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Application of electrical resistivity tomography for investigating the internal structure of a translational landslide and characterizing its groundwater circulation (Kualiangzi landslide, Southwest China)

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ABSTRACT

Electrical resistivity tomography (ERT) is a widely used tool in near surface geophysical surveys for the investigation of various geological and engineering problems, including landslides. In this study, the internal structure of the southern region of the Kualiangzi landslide, which is located in Sichuan province, China, was investigated using four ERT profiles, drill cores, and inclinometer data. The characteristics of the groundwater circulation were evaluated from variations in electrical resistivity and groundwater level. The results showed that the sliding surface corresponds to a deep zone with low resistivity and that the sliding material consists of clay, gravelly soil, and weathered sandstone and mudstone. The thickness of the sliding material is 50 m in the main tension trough and decreases to several meters in the direction of sliding. The dip angle of the sliding surface that has low resistivity is generally consistent with that of the bedrock. The groundwater level in the tension trough and in the middle transitional part from hill-country to flat terrain was highest in the landslide. The groundwater level close to the toe front of the landslide was the lowest. The groundwater is recharged by the precipitation and generally drains to the toe front by seasonal springs along the sliding surface. The rapid increment of the groundwater level in the tension trough kept pace with that of the displacement rate after intense rainfall. The improved understanding of internal structure and groundwater recirculation is beneficial for the analysis of the mechanisms of translational landslides and their hazard prevention.

1. Introduction

Translational landslides, which develop in nearly horizontal bedrock composed of sandstone and mudstone where the dip angle is commonly 3°–5°, are typical geological hazards in the Three Gorges reservoir area and Sichuan basin in Southwest China (Kong and Chen, 1989). Translational landslides are notable for their complex formation mechanisms, difficult identification, and serious destruction. Rainfall acts as the most common triggering factor for the initiation and reactivation of translational landslides. Under intense rainfall conditions, water can percolate into shear fractures or creep-tensile fractures in landslides, which increases the pore water pressure and decreases the effective shearing resistance of a sliding surface (Zhang et al., 1994; Van Asch et al., 1999; Fan et al., 2009). Thus, it is essential to estimate the thickness of sliding material, locate the sliding surface, and characterize the groundwater circulation within translational landslides to analyze their mechanisms and for hazard prevention.

The widely used direct techniques (e.g., borehole, piezometer, inclinometer, and laboratory tests) yield true parameters on the lithological, hydrological, and geotechnical characteristics of landslide bodies. However, these techniques provide information at a specific point in the subsoil, and it is costly to evaluate the spatial distribution of parameters using a large number of probes and tests in landslides. Given the advantages, including low cost, of non-invasive measurements, several geophysical techniques such as electrical resistivity tomography (ERT) have been used for the geological exploration of landslide areas that are characterized by complex geological settings (Jongmans and Garambois, 2007; Niesner and Weidinger, 2009; Perrone et al., 2014). These geophysical techniques, which provide spatial geophysical information on landslide materials, are beneficial supplements to conventional geotechnical measurements.

ERT can image 2D or 3D resistivity distributions using large numbers of four-electrode measurements. The electrical resistivity of landslide materials is mostly influenced by the lithology, porosity, and water content of soils (Rubin and Hubbard, 2005). In addition, the increase

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in water content or hydrostatic pressure can play an important role in the triggering mechanisms of landslides (Fan et al., 2009). Therefore, ERT can provide valuable information for landslide analysis and early warning. Some recent works have shown that the ERT technique can be used to define the geological setting of subsoils, reconstruct the geometries of landslide bodies, locate possible sliding surfaces and lateral boundaries to evaluate the groundwater conditions for estimating the dynamic behaviors of landslides (Suzuki and Higashi, 2001; Perrone et al., 2004; Lapenna et al., 2005; Jomard et al., 2007; Grandjean et al., 2011; Carpentier et al., 2012; Travelletti et al., 2012).

In this paper, four 2D ERT profiles were conducted in the southern area of the Kualiangzi landslide, which is a typical translational landslide located in Southwest China. The thickness of the sliding material and depth of the sliding surface were estimated using the ERT profiles, drill cores, and inclinometer data. Moreover, the groundwater circulation in the landslide was characterized by analyzing the variations in electrical resistivity and groundwater level.

2. Geographical, geological, and geotectonic settings

The Kualiangzi landslide is located 65 km southwest of the city of Deyang, Zhongjiang County, which is in the Sichuan province, China (Fig. 1a and b). The landslide area lies within the climate region of the subtropical humid monsoon, and the average annual precipitation is 844.5 mm. More than 80% of the total precipitation is concentrated in the rainy period from June to September, during which the rainfall is characterized by its long duration, high frequency, and large cumulative precipitation. The landslide belongs to the geomorphic unit of tectonic erosion, a deep mound with a width of 50–300 m and a valley depth of 100–170 m.

