

Article

Electrical Resistivity Tomography (ERT) Investigation for Landslides: Case Study in the Hunan Province, China

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Abstract: Electrical resistivity tomography is a non-destructive and efficient geophysical exploration method that can effectively reveal the geological structure and sliding surface characteristics inside landslide bodies. This is crucial for analyzing the stability of landslides and managing associated risks. This study focuses on the Lijiazui landslide in Zhuzhou City, Hunan Province, employing the electrical resistivity tomography method to detect effectively the surrounding area of the landslide. The resistivity data of the deep strata were obtained, and the corresponding geophysical characteristics are inverted. At the same time, combined with the existing drilling data, the electrical structure of the landslide body is discussed in detail. The inversion results reveal significant vertical variations in the landslide body's resistivity, reflecting changes in rock and soil physical properties. Combined with geological data analysis, it can be concluded that the sliding surface is located in the sandy shale formation. Meanwhile, by integrating various geological data, we can conclude that the landslide is currently in a creeping stage. During the rainy season, with rainfall infiltration, the landslide will further develop, posing a risk of instability. It should be promptly addressed through appropriate remediation measures. Finally, based on the results of two-dimensional inversion, this article constructs a three-dimensional surface morphology of the landslide body, which can more intuitively compare and observe the internal structure and material composition of the landslide body. This also serves as a foundation for the subsequent management and stability assessment of landslides, while also paving the way for exploring new perspectives on the formation mechanisms and theories of landslides.

Keywords: landslides; geophysics; ERT; sliding surface



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1. Introduction

As the most common geological disaster, the landslide has caused huge loss of life and property all over the world [1–3]. China is one of the countries with the most serious human and property losses caused by landslides [4–6]. Moreover, the landslide, as one of China's most significant geological hazards, displays uncertainty in both temporal and spatial dimensions. Among which, the number of landslides in Hunan Province is not only large, but also the material and property damage is extremely serious [7,8]. According to statistics from the Ministry of Natural Resources of the People's Republic of China, in 2022, a total of 5659 geological hazards were recorded in China, with landslides accounting for a staggering 3919 cases, representing 69.3% of the total number of geological hazards.

Taking Hunan Province as an example, a total of 2884 geological hazard events occurred in 2022, with landslides accounting for a significant proportion of 88.8% (2561 events). The geological environment in Hunan Province is mainly composed of residual slope deposits, which exhibit a loose structure and good permeability. As a result, the infiltration of rainfall significantly reduces the shear strength of the soil. Especially when bedrock serves as an aquiclude, it can lead to the formation of a groundwater barrier at the contact interface, potentially triggering soil sliding. These geological conditions contribute to the prevalence of small-scale soil landslides in the province, with over 90% occurring during the rainy season [9]. In this study, the Lijiazui Landslide is a typical case of a small-scale soil landslide. This landslide is particularly active during the rainy season, leading to ground swelling and cracks in residential retaining walls. This poses a serious threat to the lives and property of residents.

Today, there are numerous technologies available for landslide investigations, each with its own characteristics. Aerial and satellite methods (digital aerophotogrammetry, GPS, differential interferometric) provide information about slope surface features such as topography, morphology, landslide area, and displacement [10–14]. However, they do not offer any information about subsoil characteristics. On the other hand, direct field techniques (such as pressure gauge and displacement meters) can give us insights into the physical deformation of landslides but are limited to specific points on the landslide [15,16]. Geophysical methods can measure direct or indirect physical parameters related to landslide development, such as rock type and hydrology. These techniques are less invasive than previous methods and can provide more comprehensive information, overcoming the scale limitations of traditional geotechnical techniques [17,18]. In recent years, significant advancements have been made in the field of geophysical exploration, driven by the development of fundamental theoretical principles and the introduction of updated exploration equipment. Both field data collection and analysis of indoor data have witnessed remarkable progress [19–21]. The rapid evolution of these techniques has greatly expanded the scope of application for geophysical exploration methods [22,23]. Among them, an increasing number of scholars have introduced geophysical exploration technology in the investigation and management of landslides [24–30].

This study employs the ERT method to conduct field testing on site. To obtain an electrical resistivity tomography, the apparent resistivity values must be inverted by using inversion routines. Currently, there are numerous methods for inverting resistivity data, yet Res2Dinv remains the most widely utilized [31–36]. This study uses the software, Res2Dinv (version 3.54.44), and employs the smooth constrained least squares method, enabling the acquisition of two-dimensional cross sections through finite difference or finite element calculations with terrain corrections factored in [37,38]. ERT offers advantages such as flexible deployment and relatively low requirements for terrain, making it the preferred method for exploration in mountainous regions [39]. This method is a type of direct current (DC) electrical exploration technique that utilizes the differences in electrical resistivity of subsurface materials to extract and analyze the response characteristics of a stable underground electric field established artificially [40]. It aims to actively explore the geological structure and formation of underground layers to achieve the purpose of determining the subsurface structure and geological features [41]. The measurement results yield a two-dimensional cross-section of apparent resistivity, which, upon qualitative analysis, allow for the simultaneous study of the electrical characteristics in both the horizontal and vertical directions within a certain depth range underground [42]. The electrical resistivity is primarily influenced by the mineral composition and groundwater in the subsurface media, which can be utilized to analyze the variations in subsurface media caused by differences in grain size, water content, and rock mineralization level [43,44].

