

Locking Effect of the Inhomogeneous Tectonic Lenticular Rock Mass in the Internal Geological Structure of the Baige Landslides

Peng Cao¹, Huiming Tang^{*1,2}, Kun Fang¹, Jianhui Deng³, Zongliang Li⁴, Xinming Wu⁵

1. Department of Engineering Geology and Geotechnical Engineering, Faculty of Engineering, China University of Geosciences (Wuhan), Wuhan 430074, China

2. Badong National Observation and Research Station of Geohazards, China University of Geosciences (Wuhan), Wuhan 430074, China

3. State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resources and Hydropower, Sichuan University, Chengdu 610065, China

4. Chengdu Center, China Geological Survey, Chengdu 610081, China

5. No. 915 Geological Team, Sichuan Bureau of Geology and Mineral Resources, Meishan 620020, China

ABSTRACT: In 2018, Baige, Tibet, witnessed two consecutive large-scale landslides, causing significant damage and drawing widespread attention. From March 2011 to February 2018, the Baige landslide exhibited a 50-m displacement without complete failure, culminating in a collapse in October 2018. The mechanisms behind its resistance to failure despite substantial deformation and the influence of the complex geo-structure within the tectonic mélange belt remain unclear. To address these questions, this study utilized a multidisciplinary approach, integrating on-site geological field mapping, surface deformation monitoring, multielectrode resistivity method, and deep displacement analysis. The aim was to evaluate the impact of the intricate geo-structure within the tectonic mélange belt on the Baige landslide events. Findings reveal that the landslide's geo-structure consists of structurally fractured, mesh-like rock masses, including heterogeneous lenticular rock masses and intermittent brittle shear zones distributed around the lens-shaped rock masses. The study underscores that the inhomogeneous and weakly deformed lenticular rock masses function as natural locked segments, governing the stability of the Baige landslide. Specifically, the relatively intact and hard granodiorite porphyry play a crucial role in locking the landslide's deformation. Deep displacement analysis indicates that the brittle shear zones act as the sliding surfaces. The progressive destruction of the locked segments and the gradual penetration of brittle shear zones, driven by gravitational potential energy, contribute to the landslide occurrence. This research provides critical insights into the formation mechanisms of large-scale landslides within tectonic mélange belts.

KEY WORDS: Baige landslides, Jinsha River tectonic mélange belt, internal geological structure, macro-meso-micro scales, rock mass strength heterogeneity, locked effect, mechanisms.

0 INTRODUCTION

The Tibetan Plateau, characterized by its steep topography, diverse lithologies, and complex geological structures (Kawabata et al., 2021; Wang et al., 2015; Imayama et al., 2010), was formed through the collision of the Indian and Eurasian plates, leading to the closure of the Tethys Ocean and subsequent uplift (Ma et al., 2018; Najman et al., 2017; Wen et al., 2008). This tectonic activity has transformed plate junctions into active

faults, with their unique lithological and topographical features fostering a highly developed geological hazard chain (Zhao et al., 2023; Yin et al., 2017; Wang et al., 2000). Recently, an increase in large-scale, long-runout rockslides within these suture zones has significantly impacted the geological environment and posed risks to hydropower infrastructure and human safety (Zhang et al., 2023; Gao et al., 2020; Hewitt et al., 2011; Evans et al., 2009).

Numerous studies have explored the formation mechanisms of large-scale landslides in the Jinsha River suture zone, yet no consensus has been reached (Crosta et al., 2017; Fan et al., 2017; Dahal, 2014). The prolonged tectonic evolution, combined with uncertainties from diverse geological factors, multi-phase metamorphism and deformation, complex secondary tectonic fab-

*Corresponding author: tanghm@cug.edu.cn

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rics, and heterogeneous rock mass structures, results in highly varied and complex conditions, mechanisms, and modes of landslide initiation in this region (Zhao et al., 2022; Wang W P et al., 2020).

The stability of large-scale, long-runout rockslides in tectonic suture zones is governed by the spatiotemporal evolution of tectonic plates, climate variability, and deeply incised alpine valley landscapes (Zhou et al., 2024a; Shi et al., 2023; Rechberger et al., 2021). Among these, complex geological structures are the primary determinant of deformation and failure behavior (Vick et al., 2020; Zangerl et al., 2019; Brideau et al., 2009). Documented cases highlight the pivotal role of geological structures: the 2000 Yigong landslide was controlled by Carboniferous strata, with deformation and sliding along a weak layer (Zhou et al., 2020); the 2018 Sedongpu rockslide-debris flow in Tibet exhibited a layered block fracture structure due to multiple discontinuities (Liu et al., 2019); and the 2021 Chamoli rock-ice avalanche in the Himalayas involved a wedge-shaped gneiss mass intersected by discontinuous surfaces and overlain by a thick glacier layer (Shugar et al., 2021). These examples reflect common high-elevation, long-runout landslides on the Tibetan Plateau, which can be classified by geological structure into ophiolitic soft-rock mountains, layered structures, and wedge-shaped structures (Yin et al., 2023). The Baige landslide, specifically, is influenced by the complex geological structure of ophiolitic soft-rock mountains.

On October 11, 2018, and November 3, 2018, two high-position and large-scale landslides occurred in Boluo Township, Tibet, and led to the formation of two dams that blocked the Jinsha River at the same place. The outburst flood after the breach of the November dam caused huge losses downstream. Extensive research has been conducted on the historical deformation, formation mechanisms, and dynamic evolution of these landslides, identifying gravity as the primary driving force (Chen F et al., 2021; Chen Z et al., 2021; Yang et al., 2020). Additionally, water infiltration from the Bogong Gully, which softened the rock mass, facilitated landslide formation (Tian et al., 2020). Studies employing dynamic discrete element methods (Wang Y F et al., 2020; Zhang et al., 2020), depth-averaged equation (Liu et al., 2020), coupled model and depth-integrated continuum method (Ouyang et al., 2019) have analyzed the dynamic damage evolution and disaster chain of the landslides (Zeng et al., 2022). Other research attributes the landslides to the long-term cumulative effects of tectonic movement and surface denudation (Yi et al., 2022). While these studies primarily focus on superficial characteristics and macroscopic appearances, they often rely on outdated geological data, limiting insights into the fundamental mechanisms of landslide formation (Xue et al., 2017; Tang et al., 2015; Yin et al., 2011). These segments, critical stress-concentrated zones within rock bridges or supported arches, fail through shear or tensile crack propagation, determining landslide stability (Riva et al., 2018; Hungr et al., 2014). However, the Baige landslide's geo-

structure, characterized by diverse lithological rock masses, raises questions about their potential locking role. Furthermore, the geometry and spatial distribution of locked segments within slopes remain unclear, obscuring their relationship to landslide deformation and failure modes. Despite a 50-year deformation history (Xu et al., 2018), the slope, which displaced 50 m from March 2011 to February 2018, did not catastrophically fail until October 2018. Whether this delayed failure relates to the tectonic mélange belt's geologic structure remains unknown. This study aims to identify the complex geologic structure of the Baige landslide within the tectonic mélange belt and elucidate how this structure controlled the landslide's initial failure and formation processes.

This study investigated the geological structural features of the Baige landslide through slope profile analysis and physical exploration. Surface deformation of the residual mass, monitored via the Global Navigation Satellite System (GNSS), revealed that the landslide mass was constrained by lenticular rock mass during deformation and failure. Deep displacement data identified the sliding zone as a brittle shear zone. The landslide's evolution was characterized by four distinct phases. These findings provide critical insights into the formation mechanisms of large landslides in tectonic mélange belts.

1 REGIONAL SETTING

The Baige landslide events are situated within the Jinsha River suture zone (Figure 1a), a significant boundary between the Songpan-Ganze and Qamdo-Simao terranes that records the evolution of the ancient Tethys Ocean from the Palaeozoic Era, including its opening, subduction, and closure (Li et al., 2017; Zhu et al., 2011). Structurally, the Jinsha River suture zone represents a major lithosphere-traversing regional fault, forming a deep-cut valley (Zhang et al., 2015). Petrologically, it is dominated by ophiolitic tectonic mélanges, which delineate ancient convergent plate boundaries or accretionary blocks (Glen, 2016; Kusky et al., 2013). This mélange belt comprises an accretionary complex wedge containing fragments of oceanic crust (ophiolite) and continental detrital materials, which underwent varying tectonic environments and metamorphism before surface exposure. Late plateau uplift and active fracturing have resulted in diverse lithological lenses and properties, both in plan and section (Festa et al., 2012). The rock masses are further characterized by joints and cleavages, which affect their integrity and mechanical strength (Glastonbury and Fell, 2010).

The simultaneous interplay between the Tibetan Plateau intense uplift and river erosion has amplified topographic contrasts, creating a pronounced mountain-canyon landscape (Figure 1d). The Baige landslide, located on the right bank of the V-shaped Jinsha River Valley (Figure 1b), spans from a crown elevation of approximately 3 720 m at the valley shoulder to a toe elevation of 2 880 m at the river's concave bank, yielding an 840-m elevation difference. The landslide extends 1.43 km lin-

