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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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
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 km², and the volume is 2.55 million m³ (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 bed-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 (Q4 fl + 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 (J3p). 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 brecias (Q4 ol). 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. 2. Field plan of the geotechnical and geophysical investigations conducted in the southern part of the Kualiangzi landslide.

Table 1

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Date</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling P1-1</td>
<td>11 January 2013 to 13 January 2013</td>
<td>The coring depth was 41.50 m, and the depth of sliding surface was 34.20–35.10 m.</td>
</tr>
<tr>
<td>Drilling P1-2</td>
<td>7 January 2013 to 9 January 2013</td>
<td>The coring depth was 29.80 m, and the depth of sliding surface was 17.20–17.40 m.</td>
</tr>
<tr>
<td>Drilling P1-3</td>
<td>31 May 2013</td>
<td>18.40 m deep coring, osmotic pressure measurements.</td>
</tr>
<tr>
<td>Drilling P1-4</td>
<td>3 June 2013</td>
<td>18.00 m deep coring.</td>
</tr>
<tr>
<td>Drilling P1-5</td>
<td>9 October 2010 to 21 October 2010</td>
<td>59.30 m deep coring.</td>
</tr>
<tr>
<td>Drilling P1-6</td>
<td>10 November 2010 to 15 November 2010</td>
<td>48.80 m deep coring.</td>
</tr>
<tr>
<td>Drilling P1-7</td>
<td>16 November 2010 to 20 November 2010</td>
<td>The coring depth was 38.01 m, the depths of the sliding surface were 26.04–26.74 m and 31.70–32.10 m, and the cumulative displacement was measured with an inclinometer.</td>
</tr>
<tr>
<td>Drilling P1-8</td>
<td>7 November 2010 to 9 November 2010</td>
<td>The coring depth was 35.40 m, and the depth of the sliding surface was 13.40–14.05 m.</td>
</tr>
<tr>
<td>Drilling P1-9</td>
<td>25 October 2010 to 3 November 2010</td>
<td>The coring depth was 25.37 m, the depth of sliding surface was 13.40–13.45 m, and the cumulative displacement was measured with an inclinometer.</td>
</tr>
<tr>
<td>Drilling P1-10</td>
<td>3 October 2010 to 10 October 2010</td>
<td>The coring depth was 35.92 m, and the depth of the sliding surface was 1.80–1.90 m. 48.20 m deep coring, osmotic pressure measurements.</td>
</tr>
<tr>
<td>Drilling U1-1</td>
<td>23 May 2013 to 26 May 2013</td>
<td>The coring depth was 30.70 m, and the depth of the sliding surface was 19.80–22.50 m.</td>
</tr>
<tr>
<td>Drilling U1-2</td>
<td>27 May 2013 to 29 May 2013</td>
<td>The coring depth was 31.20 m, and the depth of the sliding surface was 29.10–29.30 m.</td>
</tr>
<tr>
<td>Drilling U1-3</td>
<td>3 January 2013 to 5 January 2013</td>
<td>The coring depth was 18.00 m, and the depth of the sliding surface was 15.50–16.00 m. 18.60 m deep coring.</td>
</tr>
<tr>
<td>Drilling U1-4</td>
<td>30 May 2013</td>
<td>The coring depth was 18.20 m, and the depth of the sliding surface was 14.00–14.50 m.</td>
</tr>
<tr>
<td>Drilling U1-5</td>
<td>2 June 2013</td>
<td>The coring depth was 16.00 m, and the depth of the sliding surface was 12.00–13.00 m.</td>
</tr>
<tr>
<td>Drilling U2-1</td>
<td>14 July 2014 to 17 July 2014</td>
<td>The coring depth was 36.50 m, and the depth of the sliding surface was 29.20–30.00 m.</td>
</tr>
<tr>
<td>Drilling U2-2</td>
<td>22 July 2014 to 28 July 2014</td>
<td>The coring depth was 46.50 m, and the depth of the sliding surface was 38.70–40.20 m.</td>
</tr>
<tr>
<td>Drilling U2-3</td>
<td>17 July 2014 to 19 July 2014</td>
<td>The coring depth was 45.90 m, and the depth of the sliding surface was 39.15–39.95 m.</td>
</tr>
<tr>
<td>Drilling U2-4</td>
<td>2 August 2014 to 3 August 2014</td>
<td>The coring depth was 45.40 m, and the depth of the sliding surface was 37.40–37.70 m.</td>
</tr>
<tr>
<td>Drilling U2-5</td>
<td>29 July 2014 to 1 August 2014</td>
<td>The coring depth was 54.22 m, and the depth of the sliding surface was 47.48–48.28 m.</td>
</tr>
<tr>
<td>Drilling U2-6</td>
<td>4 August 2014 to 6 August 2014</td>
<td>The coring depth was 53.75 m, and the depth of the sliding surface was 44.00–46.50 m.</td>
</tr>
<tr>
<td>Drilling U2-7</td>
<td>8 August 2014 to 10 August 2014</td>
<td>The coring depth was 57.30 m, and the depth of the sliding surface was 51.40–52.40 m.</td>
</tr>
<tr>
<td>Drilling U2-8</td>
<td>12 August 2014 to 14 August 2014</td>
<td>The coring depth was 52.83 m, and the depth of the sliding surface was 46.10–47.50 m.</td>
</tr>
<tr>
<td>GPS01</td>
<td>4 September 2012</td>
<td>GPS measurements.</td>
</tr>
<tr>
<td>GPS02</td>
<td>4 September 2012</td>
<td>GPS measurements.</td>
</tr>
<tr>
<td>yl02</td>
<td>26 May 2013</td>
<td>Rainfall measurements.</td>
</tr>
<tr>
<td>A–A profile</td>
<td>28 February 2014, and 19 September 2014</td>
<td>60 electrodes, 4 m apart, and 692 data points in a Wenner–Schlumberger configuration.</td>
</tr>
<tr>
<td>B–B profile</td>
<td>25 August 2013</td>
<td>43 electrodes, 6 m apart, and 408 data points in a Wenner–Schlumberger configuration.</td>
</tr>
<tr>
<td>C–C profile</td>
<td>25 August 2015</td>
<td>50 electrodes, 6 m apart, and 527 data points in a Wenner–Schlumberger configuration.</td>
</tr>
<tr>
<td>D–D profile</td>
<td>1 March 2014, 20 September 2014</td>
<td>60 electrodes, 6 m apart, and 672 data points in a Wenner–Schlumberger configuration.</td>
</tr>
</tbody>
</table>
Fig. 3. Electrical resistivity tomography results: (a) profile A-A’ on 19 September 2014; (b) profile B-B’ on 25 August 2015; (c) profile C-C’ on 25 August 2015; (d) profile D-D’ on 1 March 2014.
(i.e., from June to September) to evaluate the characteristics of the groundwater circulation.

