connection. The footing had a cylindrical seating (see detail "A" in Fig. 1(a)) so that the footing was allowed to move freely in the horizontal direction towards the slope without any restraint from the actuator. A fully rough contact with the underlying soil was achieved by cementing a thin layer