This paper selects the Lijiazui landslide in Hunan Province as a case study. With the assistance of ERT surveying and field investigation data, the paper analyzes the parameters of the geological resistivity, determines the sliding interface, depth, and range of the landslide, and explores its deformation and failure mechanism. The aim was to provide

a scientific basis for landslide control. At the same time, this research is also of great significance for the study of typical landslides in Hunan Province.

2. Materials

The Lijiazu Landslide is in Shijiang Village, Huju Town, Chaling County, Zhuzhou City, Hunan Province, China. The main landslide is on the east bank of the Mishui River, about 200 m from the river. Geologically, it is on the southwestern edge of the Chayong Basin, with the main fault being the Jiubujiang Fault, which runs NE–SW (Figure 1). In the study area, there is no significant recent tectonic activity, indicating that it belongs to a relatively stable tectonic block. According to the local geological map (Figure 1), the main exposed geological formations in the study area consist of the Devonian, Carboniferous, Jurassic, and Quaternary periods. The exposed geological formation of the landslide area is characterized by the Carboniferous Malanbian Formation.

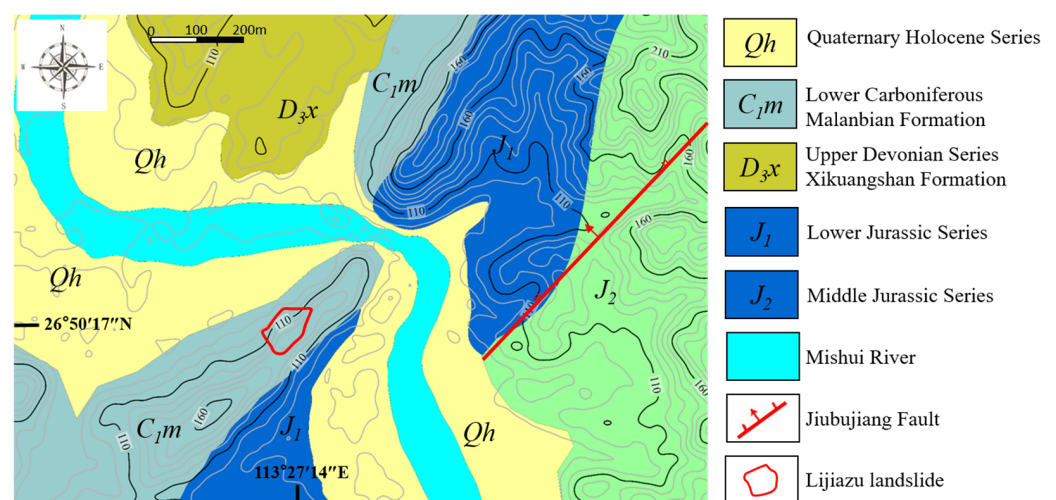


Figure 1. Geological map of the study area.

The main sliding direction of the landslide is 332° , and it exhibits an irregular shape overall. The slope gradient ranges from 20° to 35° , with an average gradient of 28° . The main body of the landslide has a length of approximately 100 m and a width of around 160 m, categorizing it as a small-scale landslide (Figure 2). On both sides of the landslide, the boundaries are marked by cracks, and these boundaries align with the transition from gentle to steep slopes on the natural hillside. The landslide front edge is located behind the residential house retaining wall, and due to the continuous development of the landslide, the retaining wall has experienced cracking and expansion (Figure 3). Based on the data consulted, the annual precipitation in the research area is around 1400 mm. The wet season spans from March to August, with monthly rainfall exceeding 100 mm each month. The rainy season, from April to June, experiences an average monthly precipitation of approximately 200 mm.

In order to analyze comprehensively the landslide and investigate the geological characteristics of the landslide strata, a total of six boreholes were deployed at the landslide site (Figure 4). Based on the findings from drilling and geological investigations, it can be determined that the landslide cover material is mainly composed of fine-grained clay and gravelly soil. The underlying bedrock consists of Carboniferous lower Malanbian Formation, which is composed of siltstone, sandy shale, and limestone (Tables 1 and 2). Borehole data reveal that the sliding surface is situated within the sandy shale stratum. Physical tests indicate that the local geological strata are relatively fragmented, with poor physico-mechanical properties.