A WDA-1 apparatus (Chongqing, China) was used to make the ERT measurements. The apparatus is a single-channel 2-D electrical survey system that uses a large number of electrodes (60 or more), which are connected to a multi-core cable. An electronic switching unit in the apparatus was used to automatically select the relevant four electrodes for each measurement. For all of the profiles, the measurements were repeated three times and completed in approximately 90 min.

To build usable data sets for ERT processing, apparent resistivity data with relative errors greater than 2% were first deleted. Then, the arithmetic mean of the data from the three repeated measurements was calculated, and the apparent resistivity data sets were built. The apparent resistivity data were then inverted using the Res2div software based on the least-squares method (Loke and Barker, 1996; Loke, 2007). For the A–A′ and D–D′ profiles, resistivity ratio tomographies for the rainy and dry periods were also calculated to evaluate the groundwater circulation.

4. Results and discussion

4.1. Results of the electrical resistivity profiles

Fig. 3 shows the results of the four ERT profiles. The simplified logs and groundwater levels of the boreholes are also depicted on the resulting tomograms. The A–A′ and B–B′ profiles were arranged along the direction of the landslide movement, whereas the C–C′ and D–D′ profiles were measured perpendicular to the landslide movement. For the A–A′ profile, a shallow conductive layer (less than 15 Ωm) between 48 and 176 m coincided with the clay layer, which is used by locals for drinking water (Fig. 4). The dip angle of the sliding surface is generally consistent with that of the bedrock. A resistive layer underlying the sliding surface was observed, which corresponds to the bedrock that is comprised of sandstone.

For the B–B′ profile, which had a larger unit electrode spacing (i.e., 7 m), the sliding surface between 0 and 112 m was located at the transition zone between the low resistivity (i.e., the sliding material) and high resistivity (i.e., the bedrock). Between 112 and 288 m, a shallow resistive layer coincided with the gravelly soil and unweathered sandstone (greater than 50 Ωm), and the sliding surface corresponded to the deep zone, which had a low resistivity that was less than 30 Ωm. The thickness of the sliding material decreased from 50 m to several meters in the direction of the sliding.

Due to topographic convenience, the C–C′ profile crossed two tension fractures with the NE–SW directions that were induced by the creeping of the landslide (Fig. 2). The ridged resistive zone of 50 Ωm between 133 and 154 m could be interpreted as the sandstone between the tension fractures. The shallow materials (between 20 and 40 Ωm) are comprised of gravelly soil. The resistivity of the sliding surface was lower than 20 Ωm due to the weathered sandstone and mudstone and the high groundwater availability. The thicknesses of the sliding materials decreased to several meters at the southern boundary (i.e., between 308 and 336 m).

