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Investigation on the shear properties of discontinuities at the interface between different rock types in the Badong formation, China

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ABSTRACT

Recent research has paid little attention to the difference in shear strength between discontinuities with different joint wall material (DDJM) and discontinuities with identical joint wall material (DIJM) and what are the controlling factors of shear properties of DDJM. Bedding planes between argillaceous limestone and mudstone in the Badong formation in the Three Gorges area of China were investigated using physical model tests. The effect of joint wall material combination on the shear properties of DDJM was first revealed by conducting tests on a series of artificial joint specimens that were made of different joint wall materials and with varying joint surface topographies under different normal stresses. The results indicate that: the peak shear strength of DDJM is not equal to the lower peak shear strength of DIJM for two joint wall materials of the DDJM, even so it is closer to the lower peak shear strength than to the higher one; effect of joint roughness and normal stress on peak shear strength of DDJM is similar with DIJM; effect of joint wall material combination on peak shear strength of DDJM is greater with larger roughness and higher normal stresses. Based on the data acquired from the physical model tests, a new empirical equation to estimate the peak shear strength of DDJM was developed. The capability of the equation was validated by comparing estimates with data from direct shear tests on natural DDJM samples gained from the Badong formation. Finally, the proposed empirical equation was applied to the stability analysis of a rock slope in the Badong formation.

1. Introduction

The Triassic middle series Badong formation (T_2b), which was formed in the Ladinian and Anisian stages, is widely spread in the Three Gorges area of China. This formation was deposited in an oscillatory environment during a regression (Li et al., 2006). It can be subdivided into 5 subformations: T_2b^1, T_2b^2, T_2b^3, T_2b^4 and T_2b^5. Based on their lithologic similarities, these 5 subformations can be divided into two groups (Bi, 2015). T_2b^1, T_2b^3 and T_2b^5 are mainly composed of yellow or grey limestone, argillaceous limestone and mudstone layers, and T_2b^2 and T_2b^4 are mainly composed of fuchsia sandstone, clayey siltstone and mudstone layers. Due to rhythmic segmentation, one lithology is usually interbedded with another in the Badong formation, such as sandstone interbedded with mudstone in T_2b^2 and T_2b^4 and argillaceous limestone interbedded with mudstone in T_2b^1, T_2b^3 and T_2b^5 (Fig. 1). Sliding along discontinuities between two different rock types is one of the main causes of rock mass failure and geological hazards in the Badong formation. During the construction of the Hurong West Highway in China, several collapses occurred at rock cuts. The collapses resulted mainly from failures at the interface between sandstone and mudstone in the Badong formation. A major slope failure, which had a volume of $1.2 \times 10^7\,m^3$ and occurred at the Chaoyaopo Highway Service Centre, led to the relocation of a village to a higher location and resulted in significant financial efforts. Failures at bedding planes between argillaceous limestone and mudstone strata in the third subformation of the Badong formation (T_2b^3) has a played significant role in the deformation and initiation of large-scale complex landslides in the new location of Wushan County in the Three Gorges area. In addition, rockslides in the Badong formation, such as the Zhaoshuling landslide and Tanjiawan landslide, occurred mainly along interfaces between hard rock and soft rock in this formation. Therefore, the shear processes at discontinuities between different rock types

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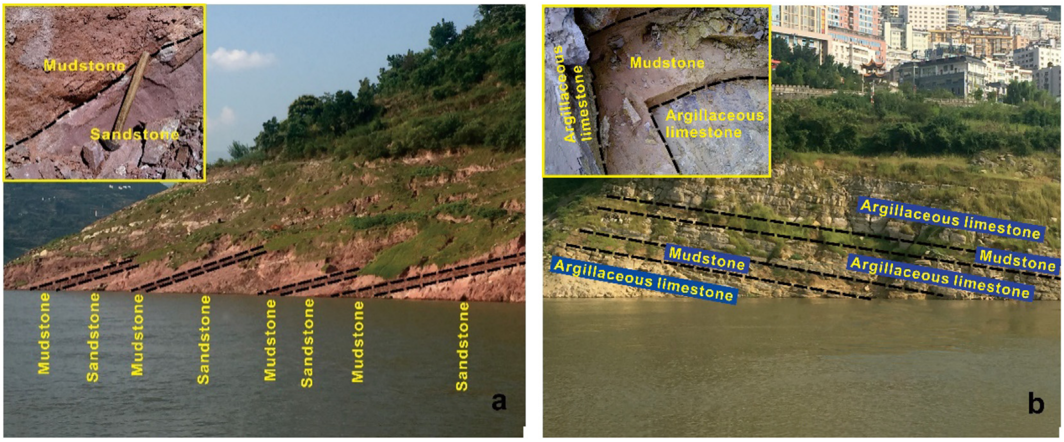

Fig. 1. Discontinuities between two different rock types in the Badong formation. (a) Bedding planes between sandstone and mudstone in the second subformation of the Badong formation (T_2b^2); (b) bedding planes between argillaceous limestone and mudstone in the third subformation of the Badong formation (T_2b^3).

especially in the Badong formation are vital in stability evaluation and hazard prevention for interbedded rock slopes, and should be studied in detail for a better understanding. However, discontinuities between different rock types have not been a focus of recent research.

