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Mechanism of the slow-moving landslides in Jurassic red-strata in the Three Gorges Reservoir, China

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ABSTRACT

Landslides in Jurassic red-strata make up a great part of geohazards in the Three Gorges Reservoir (TGR) in China. Most of them begin to move slowly with the accumulated displacement increasing stepwise, which corresponds to seasonal rainfall and 30 m of reservoir water level fluctuation (145 m to 175 m on elevation). We analyzed the movement of 21 slow moving landslides in the Jurassic red-strata in TGR, and found that all these landslides involved two differing processes; one is the sliding process with different shear speeds of soils within the sliding zone (landslide activity), and the other one is in steady state with different durations (dormant state). This means that the soil within the sliding surface may experience shearing at different shear rates and recovery in shear strength during the dormant period. To clarify the mechanism of this kind of movement, we took soil samples from the sliding surface of Xiangshanlu landslide, which occurred on August 30, 2008 in the Jurassic red-strata in TGR, and examined the shear rate dependency and recovery of shear resistance by means of ring shear tests. The results of tests at different shear rates show that the shear strength is positively dependent on the shear rate, and can be recovered within a short consolidation duration after the shearing ceased. By increasing the pore-water pressure (PWP) from the upper layer of the sample, we also examined the initiation of shearing which can simulate the restart of landsliding due to the fluctuation of groundwater level caused by rainfall or changes in reservoir water level. The monitored PWP near the sliding surface revealed that there was a delayed response of PWP near the sliding surface to the applied one. This kind of delayed response in pore-water pressure may provide help for the prediction of landslide occurrence due to rainfall or fluctuation of reservoir water level.

1. Introduction

The Three Gorges Reservoir in China (hereinafter we call TGR, its location is shown in Fig. 1) is an area with a large number of landslides (Chen, 1999; Deng et al., 2000; Wu et al., 2001; Li, 2002; Liu et al., 2004; Wen et al., 2007; Jian et al., 2009; Li et al., 2013, among others). These landslides developed in all strata, especially in the Jurassic stratum. The Jurassic lithology in TGR is continental lake facies sedimentary rocks, the colors of which are mainly fuchsia, maroon, or red brown; therefore, the Jurassic stratum is often called “red-strata” by Chinese academe (Li, 2002; Chen et al., 2004; Xu and Zhou, 2010). From the lithology structure of the Jurassic red-strata in TGR, the interbedding layer of thick silty-sandstone and thin sandy-mudstone is an important reason for the development of weak bands with a high content of clay mineral like montmorillonite and illite in the long geological history (Jian et al., 2005, 2008), which caused some typical landslides, such as Chonggang landslide (Yin et al., 2010), four landslide groups in Wanzhou area (Jian et al., 2009), Jipazi landslide (Huang, 2007), and Qianjiangping landslide (Wang et al., 2004; Liao et al., 2005). It has been reported that among the landslides selected in the second and the third phase of mitigating and monitoring projects in TGR supported by Chinese government, more than 70% are in the Jurassic red-strata (Chai et al., 2009). Up to now, many studies had been performed on the landslides occurring in the Jurassic red-strata in the TGR area with focus on examining the geological basis (say, possible clay mineral in the weak bands of potential sliding surface). However, the mechanism of the movement in the pre-failure stage, especially in the case of slow movement of landslides influenced by seasonal rainfall and periodic reservoir water level fluctuation, is not yet well understood.

In this paper, we investigate the movements of 21 landslides in the Jurassic red-strata in TGR and examined the moving types of these landslides. The ring shear apparatus developed by Disaster Prevention Research Institute, Kyoto University, was used to simulate the shear process of the soils within the sliding zone in the slow movement through the case study of a landslide which occurred on August 30, 2008, in the Jurassic red-strata in TGR. We performed three groups of tests, i.e., test with different shear rates, test with different consolidation durations and, tests with changing the pore-water pressure of shear band. Based on the results, three aspects such as shear rate effect,

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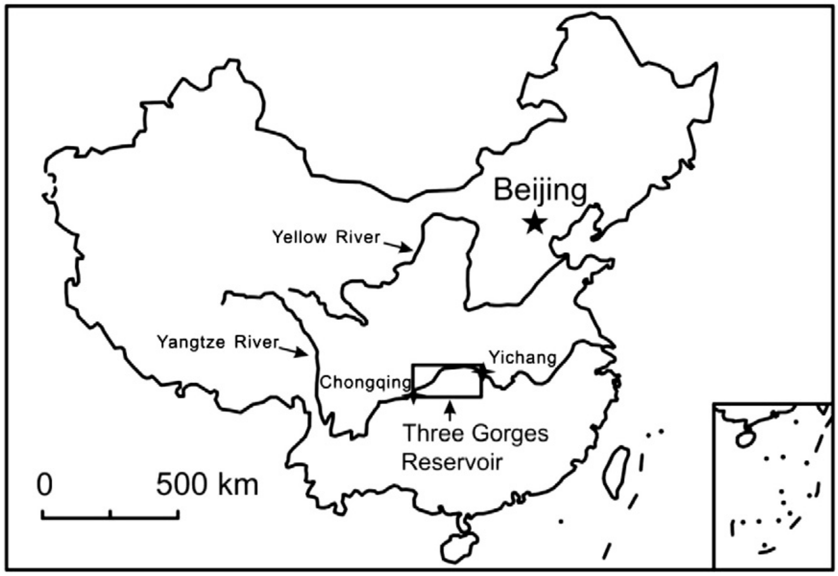