The landslide is located in the north wing of the Cangshan anticline, and the bedrock generally dips to NW20°–30° at an angle of 2°–5° (Fig. 1b). There are no faults or historical destructive earthquakes in the study area. The height relief between the main scarp and the toe front is approximately 110 m. The area of the landslide is 0.51 km^2, and the volume is 2.55 million m^3 (Zhai, 2011; Xu et al., 2015). The main body of the landslide is 360–390 m long, 1100 m wide, averages 50 m in thickness, and has a maximum thickness of 80 m (Fig. 1c and d). The rear edge of the landslide is the main scarp, which has a N–S orientation. The leading edge is comprised of the local collapse, an uplift belt, and seasonal springs.

The Kualiangzi landslide was always in a state of slow creep to the west, although the displacement could accelerate under conditions of intense rainfall in the flood season. At the beginning, some bead-like soil holes deeper than 50 m were found on the surface at the rear edge of the landslide and were gradually connected by a large and long crack. The first rapid acceleration in the displacement occurred due to intense rainfall in the flood season of 1949, which produced a large-scale tension trough extending in the N–S direction (Fig. 1c and d). The second rapid acceleration in the displacement was caused by a strong rainfall in the flood season of 1981. A large number of houses were destroyed by landsliding, and the residents were all forced to relocate. The tension trough close to the main scarp was significantly widened to a length of 1 km and a width of 60 m in the following several decades. In addition to the large-scale tension troughs, many minor tension fractures were induced by the creeping of the landslide. According to the exposure in the scarps, two sets of subvertical joints developed with trends of NW10°–20° and SW10°–29° and dipping angles of 80°–85° and 72°–82°, respectively (Fig. 1c).

The surface of the landslide is primarily covered by a layer of residuals and diluvials (Q_4^{el+dl}), of which the ingredients are silty clay mixed with gravels. The thickness of the residuals and diluvials generally ranges from 1 m to 13 m. The bedrock of the landslide is sandstone interbedded with siltstone and mudstone and dips to NW20°–30° at an angle of 2°–5°. The sandstone belongs to the Penglaizhen group, which formed in the Upper Jurassic period (J_{3p}). The thickness of the sandstone ranges from tens of meters to several meters. The mudstone, which has good water-absorbing structures and low strength, constitutes the main materials of the sliding zone (Fan et al., 2009; Zhai, 2011; Li, 2014; Xu et al., 2015). The thickness of mudstone ranges from 0.5 m to 2 m around the main sliding surface, according to the drilling cores (Fig. 1d). The unconsolidated formation in the tension trough is colluvium comprised of rock blocks, gravels, and breccias (Q_4^{col}). The diameter of the largest rock blocks could reach 5 m. The thickness of colluvium ranges from 51 m to 72.9 m (Zhai, 2011).

The groundwater in the landslide flows in the direction from the tension trough to the toe front. The joints at the rear edge of the landslide provide infiltration channels for the rainwater into the inner slope during the rainy period. The tension trough plays an important role in the storage of groundwater. The groundwater level was generally higher than the sliding surface in the flood season. In addition to three seasonal creeks, a large number of seasonal springs along the toe front act as the main discharge of groundwater. The flow rate of the springs is proportional to the rainfall, according to the survey.

3. Investigation methods

3.1. Core drilling and inclinometer measurements

Since 2010, comprehensive engineering geological exploration has been carried out in the landslide area. Twenty-three boreholes were drilled in the southern area of the landslide in 2010, 2013, and 2014. Their locations and characteristics are presented in Fig. 2 and Table 1, respectively (Zhai, 2011; Li, 2014). The lithology, stratum thickness, core recovery rate, and static groundwater level in each borehole were recorded. Moreover, the deep cumulative displacements were measured six times with inclinometers installed at P1-7 and P1-9 from 28 December 2010 to 2 May 2011 (Zhai, 2011). The measurement interval of the inclinometers was 0.5 m downwards from the ground surface, and the lengths of the inclinometers in P1-7 and P1-9 were 33.5 m and 25 m, respectively. The depth of the sliding surface was evaluated by the lithology and deep cumulative displacement.

3.2. Field real-time monitoring

The hourly surface displacement, rainfall, groundwater level, and groundwater pressure were monitored in real time using GPS (BDStar Navigation), a pluviometer, osmometers, and piezometers (Geoken), respectively, which were mainly arranged in the southern area (Fig. 2). Some osmometers and piezometers (i.e., P1-1, P1-2, and U1-2) were broken by the creeping of the landslide. The data from osmometers U1-1 and P1-3 and piezometers U1-3, U1-4, and U1-5 from 1 June 2013 to 31 December 2013 were used to evaluate the characteristics of the groundwater circulation (Li, 2014). The groundwater level was calculated from the osmotic pressures in U1-1 and P1-3. Abnormal hourly data were first deleted, and the daily values of the surface displacement, rainfall, and groundwater level were then calculated.

3.3. ERT survey

Four ERT profiles were conducted by using a Wenner–Schlumberger configuration in the study area. Their locations and measurement parameters are shown in Fig. 2 and Table 1, respectively. The A–A′ and B–B′ profiles were oriented E–W, and the C–C′ and D–D′ profiles were oriented N–S. The A–A′ and D–D′ profiles were measured in the dry period (i.e., from October to the following May) and the rainy period

Fig. 1. (a) Location of the study area in Sichuan province. (b) Tectonic outline map in the Zhongjiang District. (c) Geological schematic map of the Kualiangzi landslide. (d) Geological profile of section I–I′.