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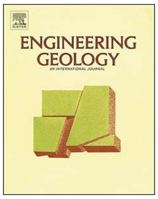

Towards a complete understanding of the triggering mechanism of a large reactivated landslide in the Three Gorges Reservoir

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ABSTRACT

The primary aim of this study is to research the characteristics of a slide motion and its relationships with environmental triggers, with reference to the Quchi landslide, which is a large, slow-moving, reactivated landslide in the Three Gorges Reservoir region. Since 2006, this instability has been involved in a slow-moving process with clearly visible signs (ground fissures, cracking of houses and road). The landslide consists of 18 Mm^3 rock masses threatening Quchi Town and a road that is crucial for local transportation. For civil protection purposes, a continuous monitoring system has been put into use since 2009. Combining four years of meteorological and hydrological data with GPS displacement measurements and in situ observations, allows a detailed identification of the key processes involved. The deformation is thought to be closely related to precipitations and fluctuating reservoir levels: slope movements have a highly distinctive pattern that is characterized by high deformation starting in June and lasting into September, when the reservoir level drops and rainfall increases, followed by a rapid transition to constant deformation until the next wet season. In order to investigate in detail the influences of rainfall and fluctuating water levels on the hydromechanical behavior of the landslide, a series of two-dimensional numerical simulations are performed using the Universal Distinct Element Code (UDEC). The modeling reveals that precipitation mainly mobilizes the slope materials on the upper part of the slope, while the other trigger factor—fluctuating water levels—destabilizes the foot of the slope into a multistage failure with a remarkable retrogressive evolution. The slide is most likely to collapse in a complex pattern characterized by en masse sliding on the upper part of the slope and a retrogressive rupture at its foot.

1. Introduction

Landslide caused by reservoir impoundment is one of the most common geological hazards occurring in reservoir areas (Jiao et al., 2014). These landslides, including reactivated ancient ones, can inflict massive human casualties and impose large financial costs on society (Massey et al., 2013). The best known example of a rock slide in a reservoir region is, of course, the 1963 Vajont Reservoir slide, which killed approximately 2000 people in northern Italy (Müller-Salzburg, 1987; Kilburn and Petley, 2003; Boon et al., 2014; Zhao et al., 2016). Another well-known example is the 1956–1969 Portuguese Bend landslide in California; though it did not cause any fatalities, the slide resulted in losses and court-imposed damages of US$86 million ($680 million equivalent value in 2016) (Merriam, 1960; Linden, 1989; Massey et al., 2013). Therefore, gaining an understanding of these unstable slopes located in reservoir regions, particularly of the likelihood of their collapse, is important.

In many studies, water is often mentioned as a triggering factor for failures of reservoir slopes formed by rocks with well-developed fracture networks and/or materials with high permeability (Erismann and Abele, 2001; Guglielmi et al., 2008). As pointed out by many researchers, a large number of reservoir rockslides are triggered by filling–drawdown operations (Gutiérrez et al., 2010; Paronuzzi et al., 2013; Jiao et al., 2014; Gu and Huang, 2016). The adverse effect of changes in the reservoir levels on bank stability was emphasized by Jones et al. (1961), who observed > 500 slope movements induced by the Grand Coulee Reservoir from 1941 to 1953. They found that about 50% of the landslides occurred during filling operations and about 30% occurred during drawdown operations. Similar results have also been reported by Nakamura (1990) in the study of reservoir landslides in Japan, 60% of which occurred during the sudden drawdown of the water level and the remaining 40% occurred in the period of filling water. For specific landslides under study, Qi et al. (2006), Zangerl et al. (2010), and Pinyol et al. (2012), found that the slope deformation

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was due to sharp drawdown rather than rise of the water level on the basis of long-term monitoring data. In addition to the fluctuating water level, another factor—rainfall—is also considered to be a significant trigger of landslides (Alonso et al., 2003; Peruccacci et al., 2012; Vallet et al., 2016; Iadanza et al., 2016). All these findings demonstrate that water (including precipitations and fluctuating reservoir levels) and mechanical deformations of the landslide are intimately coupled and in general cannot be analyzed independently of each other.

In this paper, a comprehensive analysis of the Quchi landslide is reported, which is recognized as a reactivated old instability in the Three Gorges Reservoir (TGR) region. Our study focuses on the analyses of slope deformation measurements integrated with hydrological datasets and coupled hydromechanical modeling. Slope deformations are evaluated in terms of the surficial displacement of the slide, its time-dependent activity, and possible triggers. Further, the discrete numerical modeling method, which has been widely used regarding to the landslide simulations (Wu et al., 2013; Lin and Lin, 2015; Wu et al., 2016), is used to examine the influence of each triggering factor on the behavior of the slope in detail. On the basis of these results, the possible evolution mode of the slope is proposed, and the development tendency of the landslide is also assessed. In consideration of the fact that a large number of old instabilities have been reactivated since the impoundment of the TGR, we anticipate that the present research will provide additional insight into landslide reactivation issues, such as an understanding of its movement characteristics, corresponding reactivation triggers, and possible evolution patterns, as well as provide guidelines for prevention approaches and treatments.