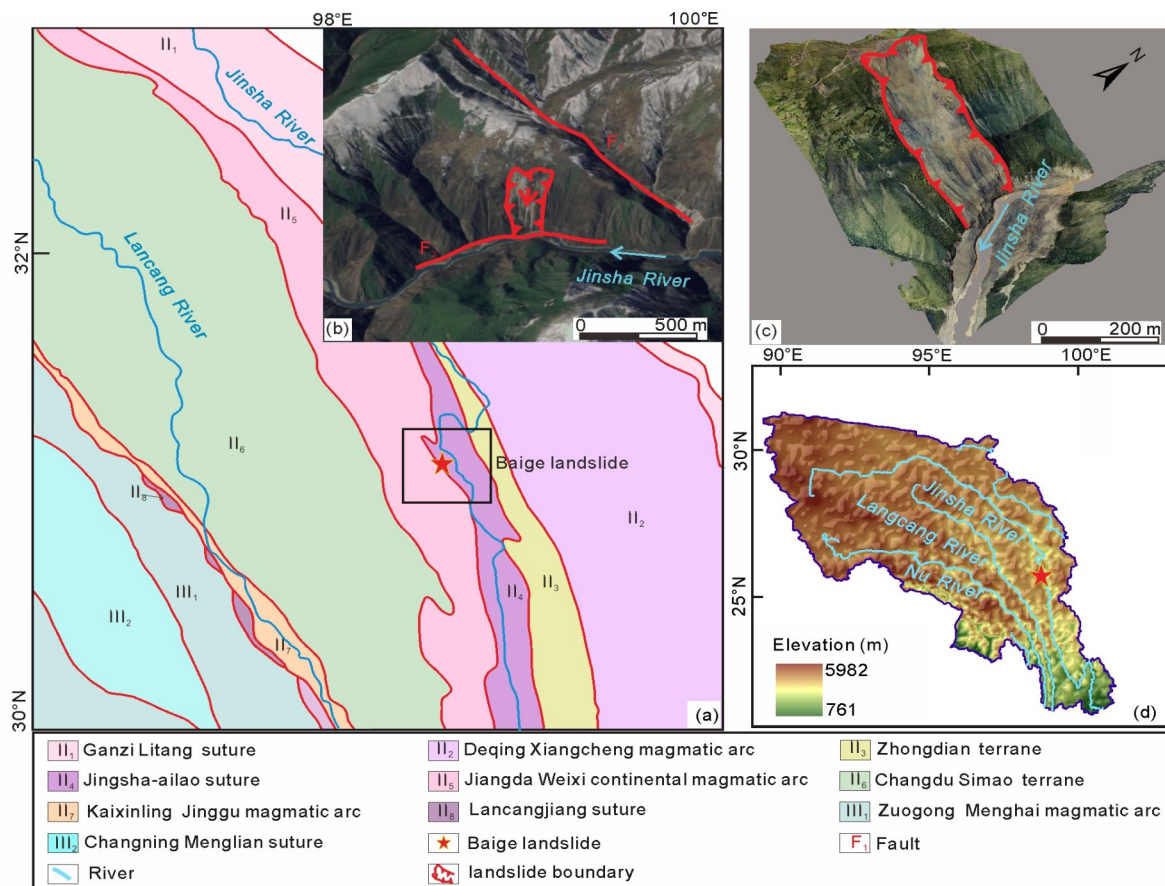


Figure 1. Topographic and geological settings of the study area. (a) Location and regional geological background. (b) The topography the Baige landslide. (c) Three-dimensional orthographic image of the Baige landslide. (d) Regional topographic feature.

early from crown to toe, with an orientation of approximately 91° and an average slope gradient of 50° (Figure 1c). These high, steep slopes provide an ideal setting for slope unloading and rebound.

2 METHODS OF GEO-STRUCTURAL INVESTIGATION OF THE BAIGE LANDSLIDES

Multiple geological mapping methods were employed to analyze the internal geologic structure of the Baige landslide (Figure 2). During field investigations, exposed rock masses were identified along road excavations on the landslide's right side, and profile measurements were conducted along four transects (A_1-A_2 , B_1-B_2 , C_1-C_2 , D_1-D_2) (Figure 3). These profiles correspond to the main deformation area prior to the landslide failure and, given the slope's location within the Jinshajiang tectonic mélange zone, align with its lithological and tectonic characteristics, effectively revealing the sliding mass' geological structure. Additionally, the multielectrode resistivity method (MRM) was applied to the landslide crown ($1-1'$, $2-2'$, $3-3'$) (Figure 3), with results cross-verified against the geological profiles. Detailed geological surveys, combined with indoor optical microscopy and sampling, provided a comprehensive understanding of the landslide's geologic structure from macro- to microscale perspectives.

2.1 Slope Profile Survey

Geological profiles were measured in situ using a laser rangefinder and compass to determine the spatial distribution, orientation, and dimensions of the rock mass. The elevation and direction of each geological profile are as follows: the A_1-A_2 profile elevation is 3 600–3 660 m, and the profile direction is 248° (Figure 4); the B_1-B_2 profile elevation is 3 540–3 600 m, and the profile direction is 247° (Figure 5); the C_1-C_2 profile elevation is 3 480–3 420 m, and the profile direction is 238° (Figure 6); and the D_1-D_2 profile elevation is 3 340–3 400 m, and the profile direction is 246° (Figure 7).

Field observations and geological profile analysis reveal that the slope's internal structure comprises weakly deformed lenticular rock masses and strongly deformed brittle shear zones (fault breccia, cataclasite, fault gouge) (Figures 4–7). The lenticular rock masses, varying in size and lithology, include albite tremolite and schist (A_1-A_2) (Figure 4), phyllitic slate, carbonaceous slate, and granodiorite porphyry (B_1-B_2) (Figure 5), granodiorite porphyry and schist (C_1-C_2) (Figure 6), and phyllitic slate, albite tremolite, and granodiorite porphyry (D_1-D_2) (Figure 7). These lenticular rock masses have been significantly altered by later tectonic activity and metamorphism, leading to the development of numerous folds, including flexural folds and other structures of various scales. In lenticular schist, a prominent schistosity zone is observed (Fig-

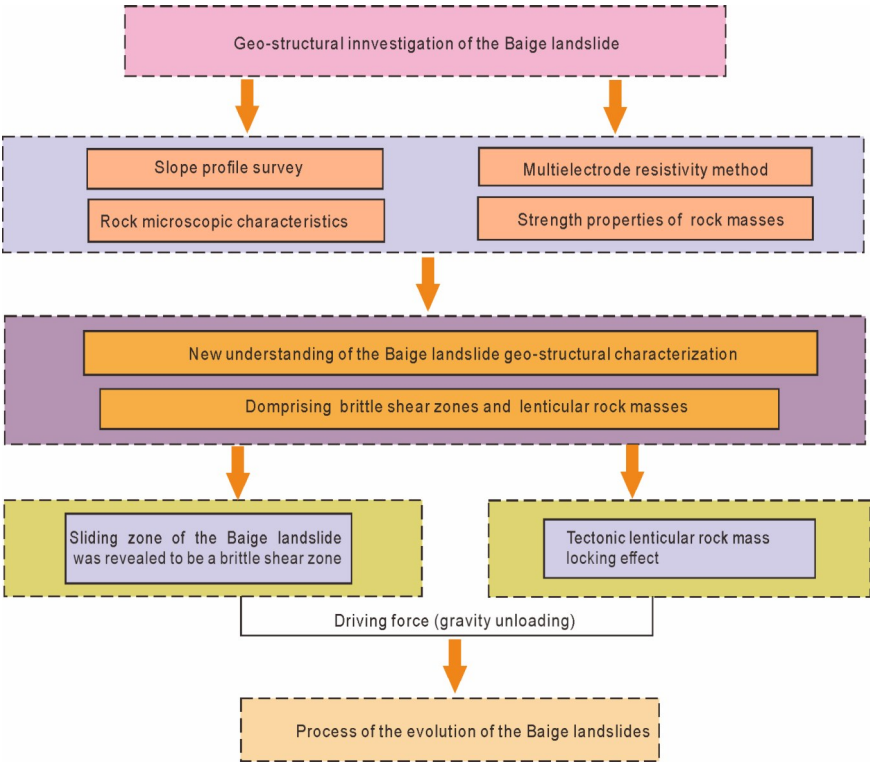


Figure 2. Flowchart of the research process for the Baige landslide.

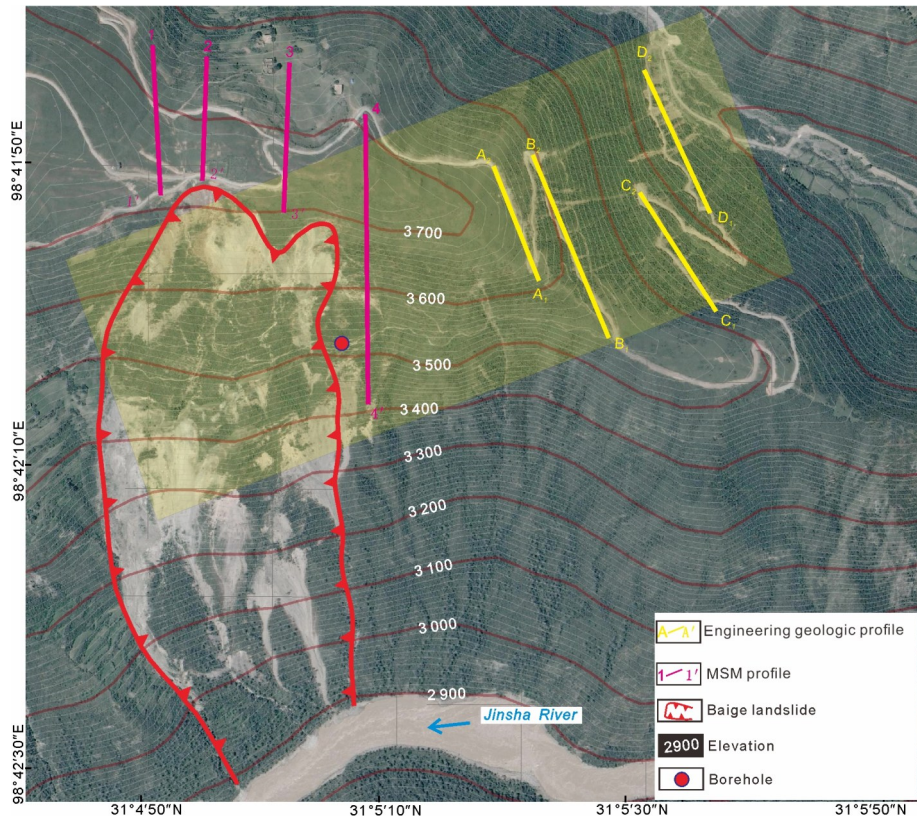


Figure 3. Layout of the boreholes, slope profile survey, and geophysical survey profiles (MRM).

ures 4d, 4g, 4h, 6c), with schistosity occurrences ranging from 210° to 250°∠35° to 46°. S-shaped folds (Figure 4f) and close folds (Figure 4e) are developed locally. These

structural features (Figure 6a) were superimposed on top of the earlier schistosity planes and generally indicate medium-scale ductile deformation. For phyllitic slate and

