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Centrifuge model tests of deformation and failure of nailing-reinforced slope under vertical surface loading conditions

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Abstract

A series of centrifuge model tests was conducted on a nail-reinforced slope under vertical surface loading conditions considering different slope gradients and nail lengths. The ultimate load of the slope decreased significantly with the increasing gradient of the slope or the decreasing nail length. The slope exhibited significant progressive failure that was captured by a displacement-based analysis. At first, the vertical load caused local slippage near the slope toe and the inner edge of the loading plate. Then, it extended to the interior of the slope and eventually to an entire slip surface. The *H-surface* was obtained according to the measured displacement to distinguish the zone where the surface load influenced the horizontal displacement of the slope. The *H-surface* and the position where the peak vertical displacement occurred in a horizontal line moved from the internal slope to the slope surface from the slope top to the slope bottom. This demonstrates the dispersion of the surface load application within the slope. The deflections of nails can be obtained from the corresponding soil deformation. The deflection of nails increased with the increasing load pressure, and exhibited diverse features in its distribution in the upper and the lower parts of the slope.

Keywords: Slope; Reinforced soils; Soil nailing; Failure; Centrifuge modelling (IGC: E06, E12, E14)

1. Introduction

Soil nails have been widely employed to improve the stability level of slopes as a cost-effective stabilising measure (e.g., Nowatzki and Samtani, 2004; Turner and Jensen, 2005). Methods based on the limit equilibrium or a limit analysis have usually been used in the design of soil–nailed structures (e.g., Shen et al., 1981; Juran et al., 1990), which are incapable of considering the soil–nail interaction reasonably. The finite element method and other types of numerical methods have also been developed or used to analyse the behaviour of nail-reinforced slopes (e.g., Kim et al., 1997; Yang and Drumm, 2000; Gui and Ng, 2006; Zhou et al., 2009).

The response of full-scale nailed slopes has been observed and measured in order to evaluate the safety levels of the slopes and to analyse their behaviour rules (e.g., Andrzej et al., 1988; Guler and Bozkurt, 2004; Turner and Jensen, 2005). As one of the most successful geotechnical laboratory techniques, centrifuge modelling has been widely used for studying the behaviour of reinforced slopes, since gravity-related deformation and failure can be

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simulated effectively (e.g., Zornberg et al., 1998; Zhang et al., 2001; Hu et al., 2010; Wang et al. 2011). Wang et al. (2010) performed centrifuge model tests to compare the response of nail-reinforced and unreinforced slopes under earthquake conditions. The nails were discovered to not only significantly decrease the deformation with more uniform distribution within the slopes, but also to arrest the possible failure that would occur in unreinforced slopes.

The footings have often been placed on different types of slopes, and have provided a surface load on the slopes. Thus, the surface loading conditions of slopes should be of concern. The bearing capacity of footings on slopes is usually significantly smaller than that of footings on the level ground, and therefore, the slopes have often been reinforced using different structures. A number of model tests and numerical analyses have been employed to study the behaviour of footings on reinforced slopes, including influence factors and failure mechanisms (e.g., Lee and Manjunath, 2000; Yoo, 2001; Alamshahi and Hataf, 2009; Sommers and Viswanadham, 2009). El Sawwaf (2005) conducted a series of laboratory model tests to investigate the behaviour, with the influence rules of different factors, of a strip footing on a sandy slope reinforced by a row of piles and a sheet pile.

Most of the previous investigations have focused on the limit bearing capacity of footings on slopes; however, very few researches have dealt with the deformation and the failure process of slopes. Significantly, the bearing capacity of a footing is often determined according to the settlement limit for deformation control. It should be recognised that evaluations of the bearing capacity of footings on slopes depends on the understanding of the deformation and the failure mechanism under surface loading conditions. Therefore, a systematic investigation is required on the deformation-failure behaviour of nail-reinforced slopes due to the application of surface loading. Centrifuge modelling is an effective approach for a thorough insight into the behaviour of nail-reinforced slopes under surface loading conditions, although such tests have hardly been conducted up to now.