2. Geographical and geological settings

The Quchi landslide is located at a distance of around 11 km from Wushan County and situated at the mouth of Qutang Gorge, which is the first gorge of the well-known Three Gorges in the middle reaches of the Yangtze River (namely, Qutang Gorge, Wu Gorge and Xiling Gorge, as shown in Fig. 1a). The geology of the area consists of two major components: a pre-Sinian crystalline basement, and a supra-crustal Sinian-Jurassic sedimentary cover (Wu et al., 2001). The former, which is composed mainly of magmatic and metamorphic rocks, outcrops only sporadically in this area. The latter is widespread and composed of thick bulk limestone and dolomite, interbedded with thin layers of sandstone and shale (Fourniadis et al., 2007; Wang and Li, 2015). The severe river incision across the massive limestone mountains of the Lower Palaeozoic and Mesozoic age (Li et al., 2001; Liu et al., 2004; Fourniadis et al., 2007) resulted in the formation of the Three Gorges as well as of a series of gentle slopes composed of colluvium from the limestone cliff. Small towns usually lie on these slopes, and thus, the potential collapse of the slopes may incur a great loss of lives and property. The most well-known example is probably the Qianjiangping landslide (Wang et al., 2008), which occurred after the first impoundment of the TGR in July 2003 and caused the loss of 24 lives. Other such examples, all located in the TGR region, are the reactivation of the Huangtupo landslide (Fourniadis et al., 2007), which forced the relocation of the new Badong town for a second time to Xirangpo; the Sanmendong landslide (Sun et al., 2016), and the Anlesi landslide (Jian et al., 2009).

Regional geological structures dominantly trend NE–SW, and they are associated with major anticline-syncline fold systems (Fig. 1b). The river and valleys are, at least, partly controlled by the tectonic structures, as they are subparallel to the mountain ranges and folds. The bedrock outcropping in the area consists of a sequence of sedimentary rock units that correspond to the transition of the Middle Triassic to the Quaternary Holocene. The stratigraphic units are listed in Table 1. The present climatic conditions in the study area are characterized by a mean daily temperature in the range of 4–39.8 °C and an annual precipitation of 1369 mm (Huang and Gu, 2017). Notably, there are recognizable landslide seasons in this area: 4/5 of the recorded geo-disaster events occurred between May and September. The rainfall during this period accounts for nearly 70% of the yearly rainfall and the maximum daily precipitation can be as high as 150–240 mm (Gu and Huang, 2016).

3. Methodology

Investigation of the Quchi landslide was performed via a combination of field mapping, ground investigation including 24 boreholes constructed through the basal shear surface, in situ monitoring, and numerical modeling. The monitoring network installed on the landslide recorded the following: i) surface displacement, ii) pore water pressure, and iii) precipitation and reservoir water levels. A total of 50 GPS antennas were installed on the slope (see locations in Fig. 3). The accuracies of the GPS in horizontal and vertical displacement measurements are $5\,\mathrm{mm} + \mathrm{D} \times 10^{-6}$ and $10\,\mathrm{mm} + \mathrm{D} \times 10^{-6}$ (D is the distance, in km), respectively. The GPS network is based on a set of single frequency stations, which transmit phase data every 30 s to the main controlling unit. Pore water pressures within the landslide were measured using vibrating wire piezometers in boreholes P1, P2, and P3, along cross-section I-I (Fig. 3). Data on the rainfall and reservoir levels were acquired at the weather station of Wushan County.

Hydromechanical modeling analyses were performed using the UDEC (Itasca Consulting Group, 2004) in order to examine in detail the influences of precipitation and changes in reservoir levels on the seasonal behavior of the slope. Calculations were first performed by considering two factors, rainfall and a periodically fluctuating water level, so as to test their separate effects on the hydromechanical behavior of the slope. Then, the possible kinematic evolution of the landslide was investigated by taking into account actual multiple factors (precipitation and reservoir water fluctuation).

4. Field investigation of Quchi landslide

Field investigations of the Quchi landslide have revealed that the entire surrounding area is an ancient base-rock landslide with noticeable features (chair-like geometry, Fig. 2). The old instability, bounded by two natural gullies on both sides (Fig. 2c), is a large slide that is about 1150 m long and 1100 m wide; it covers an area of approximately 1.26 km^2, and its volume may be on the order of 30 Mm^3. In 2006, two main sliding bodies (labeled Q1 and Q2 in Fig. 2) bounded by well-defined back scarps and lateral gully boundaries were found to reactivate at the front of the ancient landslide. A gully that runs longitudinally down to the river bisects the Quchi landslide (Gully II in Fig. 2). On the upper part of Q1 lies the Quchi Town, and the major transport artery in this area, the Wushan-Quchi road runs along the two new instabilities.

4.1. Description of active part of the landslide

4.1.1. Sliding mass Q1

The geological cross-section (see location in Fig. 2c) of Q1 is shown in Fig. 4. As can be seen in this figure, the longitudinal profile of the sliding mass Q1 shows a gentle upper slope and a steeper lower slope, with a decrease in thickness towards the toe. The back scarp of Q1 is clearly evident, and it appears at an elevation of about 300 m (Fig. 4b). The distance between the northern and southern lateral boundaries (gullies I and II in Fig. 2c) is about 500 m. Borehole core logs reveal that the maximum thickness of Q1 is about 60 m and its estimated volume is 12.7 Mm^3.

At the rear of Q1, the main scarp appears as a deep trench with clear indications of slip displacements (Fig.4b). Vertical dislocation of up to 3.5 m can be measured and a large tension crack is also formed here, both of which indicate the occurrence of significant downhill displacements. The movement of Q1 has already resulted in a great loss of property as well as damage to the town's infrastructure: cracked houses,