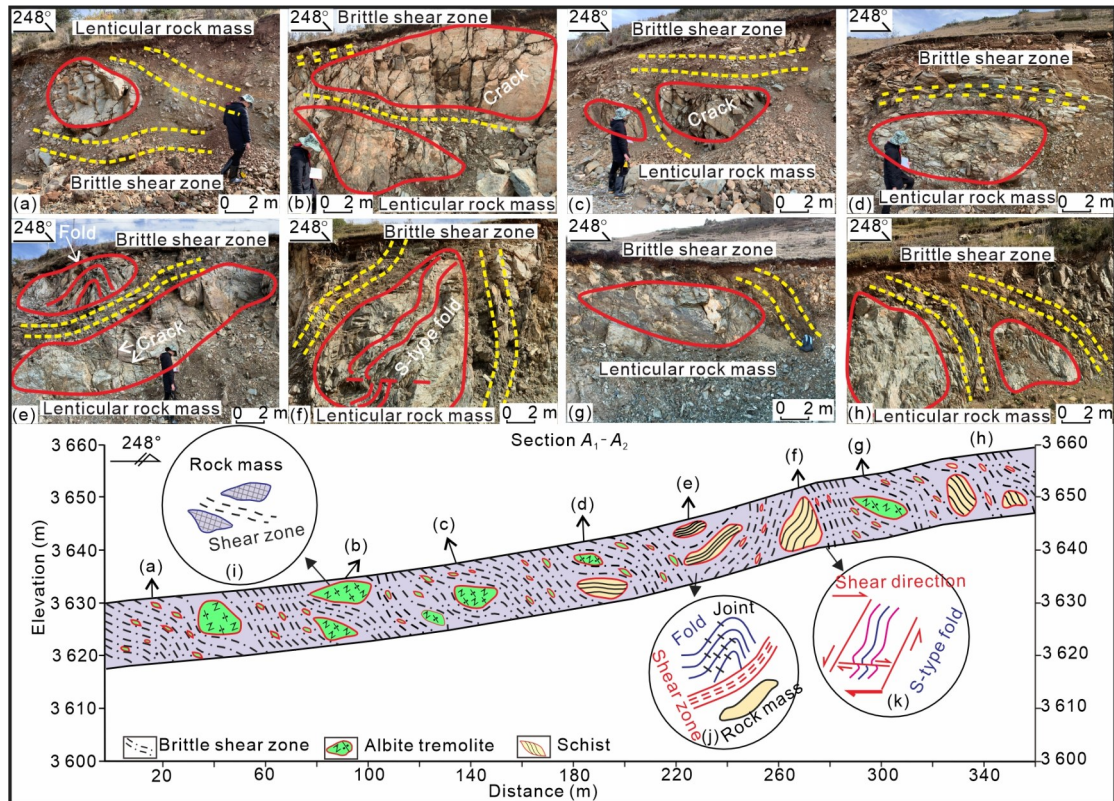


Figure 4. Geological profile A_1-A_2 . (a)–(h) Outcrops characterization of lenticular rock mass (albite tremolite and schist) and brittle shear zones; (i) the brittle shear zones cut the rock masses; (j) ductile and brittle shear structures; (k) S-type fold.

carbonaceous slate, dense joints are very developed, and they often number in the dozens (Figure 5h), appearing in an approximate X-shear form (Figures 7g, 7h). Numerous shear deformation fabrics, such as asymmetric folds and S-c fabrics, are present, which can serve as indicators for tectonic movement directions (Figure 5e). In contrast, albite diorite and granodiorite porphyry remain relatively intact with simpler joint and cleavage patterns (Figures 5a, 5g, 7c, 7d), although local conjugate shear joints are also observed (Figure 4d). The breccia in the brittle shear zone is angular and subcircular in shape (Figure 4g), with developed pores between the scree debris (Figure 5b), partially filled with uncompacted material (Figure 5c), the water permeability is strong and uneven, the maximum grain size is approximately 8 cm, the average grain size is about 1–4 cm, the hammering sound is relatively crisp, and it is easy to break under heavy impact. The cement is made of ground rock chips, rock powder and rock pressure-soluble material, which can be crumbled by hand pinching. In conclusion, throughout geological history, the geological body has undergone multiple phases of transformation through a series of tectonic processes, resulting in the formation of brittle shear zones with various shapes. These brittle shear zones have cut the intact rock masses into lenticular rock masses of different sizes. Therefore, the complex material composition and fractured geo-structure provide favourable conditions for landslide evolution.

2.2 Multielectrode Resistivity Method (MRM)

The multi-electrode resistivity method (MRM) utilizes strategically arranged electrodes to optimize resolution and depth penetration in subsurface investigations. MRM systems typically deploy 48 to 64 electrodes in linear or grid configurations. Common arrays, such as the wenner and single-side tripolar, balance resolution and depth penetration. The wenner array is preferred for its uniform sensitivity to vertical structures, while the dipole-dipole array excels in lateral resolution, particularly for detecting near-surface faults. Electrode spacing, typically 5 to 10 m, critically influences vertical resolution and penetration depth, with smaller spacing used for high-resolution shallow surveys (< 50 m). MRM systems inject low-frequency alternating currents (10–100 mA) and measure voltage differences to calculate apparent resistivity, forming the basis for generating resistivity profiles essential for subsurface interpretation.

The multielectrode resistivity method (MRM) plays a vital role in geological hazard investigations, such as landslides, particularly in the complex geological conditions and steep terrain of the Tibetan Plateau. This method allows for the rapid and detailed detection of continuous data profiles (Perrone et al., 2014) with good results, particularly in digital signal acquisition and data analysis and processing (Whiteley et al., 2019; Delunel et al., 2010). MRM reveals electrical differences among various geotechnical components and helps identify the internal geological structure, the depth and morphology of sliding

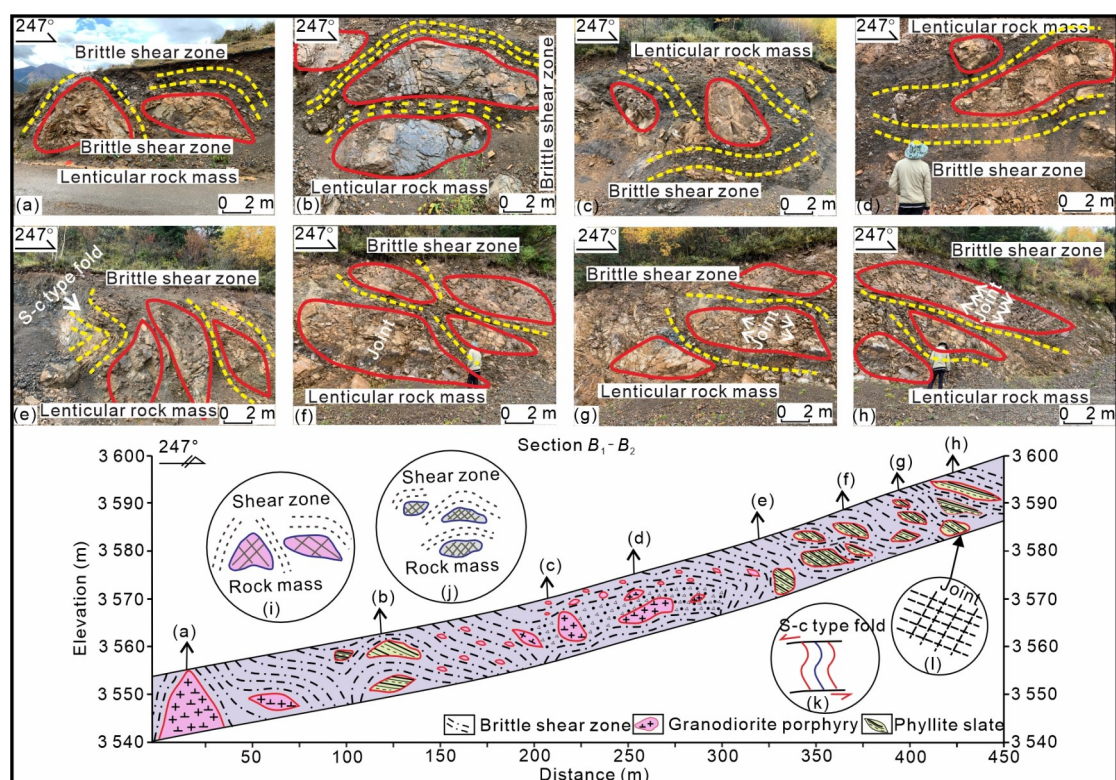


Figure 5. Geological profile B_1-B_2 . (a)–(h) Outcrops characterization of lenticular rock mass (granodiorite porphyry and phyllite schist) and brittle shear zones; (i)–(j) the brittle shear zones cut the rock masses; (k) S-c type fold; (l) joint.

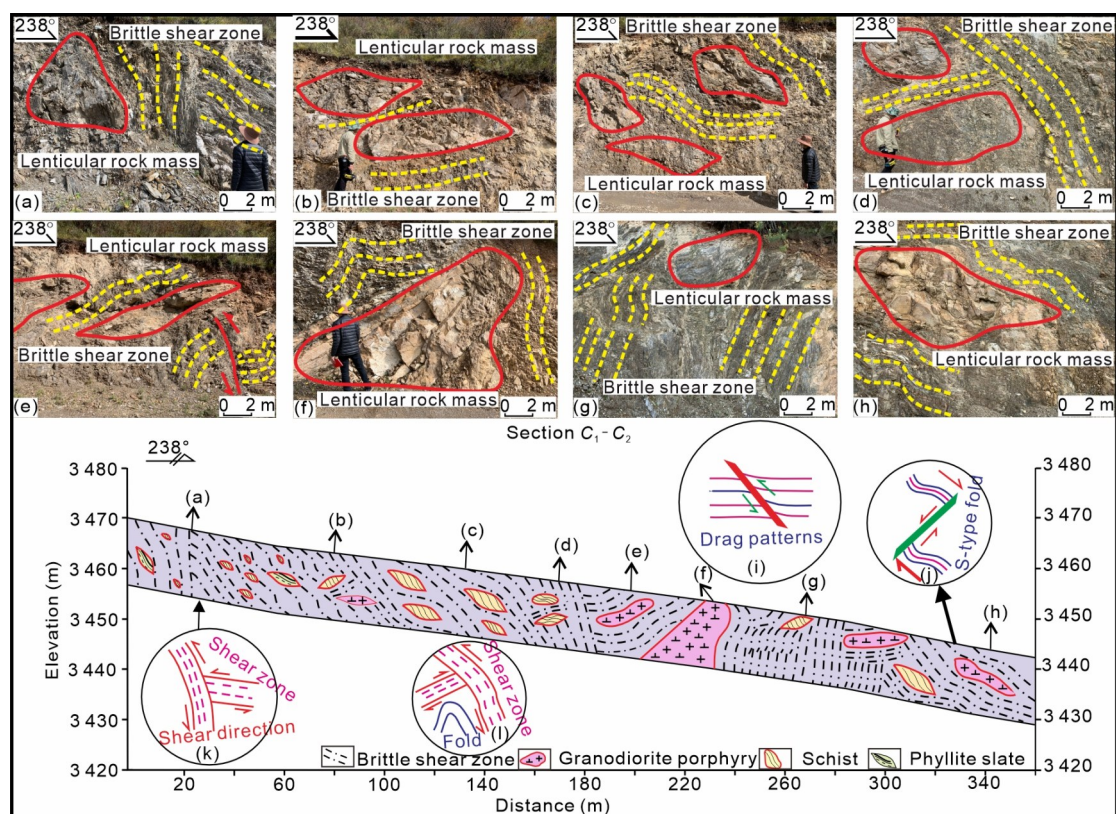


Figure 6. Geological profile C_1-C_2 . (a)–(h) Outcrops characterization of lenticular rock mass (granodiorite porphyry, schist and phyllite schist) and brittle shear zones; (i) the brittle shear zones cut the rock masses; (j) S-type fold; (k)–(l) sketch map of brittle shear structures.