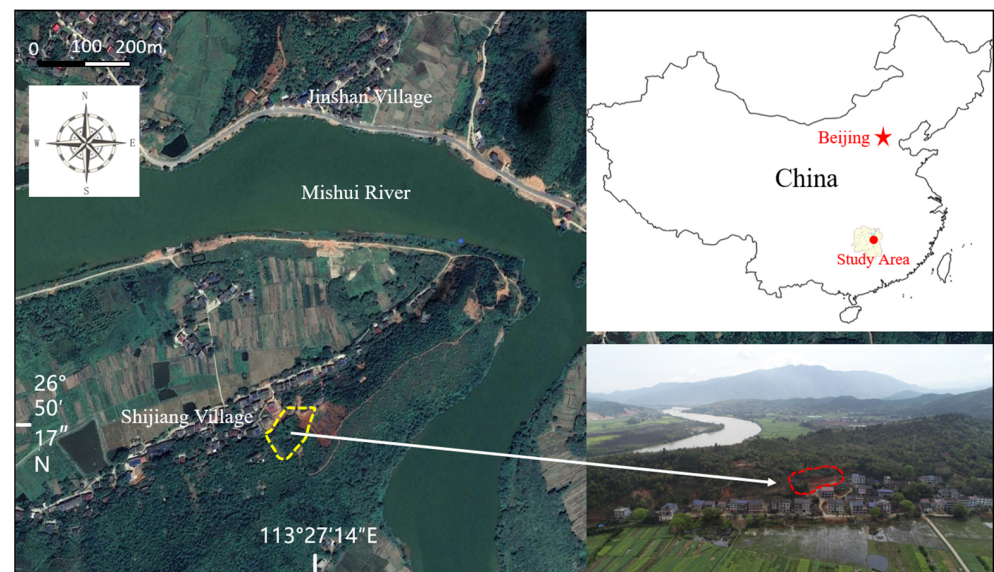


Figure 2. Map of landslide location. Yellow dashed circle: Landslide location in satellite images. Red dashed circle: Drone aerial photography of landslide location. Red spot: study area.



Figure 3. Landslide deformation signs: (a) cracks in the retaining wall at the front edge of the landslide; (b) landslide trailing edge crack.

Table 1. Physical parameters of soil mass in landslide area.

Sample ID	MC %	Sp. Gravity	Liquid Limit %	Plastic Limit %	Plasticity Index	DD (g/cm ³)	VR
1	22.35	2.72	35.65	21.55	14.1	1.56	0.75
2	24.8	2.72	37.5	22.6	14.9	1.55	0.76
3	23.2	2.71	33.1	21.0	12.1	1.57	0.73

Abbreviations: 1, silty clay; 2, completely weathered sandy shale; 3, completely weathered siltstone; MC, moisture content; Sp. gravity, specific gravity; DD, dry density; VR, void ratio.

Table 2. Physical and mechanical parameters of limestone.

Sample ID	Test	Number	Average Value	Maximum Value	Minimum Value
4	Uniaxial compressive strength (MPa)	4	62.31	77.60	45.10
	Internal friction angle (Φ)	4	42.18	44.2	41.2
	Cohesive force (MPa)	4	6.02	7.25	6.17

