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A complex rock topple-rock slide failure of an anaclinal rock slope in the Wu Gorge, Yangtze River, China

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ABSTRACT

This paper presents the results of an investigation of the Gongjiafang landslide with the volume of about 500,000 m^3 in the Three Gorges Reservoir region (TGR), occurred on 23 November, 2008. In this study, detailed geological and geomorphological surveys, in-situ and laboratory tests, and numerical simulation are carried out to reveal the failure mechanism of this landslide. The anaclinal rock slope is characterized mainly by a set of outward dipping and non-persistent joints, a hard stratum (limestone) in the middle portion and an underlying soft base (argillaceous limestone interbedded with shale). Because of the long-term intensive river erosion caused by periodic fluctuation of the reservoir water level, the soft rock masses at the toe of the slope were softened, or even washed away, inducing the first sliding-toppling failure at the toe. The collapse at the toe leaves the hard strata in the middle unsupported, like a "beam". Thus, a conceptual "cantilever beam" model is proposed to explain the failure mechanism of the landslide. The DEM simulation further highlights the failure process with a complex rock topple-rock slide failure mode, i.e., first composite sliding and toppling occurred at the toe, a composite shear and flexure failure of the middle "cantilever beam" and a simultaneous overall sliding failure of the rock masses in the upper part of the slope. The results imply that preventing water erosion at the toe could be an effective way in landslide prevention and treatment in the study area.

1. Introduction

Landslides including rockfalls (Cruden and Varnes, 1996) are one of the major geological hazards to settlements and transportation routes in mountain areas, and are been responsible for some of the most destructive natural disasters in recent history (Fort, 2000; Strom and Abdrakhmatov, 2004; Kveldsvik et al., 2009). After the completion of the Three Gorges reservoir project (TGP) in 2003, many touristic routes and settlements established along the bank slopes in the reservoir area are becoming vulnerable to landslide disasters. Since the impoundment in 2003, >5000 slope failures and unstable slopes have been found in the Three Gorges Reservoir region (TGR) due to the effect of the periodic fluctuation of the water level in the reservoir (Lin, 2012). The stability of the 5900 km long banks of the TGR region becomes a grave and inevitable problem now (Liu et al., 2004). These landslides, including reactivated ancient ones, and the consequent surges have already threatened several new relocated towns (such as Badong, Wushan and Yunyang), Yangtze shipping, and the dam stability (Akgün, 2011; Wieczorek et al., 2007; Romstad et al., 2009; Petley, 2010).

The morphology of rock slopes in the Gongjiafang-Dulong section in the Wu Gorge (Fig. 1) of the TGR is predominantly controlled by bedding planes. Cruden (2000) characterizes slopes as cataclinal when bedding planes dip in the same direction as the slope, and anaclinal when they dip in a direction opposite to the slope. Anaclinal slopes can be further divided into normal, steepened and subdued escarpments, when the bedding planes are steeper, perpendicular to the dip of slopes or less steep, respectively. According to the categorization suggested by Cruden (2000), the slopes, including the Gongjiafang landslide (labeled with G2 in Fig. 1b), in the Gongjiafang-Dulong section in the Wu Gorge (Fig. 1) of the TGR, can then be classified as steep to normal escarpments. According to De Freitas and Watters (1973), toppling failures of rock slopes are common in natural or excavated rock slopes with a closely spaced and pervasive discontinuity set which extends in the direction parallel or nearly parallel to the slope. Goodman and Bray (1976) classified toppling failures as "main" and "secondary" toppling, based on regional observations and laboratory modeling. In main toppling failure (flexural, blocky, and block-flexural), rock masses weight and other discontinuity sets parallel to the direction of slope, are considered to be the most important factors affecting the slope stability; whereas in secondary ones (slide toe toppling, slide head toppling, slide base toppling, contrasting slide toe topples, block torsion and sheet failure), other external factors cause the failure (Goodman and Kieffer, 2000). Moreover, many researchers have suggested that

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toppling mechanism lies behind many instability problems they analyzed in rock cuts (Sagaseta et al., 2001), in open pit mine walls (Sjöberg, 1999; Alejano et al., 2010), and in natural or excavated slopes (Giraud et al., 1990; Cruden and Hu, 1994; Gischig et al., 2011; Böhme et al., 2013). Mechanisms of this failure mode have also been investigated by many researchers both experimentally (Aydan et al., 1989; Aydan and Kawamoto, 1992; Adhikary and Dyskin, 2007; Zhang et al., 2007) and theoretically using limiting equilibrium models (Bobet, 1999; Adhikary et al., 1997; Nichol et al., 2002; Amini et al., 2012; Mohtarami et al., 2014). However, despite extensive studies on main toppling failure, few cases or studies have been conducted on the secondary failure types.

In the case of the Gongjiafang landslide, although a brief review of the landslide characteristics (Huang et al., 2010) and a detailed study on the landslide-induced waves (Huang et al., 2012) have been published, an in-depth geological and mechanical understanding of the landslide is still missing. Therefore, in this study, a series of comprehensive field investigations have been carried out. Field surveys have revealed that the intensive and long-term river erosion at the toe is the cause of the initial collapse, and it successfully causes the hard strata in the middle to lose underlying support. Based on these observations and interpretations, a "cantilever beam" model was developed to reveal the landslide mechanism. Then, by incorporation of this model, the Universal Distinct Element Code (UDEC) simulation highlights a complex failure mode of the landslide, including rock toppling and rock sliding.