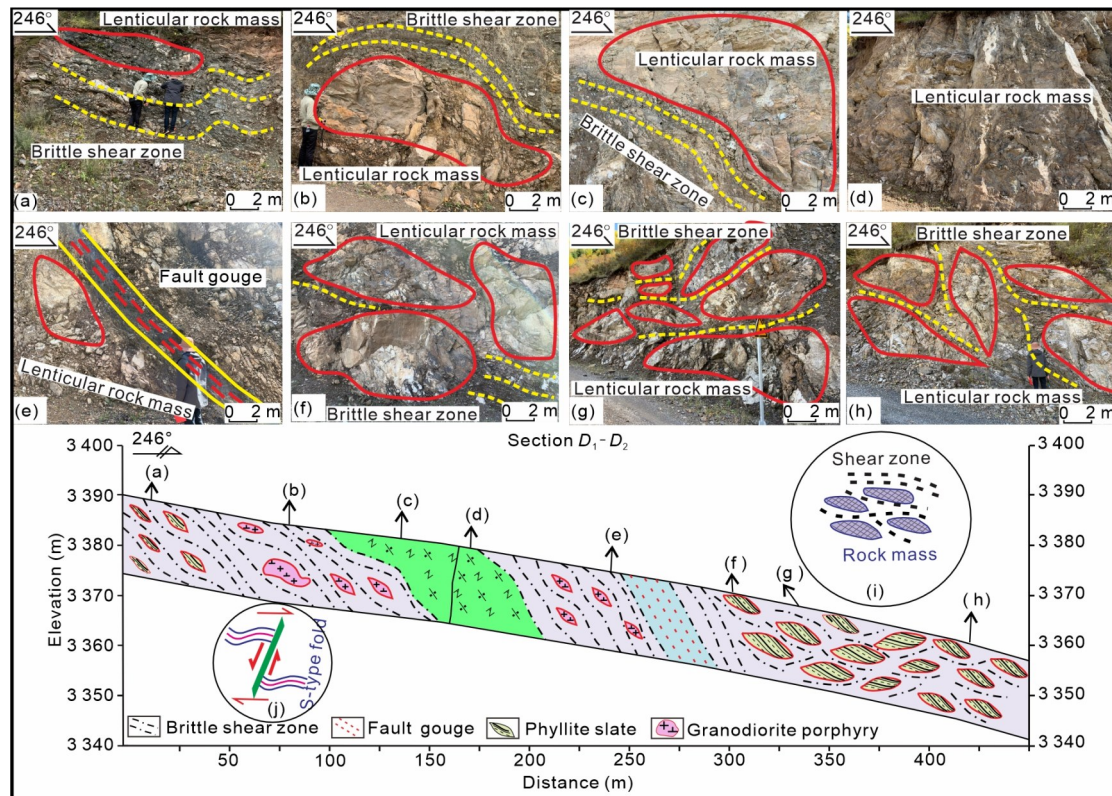


Figure 7. Geological profile D_1-D_2 . (a)–(h) Outcrops characterization of lenticular rock mass (granodiorite porphyry and phyllite schist) and brittle shear zones; (i) the brittle shear zones cut the rock masses; (j) S-type fold.

zones, and changes in groundwater associated with landslides (Pazzi et al., 2019; Bellanova et al., 2018). Furthermore, it captures the failure process of slope internal structures by monitoring resistivity changes (Senderak et al., 2019), and explores the relationship between resistivity and stress-strain through triaxial compression tests on specimens with varying water contents (Kang et al., 2023).

To accurately identify the internal structure of the landslide, this paper employs the MRM to examine the deep structure, selecting three MRM profiles at the landslide crown (Figure 3). The interpretation of the electrical and geological structure of the underground medium is based on the actual geological conditions of the landslide area. This includes the electrical characteristics of different rock masses surrounding low-resistance anomalies, the magnitude of background values in the resistivity contour cross-sections, the morphology and values of the low-resistance anomalies, and their differences from the background values, along with corresponding borehole data. In this context, extremely fractured cataclastic rock is defined as having a resistivity of less than $30 \Omega \cdot \text{m}$; resistivity values between 30 and $80 \Omega \cdot \text{m}$ are attributed to broken fault breccia; resistivity values between 80 and $200 \Omega \cdot \text{m}$ indicate relatively broken mylonite; resistivity values between 200 and $500 \Omega \cdot \text{m}$ indicate relatively intact rock masses; and resistivity values greater than $500 \Omega \cdot \text{m}$ correspond to intact rock masses.

Based on the analysis of MRM profiles 1-1', 2-2',

and 3-3' (Figures 8a, 8b, 8c), In contrast, fault fracture zones and their influence areas predominantly manifest as strip-shaped or bead-shaped low-resistance anomalies, with the most significant gradient changes corresponding to the edges of these fracture zones. The rocky contact zones are characterized by apparent differences in resistivity values on either side of gradient or transition zones, which display high- and low-resistance mass-like phases. Consequently, the resistivity profile reveals a discontinuous electrical layer of high and low resistance throughout the section. The landslide area is distinctly categorized into more intact and fractured rock bodies based on electrical resistivity differences. Resistivity values greater than $500 \Omega \cdot \text{m}$ are primarily associated with intact rock masses, which are inferred to be lenticular rock masses with varying lithologies. Conversely, resistivity values less than $200 \Omega \cdot \text{m}$ are associated with the brittle shear zone, which comprises fault breccia, mylonite, and cataclastic rocks. In addition, the MRM profile 4-4' indicates that the internal geological structure of the deformed body (Figure 3) on the right side consists of a mix of high-resistance and low-resistance clusters (Figure 8d). This configuration aligns with the structural characteristics observed in the four measured field geological profiles on the right side. Revealed the internal structure of the landslide area primarily consists of weakly deformed lenticular rock masses of different lithologies and strongly deformed brittle shear zones, with the latter surrounding the rock masses. Therefore, the MSM results

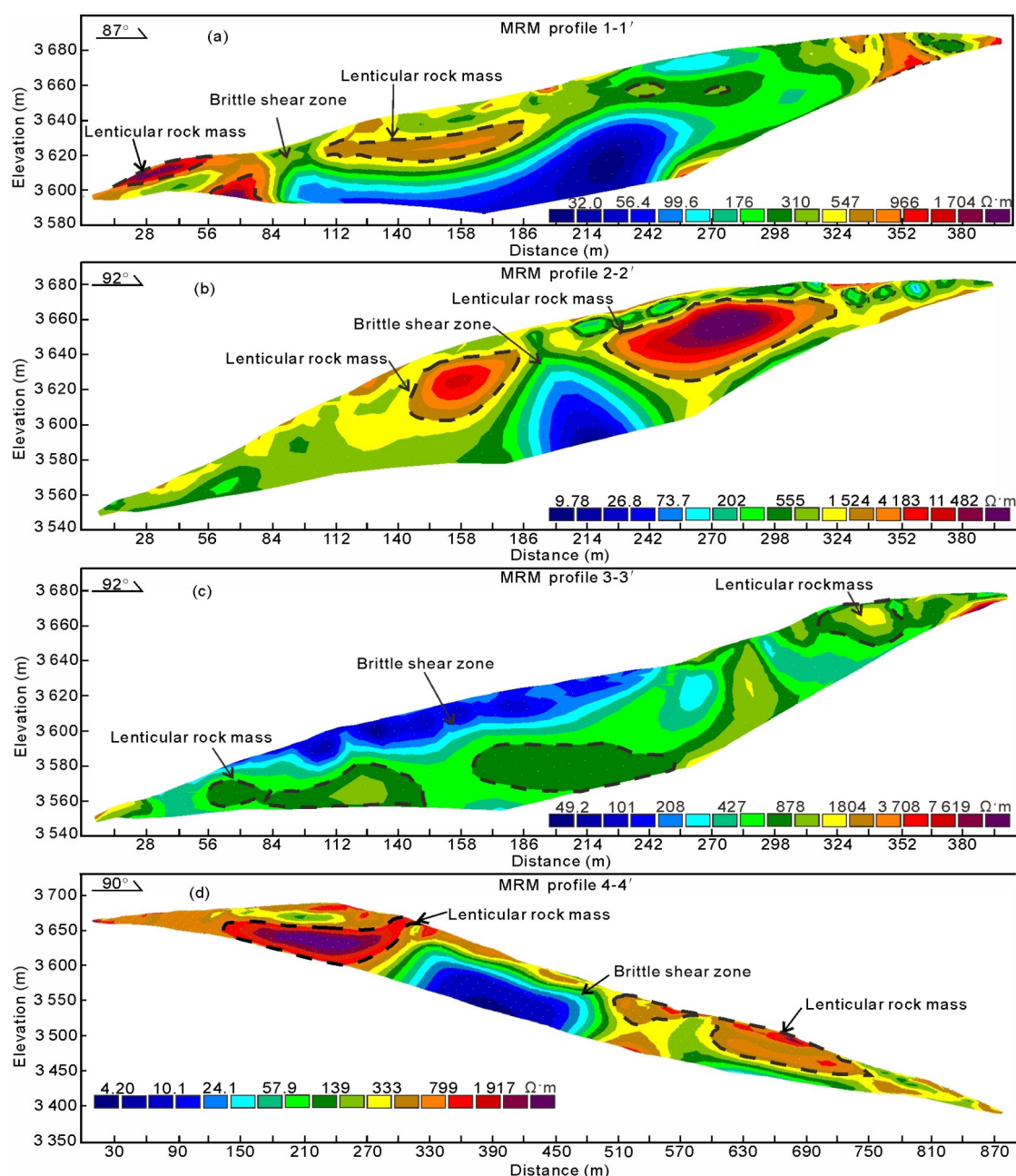


Figure 8. Geophysical survey results by MRM. (a) MRM profile 1-1'; (b) MRM profile 2-2'; (c) MRM profile 3-3'; (d) MRM profile 4-4'.

align with the field geological sections, providing insight into the internal geological structure of the Baige landslide.