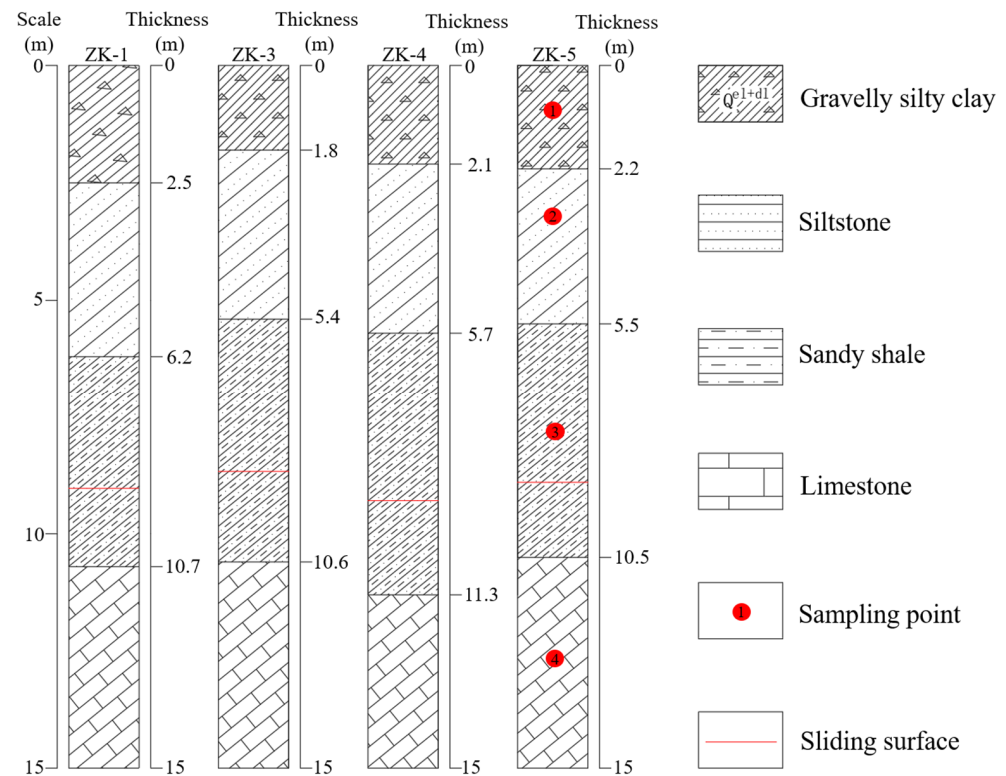


Figure 4. Drill hole column diagram.

Based on the comprehensive analysis of the on-site geological environment and the results of previous geological investigations, the ERT method was employed in the study area through grid-based field detection. A total of four survey lines (lines “a”, “h”, “i”, and “j” in Figure 5) were established for this survey. The line “a” extends from the SSE direction to the NWW direction. The line starts from residential houses at the front edge of the landslide, while the endpoint is at the top of the slope, near the rear edge of the landslide. The length of the survey line “a” is approximately 260 m, with significant variations in the vertical elevation along its profile. The vertical difference between the starting and end points of the survey line is nearly 50 m. The lines “h”, “i”, and “j” were parallel to each other and perpendicular to the sliding direction, intersecting line “a” at an angle of approximately 77°. The “h” and “i” lines are 260 m in length, while the “j” line is 240 m. The vertical variation in the profiles of these three lines is minimal. The resistivity profiles of these three lines clearly display the boundaries of geological formations, indicating that the depth of the slip surface ranges from 5 to 10 m and is located within the Carboniferous sandy shale formation. The “h”, “i”, and “j” lines intersect with line “a” at ZK1 (drill hole #1), point M, and ZK4 (drill hole #4), respectively. Due to its approximate grid-like pattern, this layout method is referred to as grid-based wiring. The Warner device was selected for field data collection in this experiment. A 3 m electrode spacing was used, and the total number of electrodes was determined based on the length of the arrangement, with a maximum of 90 electrodes.

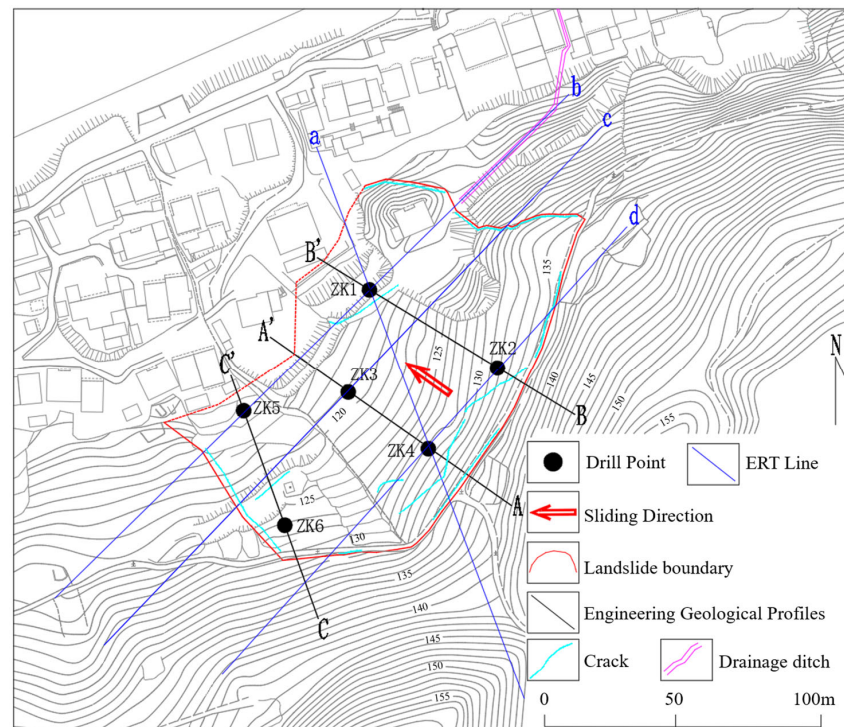


Figure 5. Topographic map of Lijiazu landslide and the layout of geological survey.