Fig. 1. Location of the Three Gorges Reservoir in China.

recovery of residual shear strength and trigger of landslide reactivation are discussed to reveal the mechanism of the slow movement of the landslides in the Jurassic red-strata in the Three Gorges Reservoir.

2. Type of the slow movement

To reduce the risk from landslides in TGR, the Chinese government approved many projects which involve systematic investigation of landslides and potentially unstable slopes, ancient landslides reactivation and their failure mechanism, especially the monitoring of large landslides (Wen et al., 2007). In many cases the surface monitoring data are much easier to be obtained through using a wide range of techniques such as survey markers, extensometers, and digital photogrammetry, as well as global position system (GPS) and interferometric synthetic aperture radar (InSAR). As a result, in the monitoring of these large landslides in TGR, GPS measurements which can provide the surface displacements have been widely used. Petley et al. (2002, 2005) demonstrated that the patterns of landslide movement provide an insight into the processes occurring in the sliding zone, and used the surface monitoring data to interpret landslide movement patterns, which mainly include four types: (1) very slow or creep movement, which occurs at the moment of formation of the tension area located on the crown or flanks of the landslide; (2) low velocity movements, caused by a gradual formation of the shear surface; (3) rapid movement because of the sliding mass disaggregating into loose materials; and (4) very rapid movement as a result of landside fails.

In this study 21 landslides monitored by GPS in the Jurassic red-strata in TGR were examined. In each landslide, 2–9 GPS stations were installed according to its scale. We obtained the accumulated displacements of monitoring points from January 2007 to November 2009 (35 months). We studied the monitoring point with the largest accumulated displacement for each landslide, and plotted 21 curves as showed in Fig. 2. These curves can be divided into two groups (Figure 2a,b) according to the displacements. In Fig. 2a, 15 curves of accumulated displacement versus time display “random oscillation” or “trending oscillation” with an average sliding rate <6 cm/year. These oscillations in the accumulated displacement might result from the measurement errors that are normally intensive in the tiny data range (Ueno et al., 2003). Other 6 landslides (Figure 2b) had their displacements increased mainly stepwise with their sliding rates greater than 6 cm/year but smaller than 1.5 m/year. For the first group, all the landslides were in a very slow movement or creep movement, which could be classified as the first style of the movement of rotational and translational landslides as described by Petley et al. (2005). However, for the second group the six landslides showed a slow movement according to the sliding rate proposed by Schuster and Krizek (1979). Because all GPS stations in each landslide were installed soon after cracks occurred in the walls of houses locating on the slope, following the interpretation by Petley et al. (2005), we inferred that the movement shown in Fig. 2a mainly resulted from the crack propagation (shear surface generation), whereas the slow movement (Figure 2b) resulted from the occurrence of movement along the existing sliding surface.

Irrespective of the differences in the accumulated displacement, all the displacements showing slow movement (Figure 2b) increased stepwise, which can be conceptually illustrated by a model shown in Fig. 3a. Differentiating this stepwise displacement gives an increasing or decreasing displacement rate, indicating that the landslide would experience alternations of accelerating and decelerating movements (Figure 3b). Therefore, it is expected that the soils within the sliding zone would undergo two processes; one is shearing at differing shear rates, and the other one is recovery of shear strength under a constant normal stress with different duration. These two processes correspond to the sliding and dormant periods, respectively. Therefore, in order to understand the mechanism of the slow-moving landslides in the Jurassic red-strata in TGR, two questions should be answered: (1) how does the landslide come into reactivation from dormant state as shown conceptually in Fig. 3; and (2) how does the movement stop and keep staying at the dormant state?

3. Ring shear test

3.1. Testing sample

To reveal the mechanism of these slowly moving landslides in the Jurassic red-strata in the TGR, we took soil samples along the sliding surface from Xiangshanlu landslide, which occurred in the early morning on August 30, 2008. This landslide is located on the left bank of Tongguluo River, a tributary of the Yangtze River in Shazhenxi Town, Zigui country in TGR (Figure 4). The landslide covers an area of 3.3×10^4 m^2 and has a volume of 0.165×10^6 m^3. The sliding mass was composed of Quaternary colluvium and eluvium, and the lithology of sliding bed rock is middle Jurassic Qianfoyan Formation (J_2q), as well as the soils along the sliding surface are silty clay with the thickness of