The unconsolidated formation in the tension troughs is comprised of weathered fractured rock, gravels, talus deposit, breccias, and soil that have a large range of resistivities (10 to 100 Ωm). From the field survey, the material with high percentages of soil showed local low resistivities (less than 40 Ωm), e.g., at distances between 0 and 80 m along the D–D′ profile. The material with a high percentage of rock blocks showed a local high resistivity (more than 50 Ωm), e.g., at distances between 186 and 216 m along the D–D′ profile. The thickness of the materials that filled the main tension trough was greater than the detection depth (approximately 40 m) in the D–D′ profile. The depth of the sliding surface close to the main scarp is 46.10–52.40 m, according to the core samples from U2-7 and U2-8. The resistivity at the bottom of U2-7 was lower than those at the bottom of U2-8 because the groundwater level of U2-7 was 4.4 m higher than that of U2-8, which is closer to the gully.

Fig. 5 shows the geological profile of section II–II′ (Fig. 2) based on the geotechnical and ERT investigations. The sliding surface located at the weathered mudstone layer with low strength that belongs to the Penglaizhen group formed in the Upper Jurassic period (J3p). Three obvious tension troughs formed due to the slipping of the landslide. The former integral sandstone layer was cut off by the tension troughs, which were filled with colluvium comprised of rock blocks, gravels, and breccias (Q3m). The middle and front parts of the landslide were covered by a layer of residuals and diluvials (Q4el + dl), of which the ingredients are clay soil and gravelly soil. The thickness of the sliding material decreases from 50 m to several meters from the rear edge to the toe.
front of the landslide. The storage and transmission of groundwater on the sliding surface speed the weathering processes of the sandstone and mudstone and hence increase the porosity and permeability. A continuous and stable groundwater level has formed around the sliding surface. The groundwater level in the tension trough and at the middle part was the highest in the landslide.

To study the characteristics of the groundwater circulation, the resistivity image measured in the dry period (i.e., 28 February 2014 and 1 March 2014 for the A–A’ and D–D’ profiles, respectively) was taken as a reference model, and the resistivity changes in the rainy period (i.e., 19 September 2014 and 20 September 2014 for the A–A’ and D–D’ profiles, respectively) in terms of a resistivity ratio with respect to the reference model are shown in Fig. 6. A general decrease in resistivity can be seen in the shallow layer of the two profiles, which is several meters thick. This decrease in resistivity is interpreted as an increase in water content related to the frequent rainfall in the rainy period. A significant resistivity drop was found at approximately a depth of 15 m in the A–A’ profile, which is consistent with the sliding surface in the weathered mudstone layer. The sandstone layer underlying the mudstone layer exhibited a slight increase in resistivity. These results imply that the groundwater recharged by the precipitation flows in the zone of the sliding surface and discharged to the toe front by seasonal springs. For the D–D’ profile, the stable groundwater level was out of range, and the overall decrease in resistivity was detected as an increase in water content due to the frequent rainfall in the rainy period.

4.2. Temporal variation in rainfall, surface displacement, and groundwater level

Fig. 7 shows the daily data of rainfall, surface displacement, and groundwater level from 1 June 2013 to 31 December 2013. Rainfall is a key factor that influences the surface displacement and the groundwater level. In the rainy season (i.e., 6/1/2013–9/30/2013), the average values of the daily rainfall and surface displacement were 4.76 mm/d and 3.70 mm/d, respectively. In the dry season (i.e., 1/10/2013–12/31/2013), the average values of the daily rainfall and surface displacement were 0.65 mm/d and 0.46 mm/d, respectively. The maximum value of the surface displacement rate was 24.15 mm/d on 24 July 2013, after 259.5 mm of rain fell in a week.

The groundwater levels of U1–1 (Fig. 7) and U2–7 (Fig. 6) in the tension trough were the highest in all of the boreholes and were approximately 10 meters higher than that closing to the leading edge (i.e., U1–5). The groundwater level decreases along the sliding surface at the rear part of the landslide (i.e., a distance from 150 to 194 m in the B–B’ profile in Fig. 3). The groundwater level at U2–1 was the lowest at the rear part of the landslide and was 10 meters lower than that in the tension trough. A reasonable explanation is that the locations of the boreholes in the tension troughs were close to the southern boundary of the landslide, and some groundwater could discharge to the southern boundary along the tension fractures with NE–SW directions.