3. Results

3.1. Measured Results and Geological Interpretation

After obtaining measured data from four survey lines, the present study employed the Res2dinv software to interpret the data, resulting in the derivation of four inversion results (Figures 6 and 7). Based on geological and drilling data, the analysis reveals that the landslide body exhibits clear stratification. The upper layer consists of Quaternary slope residual deposits, which are gravelly clay with resistivity ranging from 1200–2500 $\Omega \cdot m$. However, from the foot to the top of the slope, the gravel content in the surface clay gradually increases, with the rock component being siltstone. In the rear part of the landslide, the gravel content reaches around 35%, which also leads to a higher resistivity in the surface layer of the landslide body, ranging from 2500–8000 $\Omega \cdot m$. This can be observed by comparing the profiles in Figure 6 and line “i” and line “j” in Figure 7. The second layer consists of siltstone and sandy shale with a resistivity range of 600–1200 $\Omega \cdot m$, which is also the formation where the sliding bed is located. The third layer is limestone, and drilling data reveal that the local limestone formation has karst development, resulting in high water content within the limestone formation and thus a resistivity lower than 600 $\Omega \cdot m$.

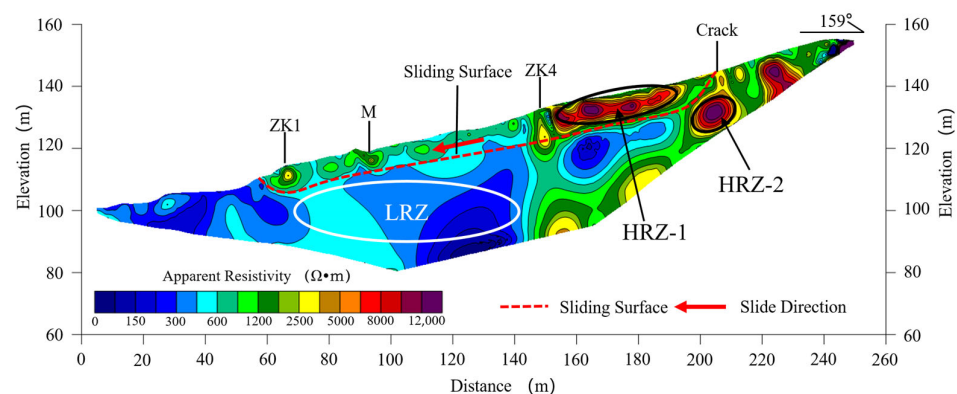


Figure 6. ERT profile of line “a”. LRZ: low-resistivity zone; HRZ: high-resistivity zone.