In this study, a series of centrifuge model tests was conducted on a nail-reinforced slope under vertical surface loading conditions. The gradient of the slope and the nail length were varied to examine their effects on the response of the slope and of the nails. The response in the load–settlement relationship of the loading plate and the displacement of the slope was measured during the loading process. The deformation behaviour and the failure process of the slope were analysed using a displacement analysis and a strain analysis. In addition, the response of the nails was examined by measuring their deflections.

2. Description of model tests

2.1. Devices

The 50 g t geotechnical centrifuge at Tsinghua University, with a maximum acceleration of 250g, was used for the centrifuge model tests. The model container used for the tests was made of aluminium alloy, 500 mm in length, 200 mm in width, and 350 mm in height. A vertical loading device was installed at the top of the model container. This device can provide a vertical load with a capacity of 10 kN on the loading plate through the shaft, which was driven by an electric motor and a corresponding reducer (Fig. 1(a)). The loading rate was maintained during the tests and could be adjusted in advance of the tests. The loading plate consisted of a pair of steel plates with a few rolling contact bearings between them so that the horizontal friction between the loading plate and the soil could be eliminated and only the vertical load was applied to the top of the slope. The loading plate was 198 mm long in the orthogonal direction to the slope, which was

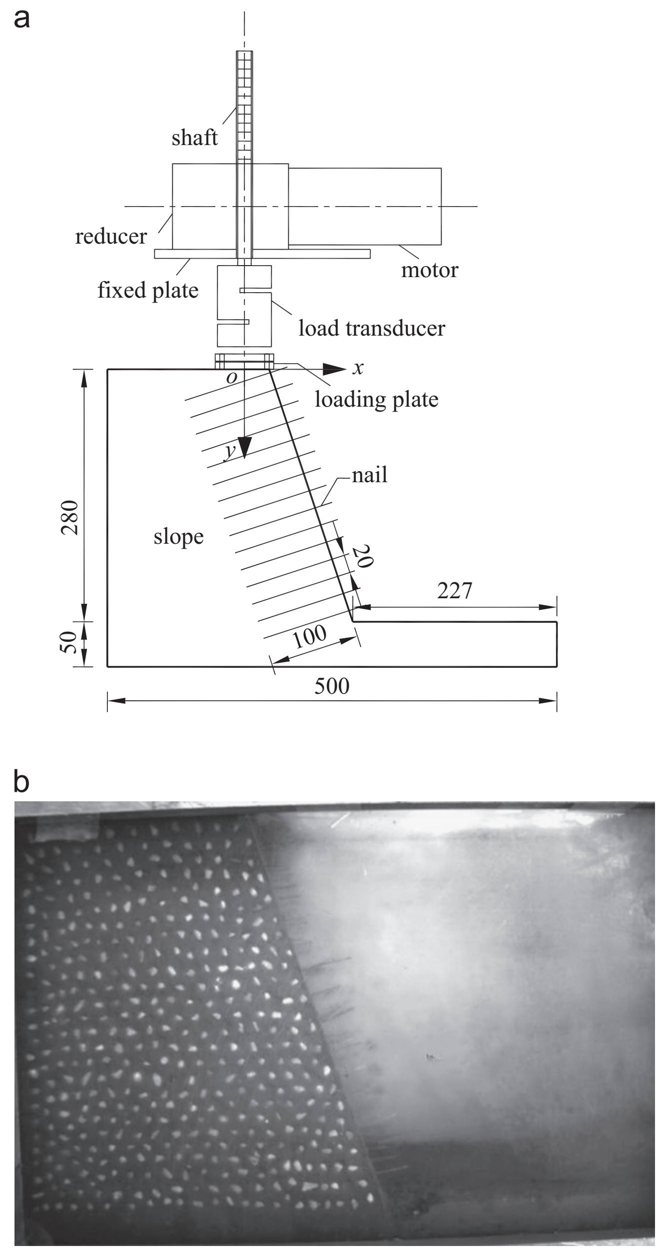

Fig. 1. Schematic views of test model for 3:1 slope with nail length of 100 mm. (a) Elevation view with loading device (unit: mm), (b) Image of slope model.