Engineering Geology 204 (2016) 65–76

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Model testing of the response of stabilizing piles in landslides with upper hard and lower weak bedrock

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ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 1 February 2016
Accepted 4 February 2016
Available online 6 February 2016

Keywords:
Landslide
Stabilizing pile
Physical model test
Bedrock with a hard upper layer and a weak lower layer
Embedded length

ABSTRACT

The behavior of stabilizing piles with different embedded lengths in bedrock with a hard upper layer and a weak lower layer is examined using physical model tests. Based on the geological model of the landslide with bedrock with a hard upper layer and a weak lower layer, the pile–landslide physical model is developed and includes the data collection system, the pile–landslide model and the loading system. The real-time deformation and moment of the stabilizing pile is obtained in the process of loading at the trailing edge of the landslide for different percentages of hard bedrock. The test results indicate that the percentage of hard bedrock has a strong influence on the deformation and moment of the stabilizing pile embedded in bedrock with a hard upper layer and a weak lower layer. A higher percentage of hard bedrock can result in a greater maximum bending moment of the stabilizing pile and a smaller displacement at the stabilizing pile head, and vice versa. The results also show that 40% of hard bedrock can be considered the critical condition in bedrock with a hard upper layer and a weak lower layer. The percentage of hard bedrock has a limited influence on the deformation of the stabilizing pile when the percentage is greater than 40%. Moreover, four tests with stabilizing piles with different embedded lengths are conducted to investigate the most suitable embedded length in the bedrock with a hard upper layer and a weak lower layer. The results indicate that 28.5 cm is a reasonable embedded length for the stabilizing pile in the two-layered bedrock with a hard rock percentage of 20%.

1. Introduction

Colluvial landslides in the Jurassic strata regions of the Three Gorges Reservoir region in China are common and have been widely reported in the literature (Wu et al., 2001; Wang et al., 2005; Wen et al., 2007; Zhou et al., 2014; Peng et al., 2014; Miao et al., 2014, Li et al., 2015). Laterally loaded stabilizing piles are commonly used to reinforce the stability of colluvial landslides. Generally, laterally loaded piles are designed to be embedded in bedrock at a certain depth to transfer the driving force of a landslide to the bedrock. Consequently, there has been growing interest in investigating the mechanism and deformation behavior of laterally loaded piles (Jongmans, 1996; Jeong et al., 2003; Ashour and Ardalan, 2012; Li et al., 2013a; Karim, 2013; Georgiadis, 2014). However, previous studies have focused on the behavior of laterally loaded piles in homogenous bedrock (Ito and Matsui, 1975; Viggiani, 1981; Reese et al., 1992; Lee et al., 1995; Won et al., 2005; Kahyaoğlu et al., 2012; Li et al., 2013b; Sánchez and Roesset, 2013; Gu et al., 2014). With additional in situ monitoring and tests of piles in the field (Frank and Pouget, 2008; Kang et al., 2009; Song et al., 2012; Lirer, 2012; Nunez et al., 2013), researchers have realized that bedrock may be multi-layered rather than homogenous, a finding that has also been validated by the exploration of landslide sites (Li et al., 2014). Therefore, it is important to study the behavior of stabilizing piles in bedrock with different layers.

In the analysis of piles subjected to horizontal movements in a multilayer medium, Martin and Chen (2005) examined the effects of spatial variations in soil displacement on the response of piles and pile groups caused by lateral soil movements using a numerical modeling method. Conte et al. (2013) conducted a study on the response of reinforced concrete piles to horizontal loading in multi-layered soils composed of silty sand and sandy silt. Salgado et al. (2014) proposed a semi-analytical method of calculating the response of a pile group in multi-layered elastic soil. Finally, Lei et al. (2015) analyzed the response of laterally loaded piles in a multilayer elastic soil using the separation-based continuum method.

A model test is an effective way to investigate the behavior of stabilizing piles (Zhu et al., 2012, 2014, 2015; Guo, 2015), and a number of laboratory physical model tests (Pan et al., 2002; Zomorodian and Dehghan, 2011) and centrifuge model tests (Chenaf et al., 2012; Wang and Zhang, 2014) related to stabilizing piles in homogenous slopes have been performed. Tang et al. (2014) conducted horizontal loading on piles in a colluvial landslide with the assumption of homogenous bedrock.

Some published studies related to the behavior of stabilizing piles under horizontal movement in homogenous medium or multi-layered

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http://dx.doi.org/10.1016/j.enggeo.2016.02.002
0013-7952/

soils exist, but few studies have addressed stabilizing piles embedded in bedrock, particularly in bedrock with different layers, via a physical model test. This paper presents a study on the response of stabilizing piles for landslides in bedrock with a hard upper layer and a weak lower layer via a physical model test. By utilizing a novel test apparatus and tilted loading system for piles and landslides, the behavior of the piles in different bedrock layer combinations is analyzed to reveal the mechanism and deformation influence of the bedrock layers on the piles.