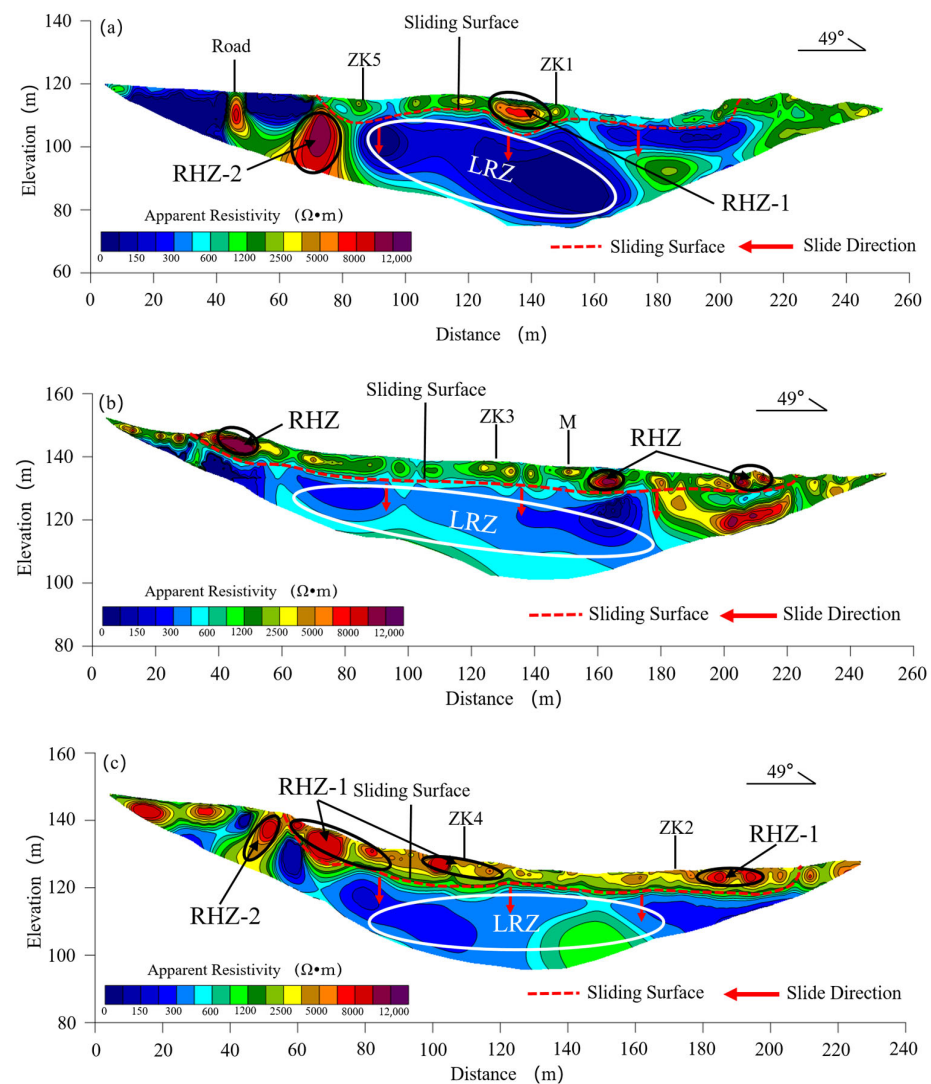


Figure 7. ERT profile of line “h” (a), line “i” (b), line “j” (c). LRZ: low-resistivity zone; HRZ: high-resistivity zone.

Figure 6 presents the electrical resistivity tomography along profile line “a” of the landslide. Due to the contrasting electrical properties of the geological layers, the resistivity profile can effectively delineate the morphological characteristics of the sliding surface. Based on the analysis of drilling data, it can be determined that the slip surface is located within a sandy shale formation with a resistivity ranging from 600–1200 $\Omega \cdot m$. The overall depth of the slip surface remains relatively consistent between 7 to 8 m. There is a high-resistivity anomaly on the surface at positions ranging from 145 to 190 m. This anomaly is attributed to the increased content of surface gravel in the upper part of the landslide body, with the majority of gravel having diameters between 3 and 15 cm. Occasionally, larger boulders with diameters exceeding 30 cm are observed, contributing to the increased electrical resistivity on the surface behind the landslide (HRZ-1 in Figure 6). Within a range of approximately 200–220 m from the starting point of the survey line, a significant high-resistivity anomaly was detected underground (HRZ-2 in Figure 6). Analysis of geological data indicates that this anomaly corresponds to the rear edge of a landslide, characterized by a prominent fissure. Thus, the presence of the high-resistivity anomaly can be attributed to this geological feature.

Figure 7 presents the inversion result of the landslide along three survey lines, namely “h”, “i”, and “j”. By examining the resistivity profiles of four survey lines, it can be observed that the geological information reflected at these common points is consistent. From the

resistivity profile, it is evident that the surface resistivity of lines “h”, “i”, and “j” gradually increases. This also corresponds to the actual situation where the content of gravel in the superficial clay layer increases continuously from the base to the top of the slope (HRZ-1 in Figure 7). At the same time, several resistivity anomalies can be observed in these three profiles: (1) In the 0–70 m section of profile “h”, the resistivity of the entire rock formation is less than $150 \Omega \cdot \text{m}$. This is due to the fact that this section of the profile is located in a drainage ditch in a residential area, resulting in a low resistivity state caused by the infiltration of surface water. (2) High resistivity anomalies can be found at the boundaries of the landslides in profiles “h”, “i”, and “j”. This is because the landslide boundaries are characterized by cracks, which lead to high resistivity anomalies (HRZ-2 in Figure 7). (3) Below the sliding surface in all three profiles, there are large low resistivity bodies with resistivity less than $300 \Omega \cdot \text{m}$ (LRZ in Figure 7). This is attributed to the underlying bedrock of high water-content limestone formation, which exhibits a low resistivity anomaly due to the influence of water.

3.2. The Three-Dimensional Morphology of Landslides

This paper presents inversion result of four survey lines obtained through grid layout testing. Based on their relative positional relationships, these four profiles are then utilized to construct three-dimensional conceptual diagrams from different perspectives (Figure 8). Figure 8 demonstrates vividly the morphological characteristics of the sliding surface and the sliding direction of the slope. The “h”, “i”, and “j” survey lines that intersect with a survey line at points ZK1 (drill hole #1), M, and ZK4 (drill hole #4), respectively. Based on the resistivity profiles of these four survey lines, it can be observed that the geological information reflected at the common points of the different survey lines is generally consistent.