2.3 Geo-Structural Investigation of the Slip Area

Detailed investigations of the deformed mass at the landslide crown, boundary flanks, sliding bed, and slope foot reveal a geologic structure comprising lenticular rock masses of varying lithologies and brittle shear zones. Notably, the geologic structure of the landslide's middle and crown sections differs significantly from that at the slope foot.

Investigations in the middle part and crown of the slip area revealed that the lenticular rock masses had been modified by multiple structural features, with vary-

ing morphologies and sizes, with a maximum long axis length of approximately 10–15 m and a short axis length of roughly 3–6 m (Figure 9a). The main scarp of the slip area exposes albite tremolite with alteration phenomena on the surface. In addition, the scarp on the left flank exhibits evidence of friction and other actions, and the grooves are a set of relatively uniform parallel fine lines. We speculated that the friction traces were generated by landslide action (Figure 9b). The integrity of the lens-shaped rock masses (schist, phyllite, phyllite slate) in the sliding area is poor (Figures 9c. 9e. 9f), with more developed joints and fissures, which notably acted as an essential factor in tension cracking and failure surfaces during the landslide broke down. In the upper and middle parts of the slip area, discontinuous brittle shear

zones are developed, and faulted mud (Figure 9d) and faulted breccia (Figure 9e) are visible in the outcrop. The brittle shear zone is relatively broken, and the breccia clasts are rounded, compressed, and oriented. The cementing material is distributed around the breccia clasts with a low degree of colluviation, but the shear zone in the crown appears to be in a denser state (Figure 9e). We inferred that this was probably caused by compaction during the multiple phases of deformation of the landslide.

Compared with the crown, the structural characteristics of the lens-shaped rock masses and brittle shear zone at the foot of the slip area are different. This is especially true for the lenticular rock masses (phyllitic slate), which have a variety of folding styles under tectonic stress (Figure 9i), such as flexural and flow folding, and local ductile deformation of the S-c fabric seen, but the rock mass is relatively intact. The brittle shear zone at the foot of the slope has a maximum width of approximately 0.5 m (Figures 9i, 9h). In particular, the breccia of the shear zone is highly consolidated (Figure 9i, 9h), and the shear zone connects the lenticular rock masses well to form complete wall.

Investigation and analysis of the deformed mass outcrops and sliding bed reveal a highly discontinuous slope structure. Structural surfaces, appearing in clusters and

groups, fragment lenticular rock masses into varying scales and shapes, creating conditions for slope evolution and instability. This structure forms the for later slope evolution and concentrated instability. Samples from outcrops of different lithologies (Figure 9k) and performed rock microanalysis using an optical microscope to determine the landslide's material composition and complex structure.

2.4 Rock Microscopic Characteristics

The lithology of the Baige landslide is complex and diverse. The results showed that the lithology of the landslide area includes albite tremolite (Figure 10a), mica schist (Figure 10b), serpentinite (Figure 10c), green schist (Figure 10d), phyllite slate (Figure 10e), granodiorite porphyry (Figure 10f), phyllite (Figure 10g), carbonaceous schist (Figure 10h), and mylonite (Figure 10i). During their long geological history, an experienced multiple phases of tectonic deformation, metamorphism, and magmatic activity have modified the rock masses. These geologic events have left varying degrees of microscopic traces in the rocks. The microscopic features of the schist show discontinuously oriented spreads (Figure 10b), and S-shaped folds are developed (Figure 10d). Second, the microcracks in the serpentinite and phyllite have apparent spacing (Figures 10c, 10g), and micro-

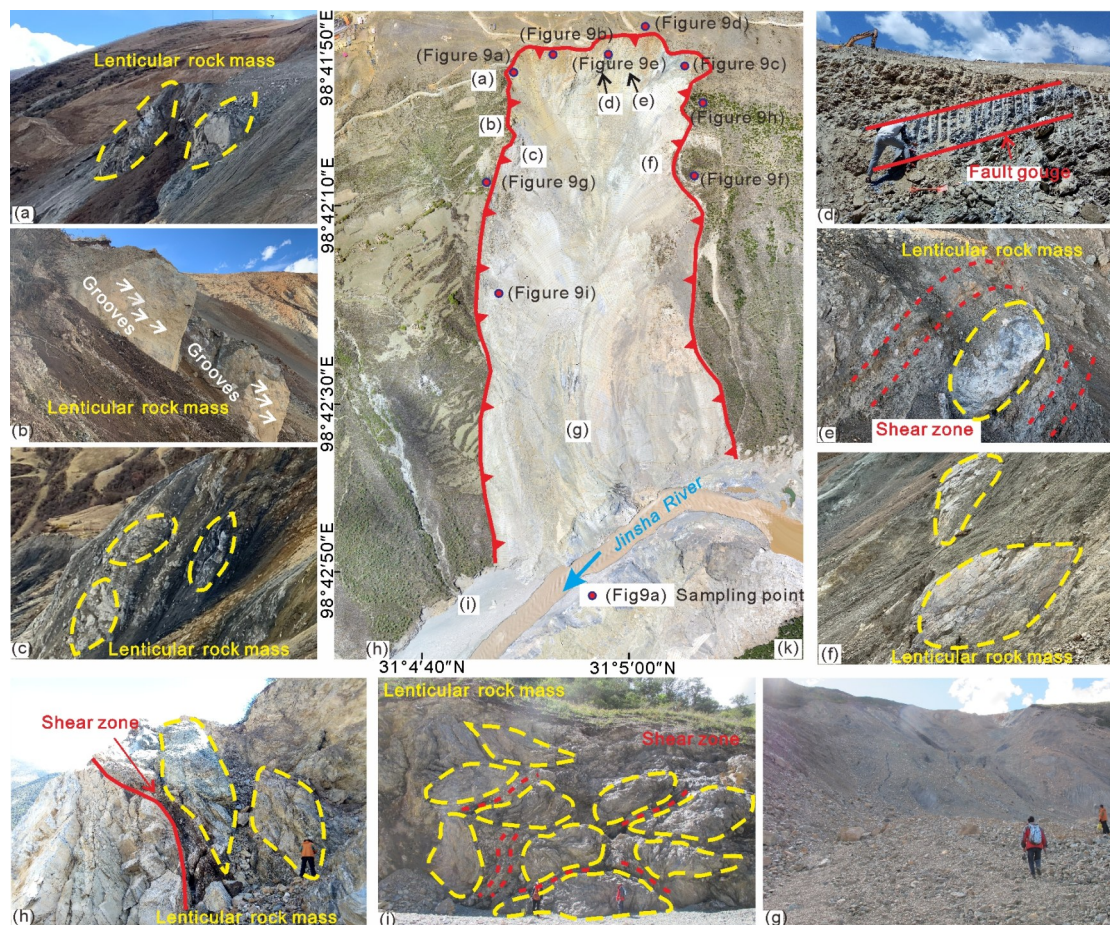


Figure 9. Geo-structure investigation of the slip source area. (a)–(c) Left flank geological structure feature; (d)–(f) right flank geological structure feature; (h)–(g) geological structure characteristics of the foot; (k) Figure 9a is the sampling point.

cracks are also developed in the granodiorite porphyry, but the spacing is not obvious (Figure 10f). The phyllite slate exhibits an S-c shaped structural fabric; in addition, the cracks have apparent displacement due to dislocation (Figure 10e). Tectonic analysis of field rock macro features and microscopic scale shows that, under the action of tectonic stress and gravity deformation, the internal microfissures of the rock gradually expanded, penetrated, and then evolve macroscopic cracks across the scale, and finally form a macroscopic rupture surface, which cuts and breaks up the rock mass into fragments, and makes the integrity of the rock mass poor and its strength deteriorate.

Notably, the microscopic characteristics of the rocks in the crown remnant show discontinuous, strongly deformed matrix bands and weakly deformed, lens-like porphyritic crystals distributed in intervals, and the overall fragmentation and fine-grained are more serious (Figure 10i), in addition, the matrix bands have obvious consistent shear direction, which is blocked by the porphyritic crystals without penetration during the shearing process. We infer that this may be a result of the changes in mineral structure that accompanied the multi-phase deformation process of the Baige landslide. However, the rock microfacies at the periphery of the slide are characterized only by the development of microfractures and kneading, with no evidence of shear fragmentation.

The connection between macroscopic structures (pictures showing in Figures 4–7) and microscopic structures (illustrated in Figure 10) is crucial for elucidating the

failure mechanism. The tectonic *mélange* belt within the landslide area extends in a north-south direction, exhibiting a trend of 230° – 250° and a steep dip ranging from approximately 48° – 56° . Microscopically, the slices are aligned in a predominantly north-south orientation (Figures 10b, 10e, 10h). Notably, the macroscopic and microscopic characteristics bear similarities. However, subsequent tectonic modifications have locally induced the development of brittle shear zones oriented nearly east-west within the slope. Under microscopic examination (Figures 10c, 10d, 10f), cracks and folds aligned in a similar east-west direction are evident. These near-east-west micro-fissures progressively evolve into macro shear zones (Figures 4–7), aligning with the direction of landslides and potentially serving as sliding zones for such events.