2. Geographic and geologic setting

The Gongjiafang landslide (labeled with G2 in Fig. 1b) is located within the Gongjiafang-Dulong section in the Wu Gorge (Figs. 1–2), which is one of the famous three Gorges along the Yangtze River, characterized by steep mountains and dissected by deep, narrow, V-shaped valleys (Fig. 3a), roughly northwest-southeast extension (Fig. 1). The steep slopes in this area are very vulnerable to instability, due to the effects of the intensive erosion of the river and unloading, weathering, specific slope structure (discussed in the Section 3 below), wave actions and others. The Gongjiafang-Dulong section is located on the northern bank of the Yangtze River, extending about 4 to 9 km from the Wushan County (as illustrated in Figs. 1–2). This area has been investigated by the Geological Survey of China (CGS) since 2006, which has carried out field surveys to observe any movements of large-scale instable structures that could potentially collapse into the river and result in high waves. Systematic mapping of rockslides and potential rockfalls has also been performed by the No. 107 geological team to further reduce the geo-hazard risks in this area after the occurrence of a series of geo-disasters between 2007 and 2008 (Huang et al., 2010).

The study area is described as an unstable mountainside, which is above 700 m high (the highest elevation is about 1211 m a.s.l.). The landform of the mountain range is characterized by the presence of a series of slopes that dip moderately to steeply south, bounded by several natural gullies, as shown in Fig. 1a. These steep slopes (with slope angles

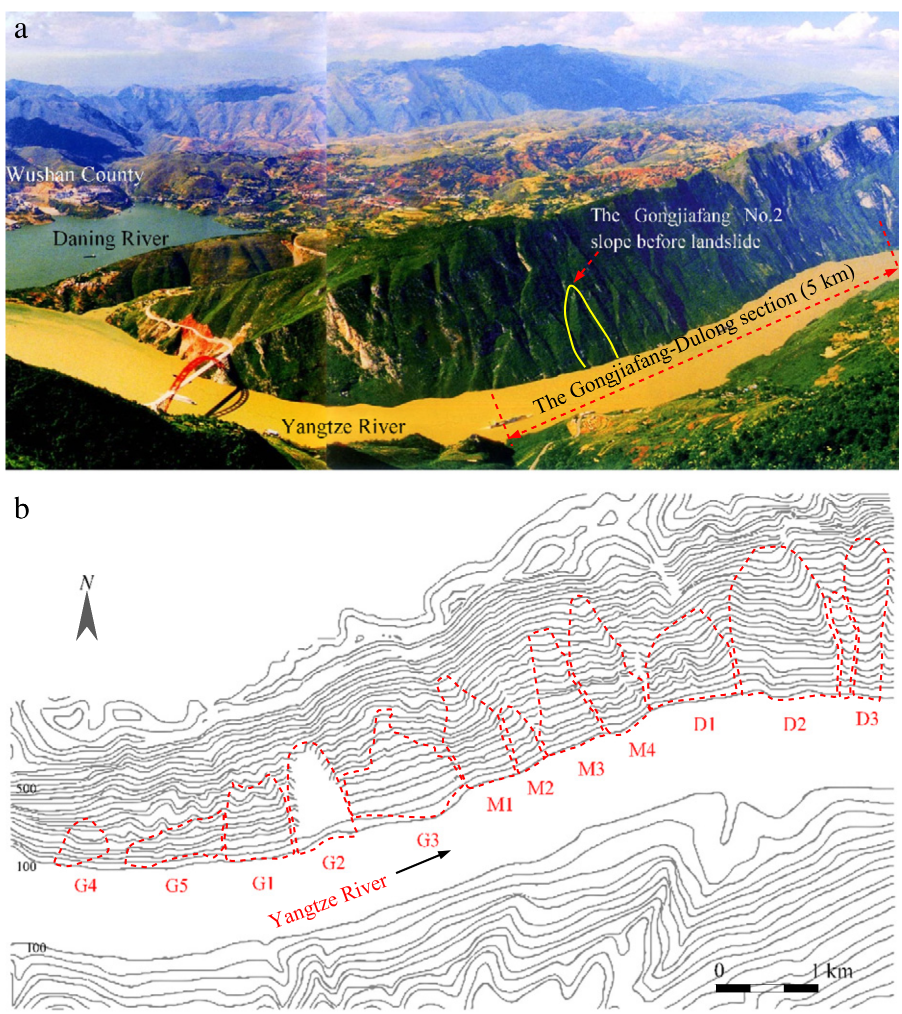

Fig. 1. Slope condition of the Gongjiafang-Dulong section in the Wu Gorge. (a) An airscape of this area and (b) labeled unstable slopes (G2 is the studied landslide) with the contour intervals are of 25 m increments. Note: G—Gongjiafang, M—Maocaoping, D—Dulong.