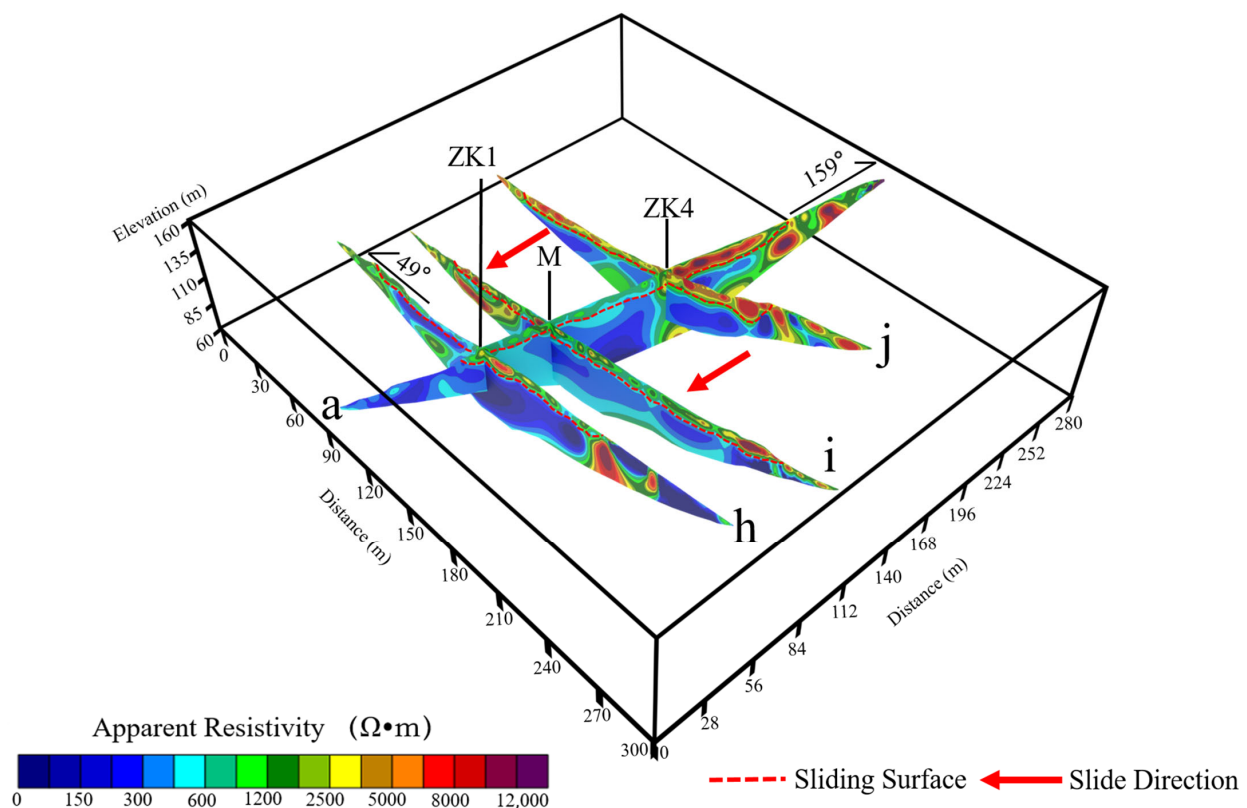


Figure 8. Fence diagram showing the location of the 2D ERT (line “a”, “h”, “i”, “j”) within a 3D space.

It can be observed that the resistivity characteristics presented at the same location on different resistivity profiles should be consistent with the geological structure. By comparing the resistivity profile intersection points, it is evident that the same location on different profiles consistently exhibits low resistivity values at a consistent depth.

4. Discussion

The formation mechanism of landslides needs to consider various factors such as displacement and precipitation. In this paper, we analyze comprehensively various aspects of landslide features by integrating ERT data, geological survey data, and drilling data. This analysis provides a more comprehensive reference basis for studying the formation mechanism of landslides. The profile data obtained from the ERT effectively demonstrate the morphology and burial depth of the sliding surface of the landslide.

Based on the measured results of ERT and combined with borehole data, Figure 9 presents a geological profile of the Lijiazuo landslide project. The existence of gravel in the soil layer provides a pathway for the infiltration of surface rainwater. When rainwater infiltrates the contact surface of the underlying bedrock, the permeability coefficient of the bedrock is relatively lower compared to the Quaternary cover layer. As a result, groundwater accumulates, leading to the softening of the weathered layer on the upper part of the bedrock. The authors believe that the presence of gravel in the soil layer serves as a pathway for the infiltration of surface rainwater. Comparatively, the permeability coefficient of the bedrock is lower than that of the Quaternary cover layer, leading to the accumulation of groundwater and the subsequent softening of the weathered layer on the upper part of the bedrock. In geological formations, mineral ions undergo physical and chemical transformations such as hydration and hydrolysis. As the moisture content increases, the electrical resistivity of these formations decreases. Eventually, when the formation reaches a state of complete saturation, the electrical resistivity is stabilized and no further changes occur. With the continuous infiltration of rainwater, the physical properties of sandy shale change and gradually soften. Additionally, the villagers in front of the slope had excavated the slope to construct houses, resulting in the formation of a steep slope on the front edge of the slope. Due to these two factors, the sliding mass continuously penetrates and forms a sliding surface under the influence of gravity. Simultaneously, cracking gradually occurs in the middle and rear of the sliding mass. These cracks provide convenient channels for surface water infiltration, causing water to accumulate at the crack locations. Under the pressure of water, the sliding surface continues to develop, and the entire slope is continuously compressed downward, leading to cracks in the houses in front of the slope.