2.5 Strength Properties of Lenticular Rock Masses

Direct shear and uniaxial compression tests provided lithologic physico-mechanical parameters for the Baige landslide, enabling quantitative assessment of rock mass properties. Uniaxial compressive strengths were determined as follows: albite tremolite (64.5 MPa), serpentinite (10.7 MPa), phyllite (16.60 MPa), schist (13.50 MPa), and granodiorite porphyry (81.5 MPa). Comparative analysis revealed that albite tremolite's strength significantly exceeds that of serpentinite, phyllite, and schist, while the latter three exhibit similar strengths. Yi et al. (2022) corroborated these findings using Schmidt's hammer tests and geological strength in-

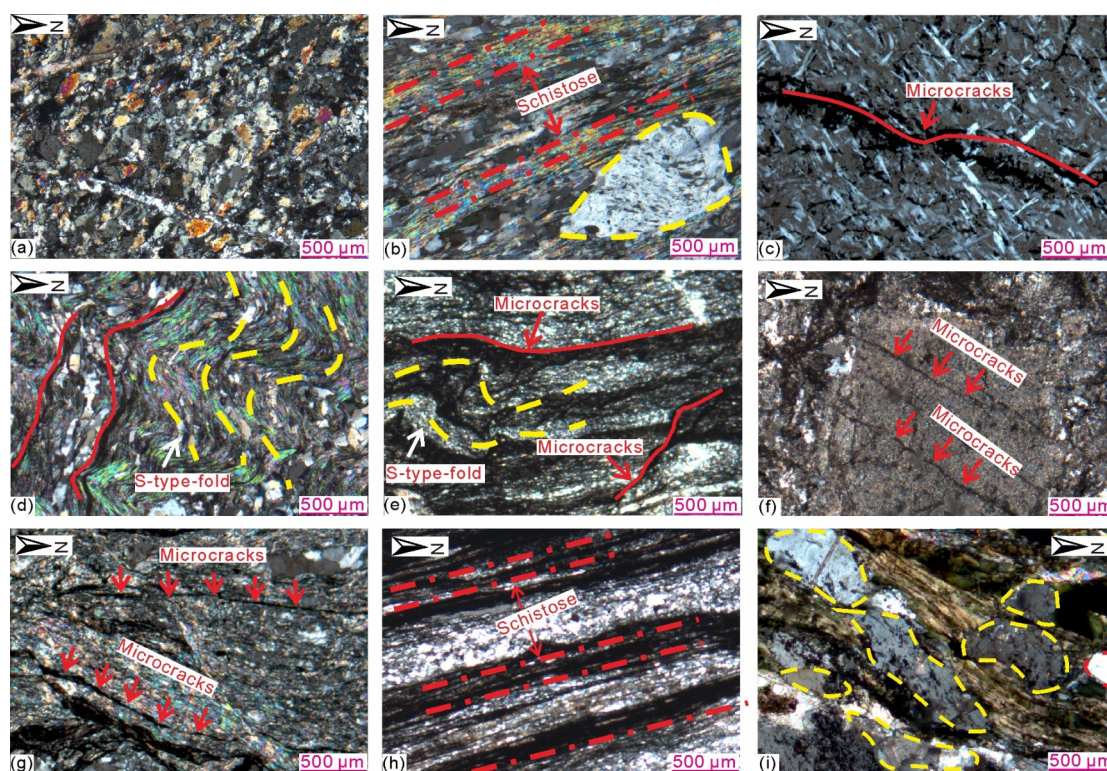


Figure 10. Transmitted light micrographs of the rock. (a) Albite tremolite; (b) mica schist; (c) serpentinite; (d) green schist; (e) phyllite slate; (f) granodiorite porphyry; (g) phyllite; (h) carbonaceous schist; (i) mylonite.

dex (GSI) assessments. Direct shear tests further quantified cohesion and friction angles for albite diorite, phyllite, and serpentinite (Figure 11), showing albite diorite's superior resistance to deformation and failure compared to phyllite and serpentinite. These results align with back-calculated shear strength values from previous studies (Wei et al., 2012).

3 RESULTS

3.1 New Understanding of the Baige Landslide Geo-Structural Characterization

Combining slope geologic profiles, oblique photography, multielectrode resistivity methods, macrostructural rock features, and microscopic rock analysis, we identified the internal geo-structure as comprising discontinuous brittle shear zones and heterogeneous tectonic lenticular rock masses (Figure 12). The brittle shear zones, distributed around the lens-shaped rock masses, exhibit a mesh-like pattern in plain view (Figure 12). Structural variability differs significantly between the landslide's foot and crown: upper lenticular rock masses are intersected by widely spaced, densely compacted shear zones, while lower lenticular rock masses are relatively intact, with closely spaced but highly consolidated shear zones forming interconnected walls. These findings indicate that the Baige landslide events involve a tectonically fragmented mass with a reticulated double-layer geo-structure.

3.2 Slip Control Effect of Complex Geologic Structures

3.2.1 Revealing the sliding zone

The study of the material composition, mechanical strength characteristics, and shear failure mechanism of sliding zones significantly impact the mechanisms of large-scale landslides (Yang et al., 2013). Slip zone evolution is the gradual deterioration of the material structure and mechanical properties. The potential slip zone rock fissures continue to expand and connect by internal and external dynamic geological effects under the shear ef-

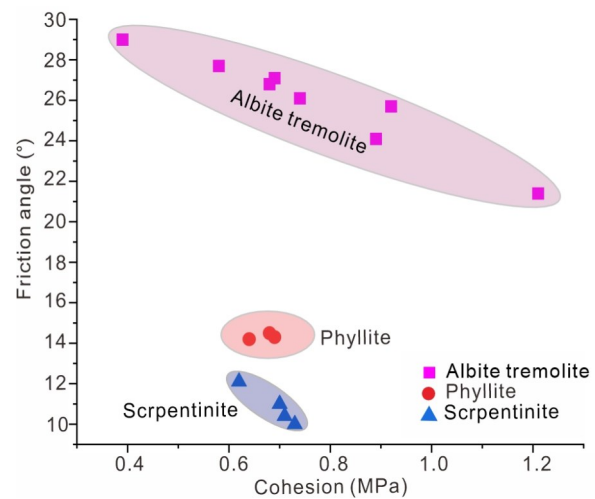


Figure 11. Mechanical strength parameters of lenticular rock masses.

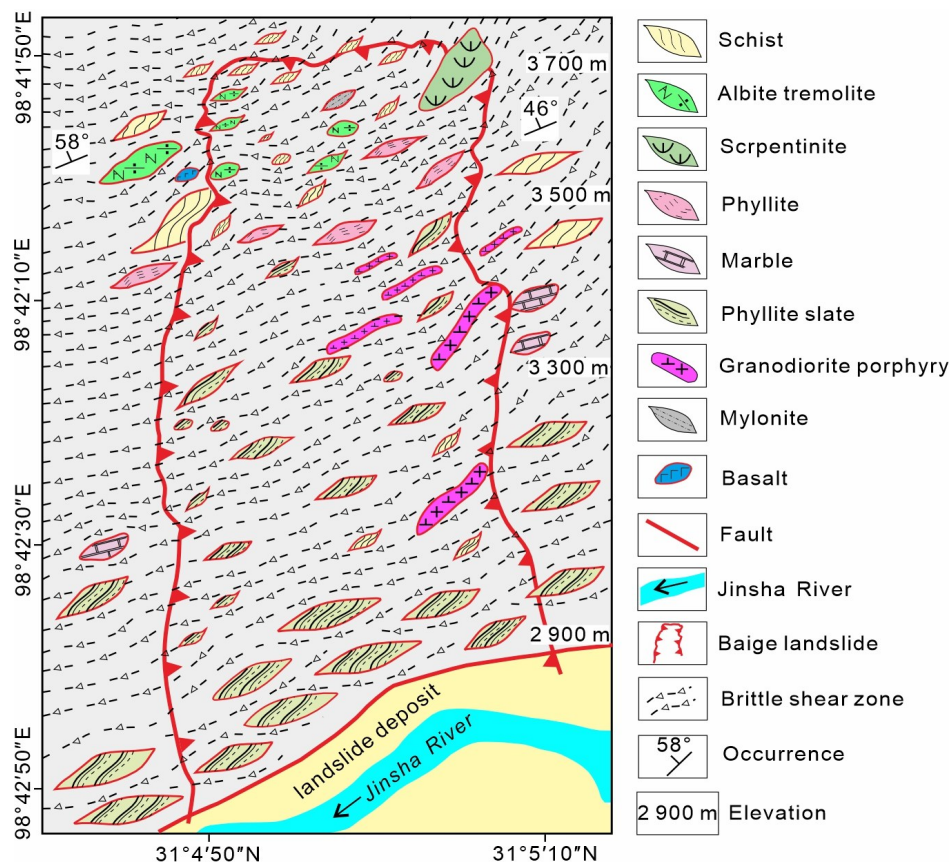


Figure 12. Geo-structural characterization of Baige landslide.

fect of gradual fragmentation and ultimately evolve into a slide zone (Wen et al., 2007). However, the sliding zone of the Baige landslide was revealed to be a brittle shear zone by deep inclinometers and borehole cores. The de-formeter on the right side of the landslide area was monitored for deep displacements (Figure 13a). The first test was performed on October 12, 2019, and the probe was lowered to a hole depth of 40 m. The second test was performed on November 11, 2019, and the probe was lowered to a hole depth of 22 m because the borehole was sheared at 22 m (Figure 13b). The third test was on November 12, 2019, and the probe was lowered to a hole depth of 22 m. Therefore, we believe that the slip zone in this borehole is at 22 m (Figure 13b). Based on the core from 22 m in the borehole (Figure 13c), this layer is a brittle shear zone of brecciation and fragmentation, the adhesion strength between the breccia fragments is low, and the mechanical properties of the brecciated material are poor. The microscopic angular gravel of the shear zone consists of fragmented patches and matrix bands (Figure 13d), which show a clear and consistent direction of shear movement and tend to be penetrating, so the brittle shear zone reduces the shear strength and is highly susceptible to deterioration when exposed to water, providing a controlling slip surface for the formation of landslide.

3.2.2 Tectonic lenticular rock mass locking effect

Pre-landslide Google Earth imagery (Figure 14a) shows that failure primarily occurred between 3 100 and 3 700 m, with material scraping and eroding the area

from 3 100 to 2 900 m, dividing the landslide into failure and scraped zones (Figure 14a). The main failure zone exhibited tension cracks and small-scale landslides by February 1966 (Fan et al., 2020), with a near-continuous tension surface forming at the crown by March 2011. Despite a 50-m downward displacement from March 2011 to February 2018, catastrophic failure did not occur until October 2018 (Xu et al., 2018). This study investigates why the failure zone remained stable despite such significant displacement.

