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Failure behavior and mechanism of slopes reinforced using soil nail wall under various loading conditions

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Abstract

Soil–nailing technology is widely applied in practice for reinforcing slopes. A series of centrifuge model tests was conducted on slopes reinforced with a soil nail wall under three types of loading conditions. The behavior and mechanism of failure process of the reinforced slopes were studied using image-based observation and displacement measurements for the slope, nails, and cement layer. The nailing significantly increased the stability level and restricted the tension cracks of the slopes. Increasing the nail length improved the stability of the reinforced slopes with deeper slip surfaces. The reinforced slope exhibited a significant failure process, in which slope slippage failure and cement layer fracture occurred in conjunction with a coupling effect. The deformation localization was induced by the loading within the slope and ultimately developed into a slip surface. The nailing reinforced the slope by significantly delaying the occurrence of the deformation localization within the slope. The failure of nails was recognized as a combination of pull-out failure and bend deformation. The loading conditions were shown to have a significant effect on slope deformation and nail deflection, and they consequently influenced the failure behavior and its formation sequence.

Keywords: Slope; Reinforced soils; Soil nailing; Failure; Centrifuge model test

1. Introduction

As soil–nailing technology is increasingly applied to reinforce slopes, the number of studies on the design of nail-reinforced slopes has also increased. The effective designing method depends on the robust evaluation of the stability level of the reinforced slopes, which should be based on a sound understanding of failure behavior and reinforcement mechanisms.

A diverse range of methods have been proposed for analyzing the stability of nail-reinforced slopes, including the limit equilibrium method, the finite-element method, and the kinematics method. Based on the different hypotheses for slope failure surface and/or the soil–nail interaction model, soil nail behavior was analyzed and the design was optimized with respect to various parameters, including length, spacing, inclination, diameter and geometric arrangements (e.g., Shen et al., 1981; Juran et al., 1990; Kim et al., 1997; Yang and Drumm, 2000; Guler and Bozkurt, 2004; Cheuk et al., 2005; Patra and Basudhar, 2005; Gui and Ng, 2006). A non-linear finite element program, PLAXIS, used to analyze the stability level of nail-reinforced slopes has revealed that the optimal nail orientation decreases as the gradient of the slope increases (Fan and Luo, 2008).

The reinforcement effect and mechanism for soil nailing in slopes was investigated via observations of the strain-stress

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performance of nails, the safety level of soil nail wall, and the soil–nail interaction (e.g., Wong et al., 1997; Junaideen et al., 2004; Zhou and Yin, 2008; Zhou et al., 2009). The strength reduction method and the limit equilibrium method were utilized to analyze the soil–nail interaction in reinforced slopes and showed that failure modes influence the line of maximum tension (Wei and Cheng, 2010).

Field observation has played an important role in understanding the behavior of slopes reinforced with soil nailing (e.g., Andrzej et al., 1988; Nowatzki and Samtani, 2004). Another study analyzed the response of a full-scale nail-reinforced slope using observed and measured data (Turner and Jensen, 2005). Centrifuge model tests have been effectively used to explore the deformation and failure behavior of nail-reinforced slopes under various loading conditions through producing an equivalent gravity-induced stress field between the model and prototype (e.g., Zornberg et al., 1997; Zhang et al., 2001; Wang et al., 2010). The aseismic nail-reinforcement mechanism was demonstrated by comparing the deformation between reinforced and unreinforced slopes via centrifuge model tests under earthquake conditions (Wang et al., 2010) and 1*g* shaking table tests (Tatsuoka et al., 2012). Zhang et al., (2013) employed centrifuge model tests to analyze the deformation behavior and failure process of a nail-reinforced slope under the surface loading condition, and they illustrated the influence rules of different nail layouts.

The objective of this paper is to investigate the failure mechanism of slopes reinforced with soil nail wall using serialized centrifuge model tests. The steps were as follows: (1) the shotcrete wall and different loading conditions were simulated to systematically understand the actual response of the reinforced slopes; (2) the failure modes were clarified according to the test observations; (3) the slope failure process, together with the fracture and deformation of the reinforcement structures, was captured according to the test observations and measurement results: and (4) the failure and reinforcement mechanisms were elucidated through integrated analysis of the deformation and failure processes, which was accomplished by accurately measuring the displacement of entire slopes.

2. Tests

2.1. Schemes

All centrifuge model tests were conducted using a 50*g*-ton geotechnical centrifuge at Tsinghua University, which has an effective radius of 2 m and a maximum centrifugal acceleration of 250*g*. The deformation and failure processes of nail-reinforced cohesive soil slopes were observed under different loading conditions, including self-weight loading, vertical loading on the top of the slope, and excavation at the toe of the slope (Table 1, Fig. 1).

The slope gradient and nail length were varied to investigate their influence on the response of the reinforced slopes. The gradients of slope for the tests ranged from 1.2:1 to 5:1 (Horizontal:Vertical). Three nail lengths from 4 cm to 8 cm were used in the tests. Unreinforced slopes were also simulated for comparison with the reinforced slopes, to analyze the reinforced mechanism.

Table 1
List of centrifuge model tests.

Loading condition	Gradient (V:H)	Nail length (cm)	No.
Self-weight loading	5:1	8	G5-R8-S
		4	G5-R4-S
		–	G5-U-S
	3:1	8	G3-R8-S
		6	G3-R6-S
		4	G3-R4-S
Excavation	3:1	8	G3-R8-E
	2:1	8	G2-R8-E
		6	G2-R6-E
		4	G2-R4-E
	1.2:1	8	G1.2-R4-E
Vertical loading	3:1	8	G3-R8-L
		6	G3-R6-L
	2:1	6	G2-R6-L

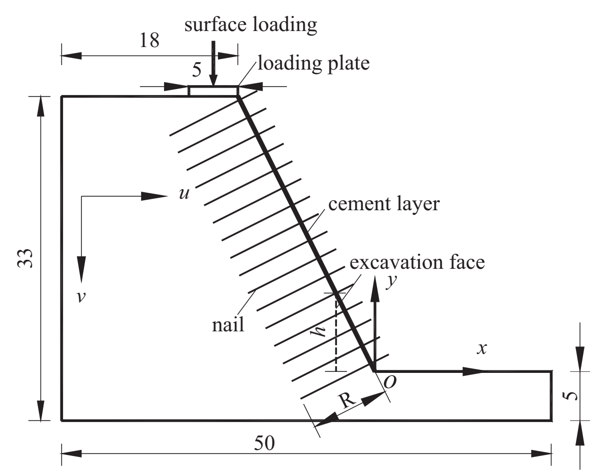

Fig. 1. Schematic views of test model under different loading conditions applied to the slope in various separate tests (unit: cm).

2.2. Model preparation

The model slope was placed in an aluminum alloy model container that was 50 cm in length, 20 cm in width, and 35 cm in height. All the slope models were 28 cm in height with a 5-cm-deep horizontal ground layer. The container sides in contact with the slope were coated with silicone. This measure, together with the ground layer, was used to diminish the influence of the model container on the slope response.

A cohesive soil with a specific gravity of 2.7 was retrieved from the soil base of a high-rise building in Beijing for use in the slope model in the tests. The liquid limit and plastic limit of the soil were 33.5% and 15.5%, respectively; indicating that the soil is a type of clay. The average particle size (d_{50}) of the clay was 0.01 mm, and particle sizes d_{10} and d_{60} of the clay were 0.001 mm and 0.02 mm, respectively. The maximum density of the clay was about 1.8 g/cm^3. The soil was