Past research has focused mainly on the properties of discontinuities within identical rock types where wall strength is comparable. Their shear behaviour has been investigated using experimental and numerical shear tests (Goodman, 1976; Seidel and Haberfield, 1995; Homand et al., 2001; Jiang et al., 2006; Ge et al., 2014; Bahaaddini et al., 2015; Tang et al., 2017; Zhang et al., 2014, 2017). Several researchers have proposed shear strength criteria for this type of discontinuities. Patton (1966) established a bilinear failure envelope based on the dilation angle of asperities that separated asperity sliding and asperity shearing modes of failure. Barton (1973) modified Patton's formula to consider the effects of the joint roughness coefficient (JRC), the compressive strength of the rock joint wall (JCS) and the normal stress (σ_n) and used JRC log 10 (JCS/σ_n) instead of the dilation angle. Ladanyi and Archambault (1977) theoretically and experimentally studied the transition from dilatancy to shearing by examining joints with two-dimensional saw-tooth profiles, and they approached the problem of the joint shear strength by identifying the areas on the joint surface where sliding and breaking of asperities were most likely to occur. Barton and Bandis (1990) tried to overcome scale effects due to dimensions of the sliding surface and proposed correction equations. Kulatilake et al. (1995) suggested a strength criteria for modelling the anisotropic peak shear strength of rock joints at low normal effective stresses. Grasselli and Egger (2003) introduced a three-dimensional surface parameter to describe roughness instead of previously used two-dimensional profiles in their approach to estimate peak shear strength of joints. Cottrell (2009) modified the equation suggested by Grasselli and Egger (2003) and proposed new strength criteria for anisotropic rock joints. Xia et al. (2014) suggested an empirical criterion for joints expressed by three-dimensional quantified surface roughness parameters without any averaging variables. Finally, Jang and Jang (2015) established a power law equation used in shear strength determination based on a regression analysis of direct shear test results. However, these shear strength criteria cannot be used to predict the shear strength of discontinuities at the interface between different rock types.

Only a few studies have investigated the shear behaviour of discontinuities between different rock types. Considerable attention has been given to rock-concrete interfaces (Lam and Johnston, 1989; Lo et al., 1991; Kodikara and Johnston, 1994; Haberfield and Seidel, 1999; Seidel and Haberfield, 2002; Gu et al., 2003; Hong and Jeon, 2004; Moradian et al., 2010; Tian et al., 2015; Andjelkovic et al., 2015; Krounis et al., 2016). Ghazvinian et al. (2010) divided rock discontinuities into two categories: the first category includes discontinuities with identical joint wall compressive strength (DIJCS), and the second considers discontinuities with different joint wall compressive strength (DDJCS). They studied the shear behaviour of bedding planes between two different rock types with a high strength difference and analysed the effects of the roughness and compressive strength of the soft joint wall. Fang et al. (2014) simulated shear tests with numerical methods using a particle flow code to investigate the shear behaviour at bedding planes between two different rock types of the Badong formation in China. The most widely used strength criterion for predicting the shear strength of DIJCS is still Barton's empirical criterion. Ghazvinian et al. (2010) compared the experimental results from a soft-hard interface and predictions obtained by Barton's equation using the parameters of a soft joint wall. The results indicated that Barton's equation is not capable of predicting the shear strength of DDJCS. They modified Barton's equation and proposed a new empirical criterion for DDJCS with high strength differences. According to Barton's equation, of the parameters used to determine the shear strength of a discontinuity, the compressive strength of the joint wall and the basic friction angle are related to the joint wall material. Terms of DIJCS and DDJCS could not include the effect of basic friction angle on shear property of rock joints. Therefore, in this paper, rock discontinuities are categorized into discontinuities with identical joint wall material (DIJM) and discontinuities with different joint wall material (DDJM). The materials on the two walls of DDJM are different, which distinguishes DDJM from DIJM. The joint wall material combination, which expresses the materials on both sides of the joint and their differences, is an important characteristic of DDJM. Thus, the material and mechanical properties of the different rock types representing the rock walls and their interaction are essential to predict the shear behavior of DDJM. However, recent research has paid little attention on the relevance of the joint wall material combination and interaction on the shear properties of DDJM. This is the aim of this research.

Physical model testing using artificial analoges is a basic way to derive deeper insight into the shear behaviour of discontinuities and control factors affecting deformation as well as failure process. They can overcome the disadvantages of sampling heterogeneity of natural specimen and the high cost of tests of natural rock samples. Physical model tests also have the advantages that repeatability or reproduction of experiments is facilitated and distinct modification of single parameters like surface topography is easy to implement. Therefore, they have been widely used to study discontinuities in recent years. Patton (1966) first performed direct shear tests on artificial joint specimens with regular teeth inclinations. Using this methodology, several scholars have studied the shear behaviour of joints considering the effect of joint scale, joint roughness, shear velocity and normal loading (Barton,