The Baige landslide's geological structure, comprising lenticular rock masses and shear zones, has been previously established, including the spatial distribution of lithologically diverse lenticular masses. To reconstruct the slope's original geological structure, we analyzed the post-landslide accumulation layer, which preserved the original slope sequence and displayed clear lithological stratification (Figure 14e). Comparative analysis enabled the recovery of the slope's original geological structure and lithological distribution (Figure 14d). Additionally, magnetotelluric sounding and engineering verification revealed granodiorite porphyry veins in the failure area's midsection (3 300–3 500 m) (Figures 14b, 14c). Borehole samples confirmed the veins' relative integrity (Figure 14c), with a uniaxial compressive strength of 81.5 MPa. Field observations showed that these veins, embedded within the slope, functioned as natural anti-slip piles, blocking the main slide mass. This explains why the slope, despite a 50-m downward displacement from March 2011 to February 2018, did not fail catastrophically until October 2018, as the granodiorite porphyry veins

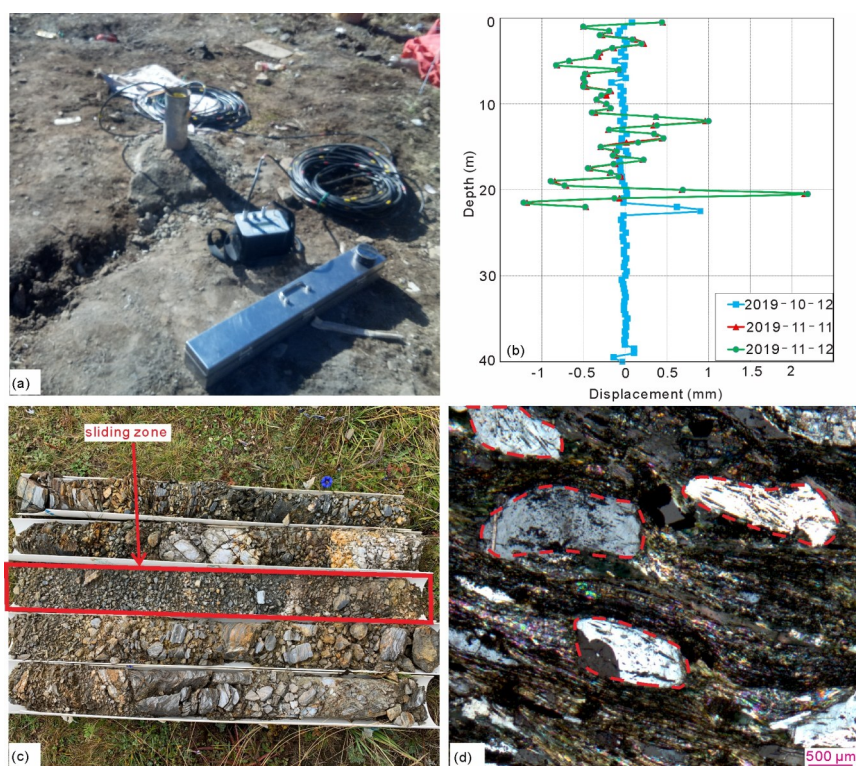


Figure 13. (a) Deep displacement test hole location; (b) deep displacement observation curve; (c) sliding zone; (d) sliding zone microscopic characteristics.

provided significant locking resistance.

Ollowing the two sliding events, the Baige landslide significantly disturbed the mountain, triggering unstable deformations K1, K2, and K3 at the crown and flanks (Figure 15a). To further assess the roles of granodiorite porphyry as locking mechanisms, we monitored the sur-

face deformation of the residual deformation body and analyzed the locking mechanisms of locked segment. Surface deformation was monitored using GNSS technology. As of December, 2020, the slope at the G1 monitoring point had deformed and partially failed, the equip-

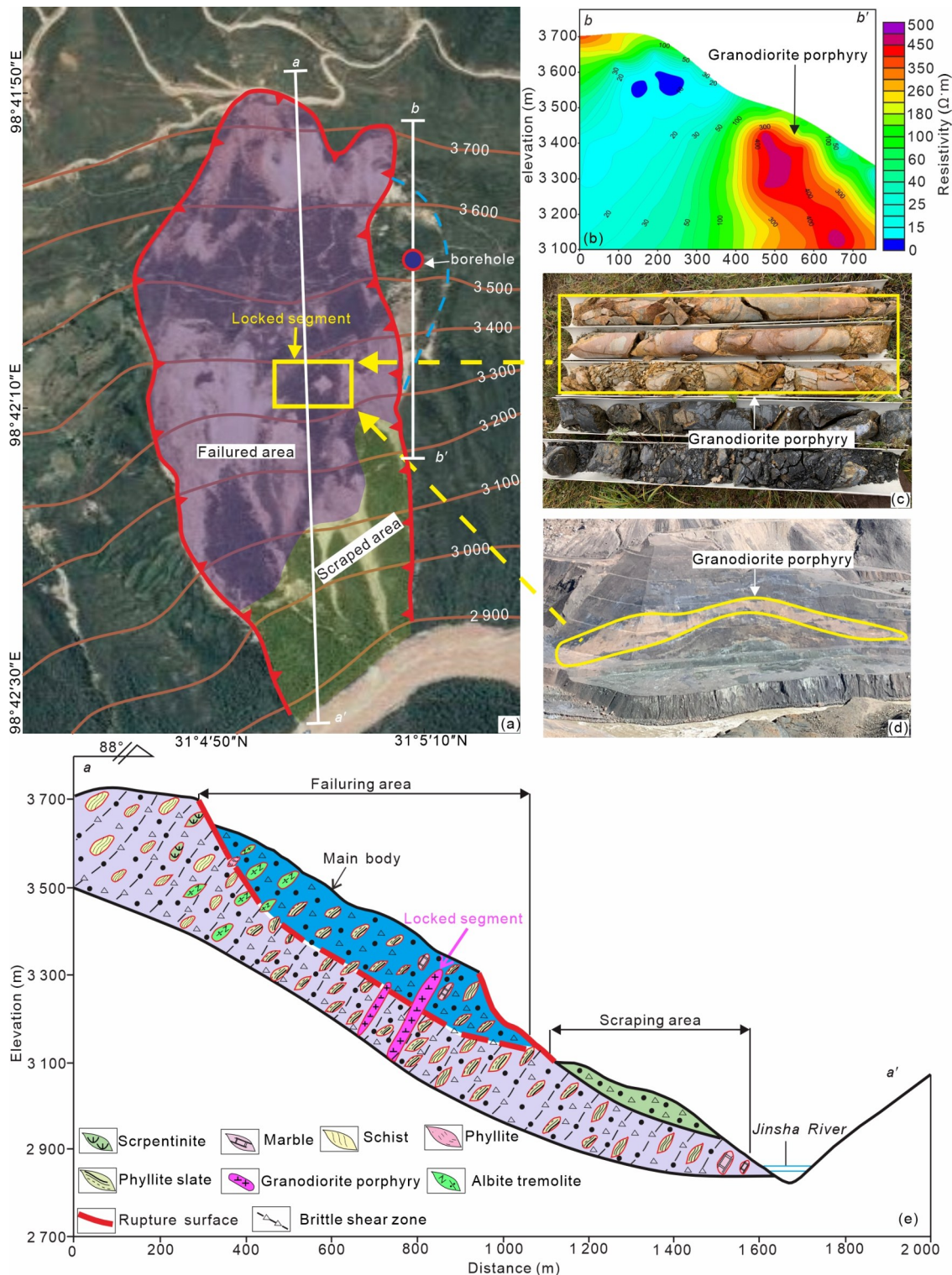


Figure 14. (a) Zoning map of Baige landslide and main locked segment location distribution; (b) geomagnetic bathymetric inverse performance of granodiorite porphyry veins; (c) drilling reveals granodiorite porphyry veins; (d) accumulation layer after excavation; (e) model of the locking mechanism of the locked segment of the Baige landslides.

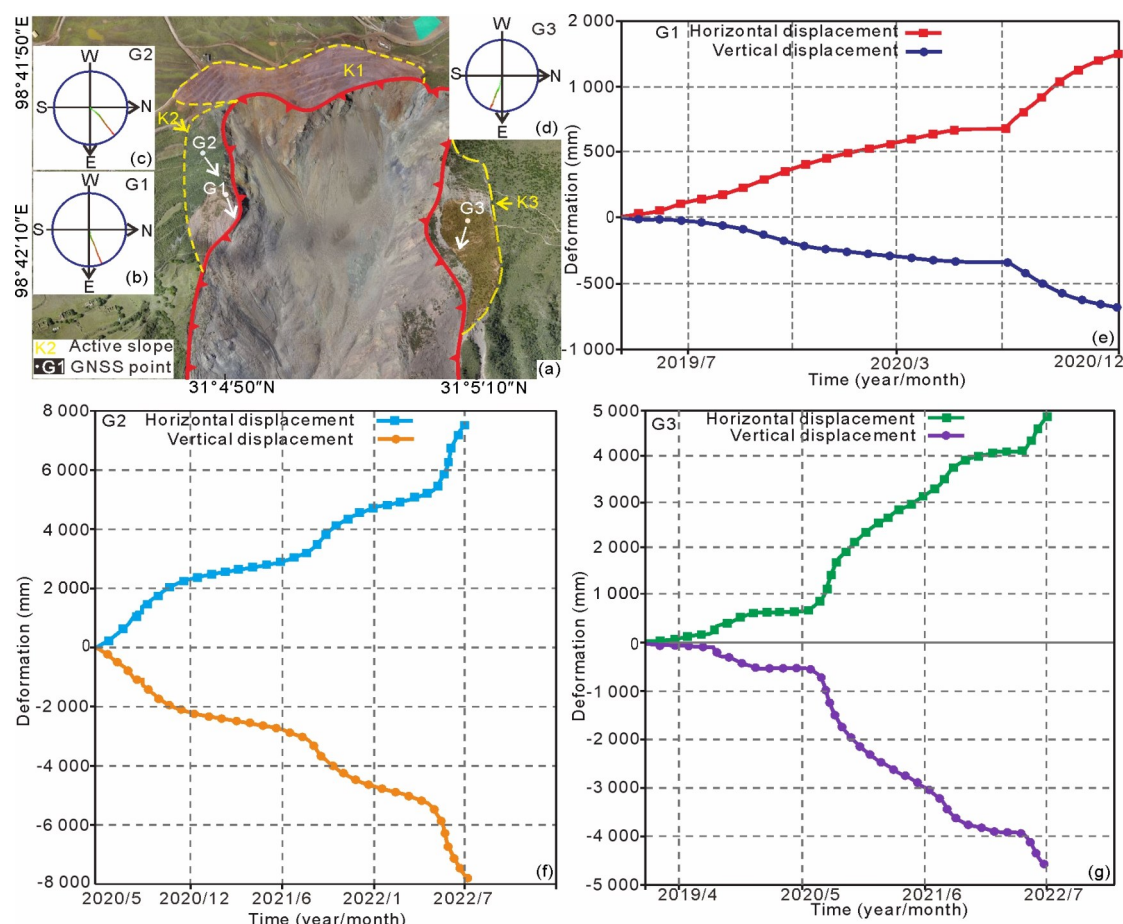


Figure 15. (a) Zoning map of Baige landslide, main locked segment location distribution; (b) G1 point sliding direction; (c) G2 point sliding direction; (d) G3 point sliding direction; (e) horizontal and vertical displacement versus time on G1; (f) horizontal and vertical displacement versus time on G2; (g) horizontal and vertical displacement versus time on G3.

was approximately 1 500 mm, and the vertical displacement was approximately -700 mm (Figure 15e). The G2 and G3 deformed also experienced deformation. By of July, 2022, the G2 monitoring point recorded a horizontal displacement of approximately 7 800 mm and a vertical displacement of approximately -7 900 mm (Figure 15f). The G3 monitoring point showed a horizontal displacement of about 4 800 mm and a vertical displacement of approximately -4 650 mm (Figure 15g). The amount of deformation displacement in the K2 is much larger than that in the K3. Our analysis indicates that the main cause of deformation and partial failure at the G1 and G2 monitoring point was the lenticular rock mass of internal schist and phyllite, which exhibited poor physical and mechanical properties and low strength, making it susceptible to shear failure under gravity unloading. While granodiorite porphyry veins developed within the slope at monitoring point G3. The physical and mechanical properties of granodiorite porphyry are robust, and blocking deformation of slope. Through the analysis of the failure cause at G1 and the cumulative displacement at G2 and G3, we have demonstrated that the granodiorite porphyry (locking section) functions as a locking segment in the process of landslide deformation, and also in the K3.