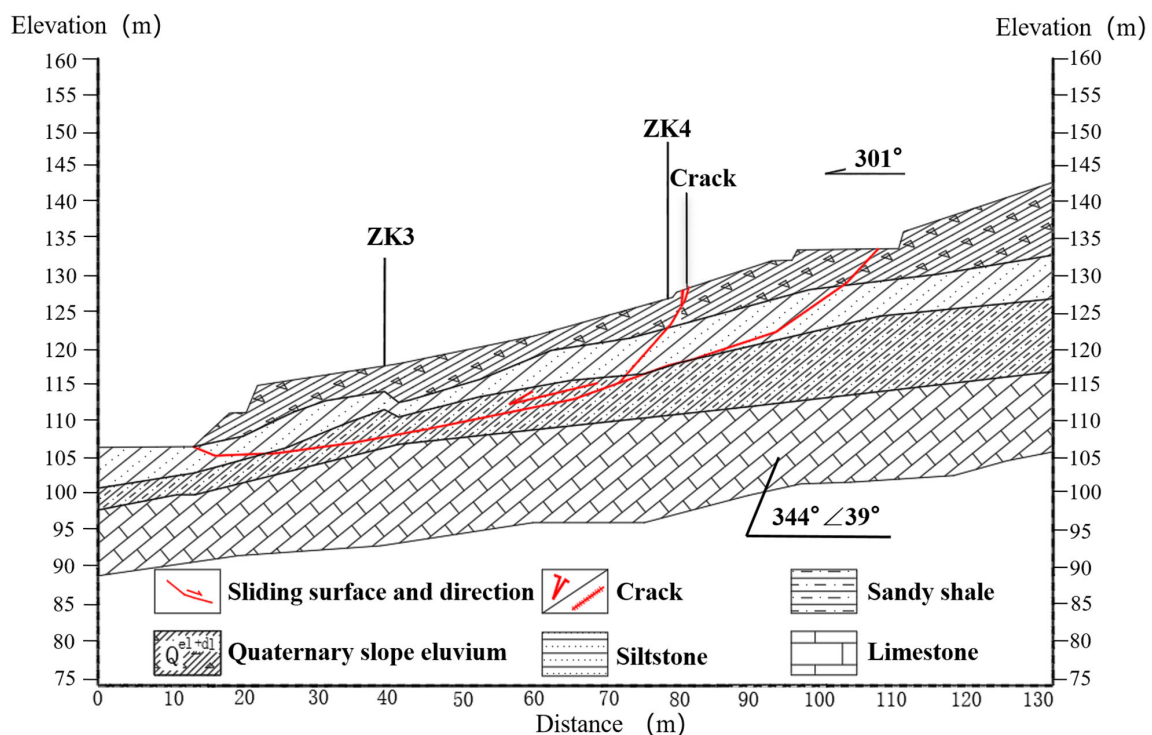


Figure 9. Engineering geological profile AA' of Lijiazuo landslide.

Through the investigation of the landslide and geophysical surveys, along with the collective data analysis, it was determined that the landslide had entered the stage of creeping deformation. The occurrence of cracking in residential houses in front of the landslide indicates that the entire slope is still undergoing continuous development. Under the influence of heavy rain or prolonged rainfall, the landslide may further expand its movement, leading to an increased extent of displacement. Consequently, this poses a threat to the lives and properties of individuals in the vicinity, as well as endangering buildings and infrastructure in the area. Given the substantial threat the landslide poses to both individuals and buildings, the high cost of re-homing the population makes it advisable to address promptly the landslide through effective remediation measures.

5. Conclusions

This study involved a comprehensive collection of geological data including regional tectonic background and lithology of the study area. Electrical resistivity tomography (ERT) was employed in the study area to obtain multiple ERT profiles through data inversion. By combining geological information from boreholes and other sources, the morphological characteristics and depth of the sliding surface could be determined. The following conclusions were drawn:

- (1) In this study, the Lijiazui landslide was investigated using a grid ERT method for geophysical measurements. The measured 2-D resistivity profiles were compared and interpreted alongside drilling data to determine the depth and morphology of the landslide's sliding surface. Furthermore, three-dimensional visualization of the landslide information was constructed by combining the two-dimensional resistivity profiles, providing a more intuitive display of the internal morphology of the entire slope.
- (2) Through comprehensive analysis, it is evident that the landslide is currently in a creeping phase, with the possibility of unstable collapse. Considering the high cost of relocation, it is recommended to implement promptly measures to mitigate the landslide.
- (3) The application of ERT provides a new approach for landslide exploration. In subsequent landslide investigations, geological data can be combined with geophysical methods to further obtain three-dimensional structural information and geological characteristics of landslides, thereby providing valuable insights into the mechanisms and stability of landslides.

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