The groundwater level of U1–4 was the highest at the middle-leading part of the landslide. The shallow depth of the sliding surface (i.e., 16.50–16.90 m) and the flat terrain allowed the groundwater to recharge easily from precipitation. The groundwater level of U1–5 closest to the leading edge of the landslide was the lowest in all of the boreholes. The results of the resistivity variations and the groundwater level monitoring showed that the groundwater in the middle-leading part of the landslide is recharged by vertical infiltration and drains to the creek by springs (Fig. 1) along the sliding surface.

The groundwater levels of the boreholes respond to the rainfall by different modalities. The increment in groundwater level (i.e., U1–3, U1–4, and P1–3) measured at the leading-middle part of the landslide was less than 2 m and dissipated rapidly over several days. In the tension trough, the unsaturated thickness of the colluvium is greater than 40 m. The water content of the colluvium is a key factor that influences the variation modes of the groundwater level. At the initial stage of the rainy period, the water content of the colluvium gradually increases to the upper water retention from the frequent rainfall, and the ratio of the groundwater level increment to rainfall increases simultaneously. For example, from 19 June 2013 to 28 June 2013, the total rainfall was 107 mm, and the ratio of the groundwater level increment to rainfall was 4.6. However, from 29 June 2013 to 10 July 2013, the total rainfall was 127 mm, and the ratio of the groundwater level increment to rainfall reached 27.0. After the water content of the colluvium reached the water retention, the groundwater level rapidly and obviously responded to the rainfall. From 18 July 2013 to 25 July 2013, the total rainfall was 259.5 mm, and the maximum value of daily rainfall was 112.5 mm on 22 July 2013. The groundwater level (i.e., U1–1) in the tension trough rapidly increased by 9.28 m, and the ratio of groundwater level increment to rainfall reached 82.5, which implies that the groundwater was mainly stored in the limited tension fractures. The groundwater level dissipated slowly until October 2013. The variations in groundwater level in the tension trough indicated that the groundwater

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**Fig. 5.** The geological profile of section II–II’.
Fig. 6. The resistivity changes in the rainy period in terms of the resistivity ratio with respect to the reference model in the dry period. (a) Resistivity ratios of the A–A’ profile at 19 September 2014, considering the data set of 28 February 2014 as a reference. (b) Resistivity ratios of the D–D’ profile at 20 September 2014, considering the data set of 1 March 2014 as a reference. The sliding surface and groundwater levels within U2-7 and U2-8 are indicated.

Fig. 7. The daily variations in rainfall, surface displacement, and groundwater level from 1 June to 31 December in 2013. The increment in groundwater level (i.e., U1-1) in the tension trough almost kept pace with the displacement rate of the landslide.
ran off mainly in the limited fissured medium and drained through the sliding surface slowly. The surface displacement rate increased to 24.15 mm/d on 24 July 2013. The rise in the groundwater level in the tension trough almost kept pace with the displacement rate of the landslide, which shows that the driving force of the landslide is the positive pore water pressure (Fan et al., 2009; Xu et al., 2015).

5. Conclusions

Translational landslides are a typical geohazard in Southwest China. In this paper, four ERT profiles were conducted to investigate the internal structure in the southern region of the Kualiangzi landslide using drill cores and inclinometer data. The variation in the resistivities of two profiles and groundwater levels in boresoles were used to evaluate the characteristics of groundwater recirculation within the landslide. In the ERT profiles, the sliding surface was located in a deep zone with low resistivity that corresponded to weathered sandstone and mudstone. From the rear part to the leading part of the landslide, the thickness of the sliding material decreased from 50 m to several meters. The complex compositions, i.e., gravelly soil, weathered fractured rock, talus deposit, and breccias, led to heterogeneity in the resistivities in the tension troughs. The areas with low resistivity corresponded to materials with high percentages of soil.

The variations in the resistivity profiles in the rainy period with respect to the profiles in the dry period showed that a significant resistivity drop was found at the sliding surface. The groundwater level in the tension trough and at the middle transition part from the hill-country to flat terrain was the highest in the landslide. The groundwater level closing to the toe front of the landslide was the lowest. The results of the electrical profiles and groundwater level measurements showed that the groundwater is recharged by precipitation and generally drains to the toe front by seasonal springs along the sliding surface.

The groundwater levels in different parts of the landslide respond to rainfall in different modes in the rainy period. When the water content of the colluvium reaches the water retention, the rapid and large increment to the toe front by seasonal springs along the sliding surface. The groundwater levels at the leading part of the landslide increased by a small value and dissipated over two months. However, the groundwater level at the leading-middle part of the landslide increased by a small value and dissipated rapidly over several days. The improved understanding of the internal structure and groundwater recirculation is beneficial to analysis of mechanisms and for hazard prevention in the translational landslide.

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