4 DISCUSSION

4.1 Evolution of the Baige Landslide Events

Although the Baige landslides occurred over a short duration, their formation process was prolonged. In this study, the Baige landslide process is categorized into four stages: the geological evolution stage, the brittle shear zone penetration and locked segment locking stage, the locked segment shear-induced failure stage, and the rock avalanche dynamic erosion and accumulation stage.

The geological evolution stage: The intense collision between the Indian and Eurasian plates in the Himalayan region, along with the rapid uplift of the Tibetan Plateau driven by crustal dynamics, resulted in river down cutting and erosion that formed high and steep slopes. Additionally, the long-term development of active faults provided a continuous source of destructive force to the landslide rock masses (Zhang et al., 2015), leading to a complex, diverse, and disorganized internal slope structure. This structure primarily comprises tectonically induced lenticular rock masses and brittle shear zones (Figure 16a). Consequently, the high and steep complex geological structure created highly favorable topographic, geomorphological, and material base conditions for landslide formation.

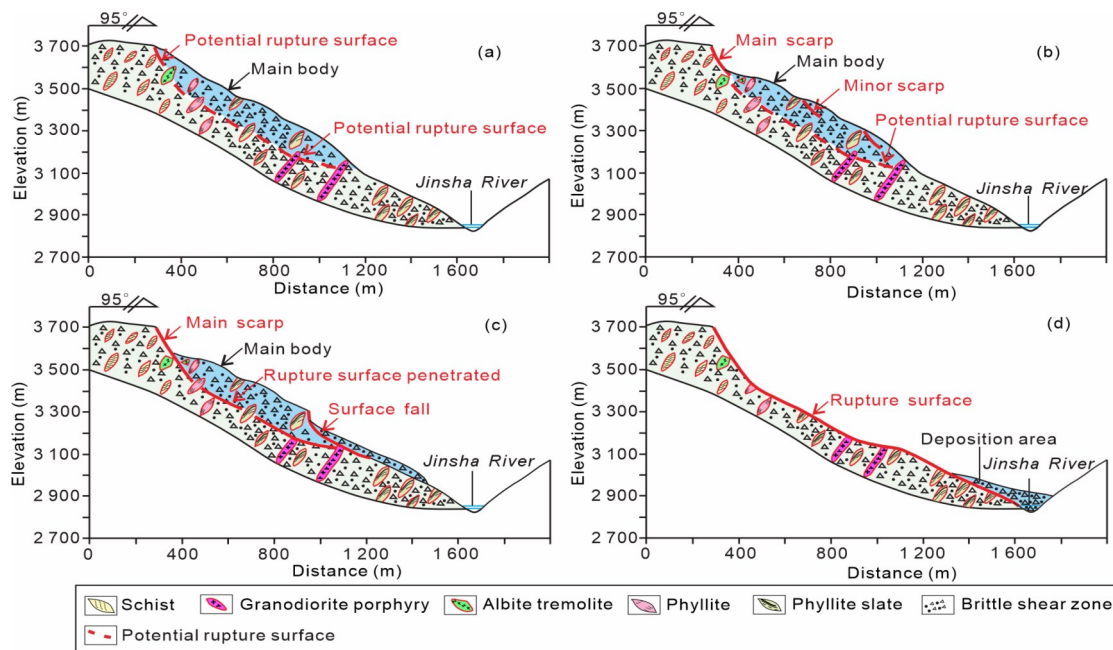


Figure 16. Process of the evolution of the Baige landslides. (a) Geological evolution stage; (b) the brittle shear zone penetration and tectonically induced lenticular rock mass blocking stage; (c) the lenticular rock mass shear-induced failure stage; (d) the rock avalanche dynamic erosion and accumulation stage.

The brittle shear zone penetration and locked segment locking stage: The geological body within the slope undergoes active fault shear failure, leading to the formation of various discontinuities (Figure 16b). These discontinuities extend to the slope surface due to geological process, creating longitudinal shear fractures and tension fractures, which result in observable deformation in the shallow surface layer. Under gravitational unloading and ongoing erosion by the Jinsha River, the surface material in the middle part of the slope collapsed locally and underwent gradual deformation. Despite this, the overall resistance of the locked segment to sliding exceeded the sliding forces, keeping the slope in a relatively stable condition. However, over time, the effects of rainfall, freeze-thaw cycles, earthquakes, and gravitational and tectonic stresses gradually activated the potential sliding surface, initiating sliding and shearing of the lenticular rock masses, with some potential sliding zones beginning to expand. This stage persisted for nearly 50 years (Xu et al., 2018), but the landslide mass had not yet failed (Figure 16b). From a traditional mechanic's perspective, the crown material was compressed and pushed toward the central part of the slope due to potential energy, resulting in traction deformation at the damage zone's center. Therefore, the Baige landslide events are considered compound landslides, characterized by both slumping-slide and retrogressive-slide types.

The locked segment shear-induced failure stage: After 2011, the deformation process of the Baige landslides gradually accelerated (Fan et al., 2020). As shear displacement developed, the concentration of shear stress in the locked segment increased continuously. Concurrently, the dilatancy force generated by shear displace-

ment along the undulating rupture surface, combined with the influence of the overlying crushing zone, significantly weakened the shear resistance of the granodiorite porphyry (locked segment) (Figure 16c). However, the slope remained free of catastrophic failure at this stage, primarily because the locking section had not yet achieved peak strength. Under the influence of internal and external dynamic geological factors, the potential sliding surface will undergo progressive and accelerated development once it is penetrated. At this stage, shear stress becomes concentrated on the locking section of the granitic diorite porphyry vein, leading to its shearing due to the stress concentration caused by the breakthrough. Consequently, the locked segment was sheared, resulting in a sudden landslide.

Rock avalanche dynamic erosion and accumulation stage: After the failure area of the Baige landslides became unstable, the sliding mass moved at high speed, eroding and entraining the lower material before eventually entering the Jinsha River. During the sliding process, the rock and soil masses disintegrated further upon impact with the riverbed, resulting in a rock avalanche. Upon reaching the Jinsha Riverbed, the rock and soil mass struck the opposite bank slope, rebounded, scattered, and accumulated. This accumulation ultimately blocked the Jinsha River, forming a barrier lake (Figure 16d).

4.2 Comparison with Other Locked-Type Rock Slides

The proposed locking mechanism is likely applicable to other mélange belts globally, particularly those with similar structural characteristics—strong blocks within a weaker matrix. Mélange belts are common in subduction

zones and other tectonic settings where intense deformation occurs. For example, the Franciscan Complex in California (Wakabayashi, 1992), and the Apennines in Italy all exhibit similar structural features (Carminati and Doglioni, 2012). In these settings, the presence of strong blocks within a weaker matrix could similarly lead to strain localization and a locking mechanism that inhibits slip (Festa et al., 2010). However, the effectiveness of the locking mechanism may vary depending on factors such as the proportion of strong blocks to weak matrix, the orientation of the blocks relative to the principal stress directions, and the rheological properties of the matrix (Scholz, 1998). In some cases, the matrix may be too weak to effectively transfer stress to the blocks, reducing the locking effect. Conversely, in other cases, the blocks may be too widely spaced to significantly influence the overall deformation of the mélange (Raimbourg et al., 2017).

Various locking methods have been proposed for landslides with locked upper sections, but most landslides exhibit only a single locking method related to the slope. For instance, the Jiweishan extralarge landslide is classified as an anti-slip block-type landslide. In this case, the crown of the landslide block has favorable sliding conditions, and the locked segment at the base controls its deformation. As thrust increases and the strength of the block decreases, the locked segment experiences shear, leading to the formation of a complete slumping slide (Xu et al., 2010). The Touzhai landslide, a retaining wall-type landslide, is governed by the stability provided by a central high-strength cantilever beam-type locked segment. Over time, as deformation progresses, the locked segment eventually shears off (Ren et al., 2018). The central part of the Xintan landslide contains a high-strength blocking body, which is characterized by three segments: a wide segment at the top, a narrow segment in the middle, and a wide segment at the bottom. The slide mass is a loose accumulation with low strength. Under the effect of static time-lapse deformation, creep slip occurs in the upper wider active slip area, and “arch-shaped” stress concentration occurs in the middle narrower area of the developed blocking body and plays a key supporting role for the sliding mass (Zhou et al., 2024b; Chen et al., 2018).

The Baige landslide displays complex failure forms, primarily due to factors such as the deep subduction of the subducting plate, its retrograde thrusting, and associated tectonic intrusions. These factors result in significant variations in the morphology and structure of the lenticular rock masses within the slope. Consequently, the complex geological evolution and diverse rock types contribute to the intricate locking patterns observed in the Baige landslides. During large shear deformation associated with landslides, we demonstrate that granodiorite porphyry can function as natural anti-slip piles to mitigate landslide movement. Despite the catastrophic failure that has occurred to the main body of the slope, the locking effect of the granodiorite porphyry veins is evident in the residual deformation body (K3).

5 CONCLUSIONS

This study employs a multidisciplinary approach to analyze the geostructural characteristics of the Baige landslide, aiming to clarify the relationship between geological structure, shear failure, and landslide evolution. The key conclusions are as follows.

(1) The geologic structure of the Baige landslide is a two-layer geological unit with tectonic fragmentation. This structure encompasses lenticular rock masses and brittle shear zones (fault breccia, cataclasite, fault gouge). The granodiorite porphyry functioned as locked segments, obstructing the multi-deformation of the sliding mass.

(2) The Baige landslide process can be divided into four distinct stages. The first stage involves geological evolution, followed by the penetration of the brittle shear zone and the subsequent locking of the locked segment. The third stage is characterized by shear-induced failure of the locked segment, while the final stage involves dynamic erosion and the accumulation of rock avalanche.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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