2. Development of a test apparatus for landslides

2.1. Model of a pile-reinforced landslide

Jurassic strata in the Three Gorges Reservoir area mainly consist of interbedded gray sandstone and brownish red mudstone, and it is known to be prone to sliding. Due to various degrees of sedimentation and denudation, the percentages of weak and hard rock vary in the landslides that develop in the Jurassic strata. Consequently, the study of the embedded effect of stabilizing piles in bedrock with different percentages of weak and hard layers is of great importance to the treatment of the landslides. The pile–landslide physical model is established to examine the deformation properties and behavior of stabilizing piles under different percentages of hard rock in bedrock with a hard upper layer and a weak lower layer.

2.2. Development of a test framework

Based on the geological model of interbedded bedrock layers and the interaction between stabilizing piles and landslides, a pile–landslide physical model device is developed to study the mechanism and deformation of stabilizing piles embedded in bedrock with a hard upper layer and a weak lower layer. The functional block diagram of the pile–landslide physical model device can be divided into three parts (see Fig. 1), namely, the data collection system, the pile–landslide physical model and the loading system. The data collection system is composed of a data taker apparatus and a PC control system. The pile–landslide physical model consists of a sliding mass, bedrock, slip surface and stabilizing pile. The loading system at the trailing edge of the landslide is an automatic load. The two-layered bedrock is characterized by a typical layered structure, which greatly affects the behavior and deformation of the stabilizing piles. Therefore, it is important to conduct further research into the design of stabilizing piles embedded in bedrock with a hard upper layer and a weak lower layer. For the principle of a single variable, we assume that the dip of rock formation is the same as the slip surface.

2.3. Development of an automatic tilted loading device

A driving-force-load-caused landslide is always caused by the continuous accumulation of colluvial deposit at the trailing edge of the landslide. This accumulation of deposits increases the loading and leads to the final failure of the landslide. Thus, a ladder-type loading system is used to simulate the surface loading at the trailing edge of the driving-force-load-caused landslide. The system consists of a jack, stepping motor, controller and pressure transducers. The actual device graph of the loading system is shown in Fig. 2.

In view of the loading scheme of the modeling test, a program is developed and imported into the controller to achieve automatic loading. To study the deformation of a stabilizing pile under different driving forces, the loading increases uniformly and hierarchically as time passes.

3. Model test of a pile-reinforced landslide

3.1. Model materials

To accurately simulate the process of the driving force caused by the landslide and the practicability of the model tests, the materials in the tests are matched using the principle of similar materials. The materials include the sliding mass, slip surface, bedrock (weak rock and hard rock) and stabilizing pile. To simulate the interaction of a stabilizing pile and a landslide, the sliding mass is made of standard sand and clay with a ratio of 1:1. The bedrock of the pile–landslide physical model consists of a hard upper layer and a weak lower layer. The percentage of hard rock varies among the different cases. Considering the different strengths of weak rock and hard rock and the convenience of the tests, we used the same materials to simulate the hard rock and weak rock. The materials of the hard rock and weak rock include sand, concrete, plaster and water with a ratio of 3:1:1:1 and 9:1:1:1.75, respectively. The bedrock of the landslide is bedded rock. The thickness of the slip surface is 2 cm, with a slope angle of 10°. The slip surface is composed of sand, plaster, glass beads and rubber powder with a ratio of 4:1:1:1. The modeling pile is a nylon pile with cross-section of 2.5 cm * 3.5 cm. Nylon has strong wear resistance and good tensile bending performance and plasticity; thus, it is used to simulate a stabilizing pile. The relevant parameters of the materials are shown in Table 1.

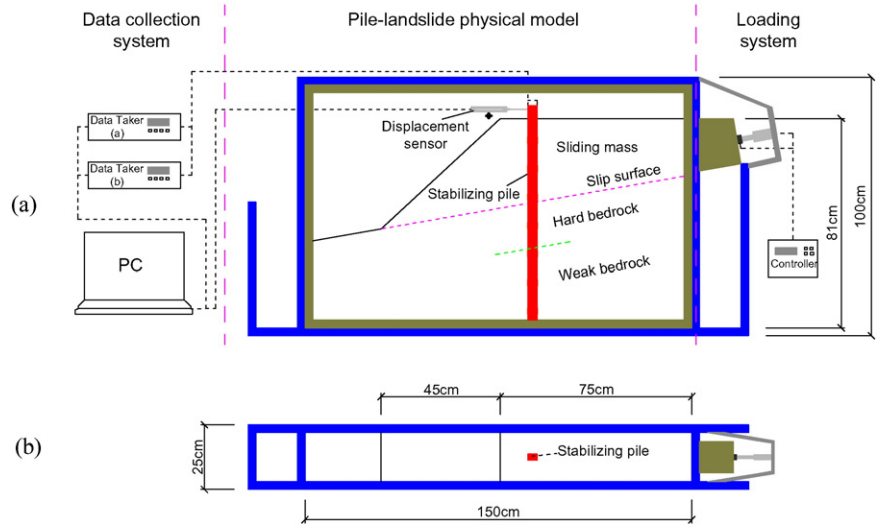

Fig. 1. Functional block diagram of the pile–landslide physical model device ((a) slide view; (b) top view).