

Exploring the Failure Mechanism of the Baige Landslide via Field Observations and Physical Model Tests

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ABSTRACT: In 2018, a catastrophic high-altitude landslide occurred at Baige, located within the tectonic suture zone of the Upper Jinsha River. The failure mechanism of this event remains poorly understood. This study aims to elucidate the deformation characteristics and failure mechanism of the Baige landslide by employing a comprehensive methodology, including field geological surveys, analysis of historical remote sensing imagery, high-density electrical resistivity surveys, and advanced displacement monitoring. Additionally, the physical modeling experiments were conducted to replicate the unique failure modes. The findings propose a novel perspective on the failure mechanism of the Baige landslide, which involves two critical stages: first, the brittle shear zone bypasses and fails at the lower locked segment, and second, the failure of the upper locked segment, combined with the shear zone's impact on the lower locked segment, triggers overall slope instability. Physical modeling experiments revealed a transition from initial acceleration to a rapid acceleration phase, particularly marked by a significant increase in velocity following the failure of the upper locked segment. The intensity of acoustic emission signals was found to correlate with the failure of the locked segments and the state of particle collisions post-failure. It offers new insights into the failure mechanisms of tectonic mélange belt large-scale landslides in suture zones, contributing to the broader field of landslide research.

KEY WORDS: Baige landslides, Jinsha River tectonic mélange belt, failure pattern, physical model experiments, mechanisms.

0 INTRODUCTION

As a result of plate collisions, the tectonic mélange belt of the Tibetan Plateau is characterized by a complex geological evolution and a fragile geological environment (Kawabata et al., 2021; Imayama et al., 2010). This belt consists of a range of tectonic rock masses with varying scales, lithologies, and degrees of deformation, as well as highly deformed brittle shear zones. The spatial distribution of these features is locally ordered but disordered overall (Ogata et al., 2021; Festa et al., 2019). Recently, high-altitude landslides have frequently occurred in the

tectonic mélange belt, posing significant risks and threatening the safety of major construction projects and people's lives and property. The tectonic rock blocks and shear zones within the mélange belt play critical roles in the formation of large landslides and are primary contributors to major geological hazards (Zhang T T et al., 2023; Gao et al., 2020). Given the substantial variations in lithology, metamorphic types, and physical-mechanical properties within the tectonic mélange belt, the landslide-prone geological structures and their catastrophic impacts remain unclear. This knowledge gap directly affects our understanding of the background, formation mechanisms, and evolution of high-elevation and long-term landslides. Therefore, investigating the destabilization mechanisms, disaster modes, and risk management of large landslides in the tectonic mélange belt is essential, as this information can provide valuable insights for mitigating similar catastrophic landslides in other tectonic

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mélange belt areas in the future.

On October 11 and November 3, 2018, two high-elevation landslides in Boluo Township, Tibet, dammed the Jinsha River. Subsequent studies employing image correlation techniques revealed that these events exhibited high-speed sliding and high-shear exit characteristics (Ding et al., 2021; Fan et al., 2020). Further investigations into historical deformation and failure mechanisms suggested that late-stage strong deformation zones primarily underwent progressive disintegration (Chen et al., 2021; Yang et al., 2020; Zhang et al., 2020). Yi et al. (2022) attributed the Baige landslide's failure to the long-term coupling effects of tectonic activity and surface erosion, while highlighted the role of water infiltration from Bogonggou in weakening rock mass strength along structural planes, facilitating slope instability (Tian et al., 2020). Numerical simulations have also advanced understanding of the landslide dynamics. Bao et al. (2023) developed a 3D finite-discrete element method-smoothed particle hydrodynamics (FDEM-SPH) model to reconstruct the event, analyzing kinetic energy evolution, frictional dissipation, and fracture energy. Similarly, Zhang W et al. (2023) proposed a material point method (MPM)-based terrain contact algorithm to simulate sliding body movement, accounting for complex terrain interactions. Despite these contributions, key questions remain unresolved. The influence of the Baige landslide's tectonic mélange structure on deformation and failure mechanisms, as well as the failure modes of landslides within such complex geo-structural settings, requires further investigation.

Physical modeling serves as a critical tool for investigating landslide deformation, failure mechanisms, and post-failure dynamics (Zhu et al., 2020; Yan et al., 2019; Alzo'ubi et al., 2010), particularly due to its capacity to facilitate comprehensive monitoring of landslide processes (Huang et al., 2020; Xie et al., 2020). The intuitive and effective nature of physical modeling has led to its widespread application in landslide mechanism studies (Wang C T et al., 2023; Ahmadi et al., 2018; Zarrabi and Eslami, 2016). Shaking table tests have been employed to examine the dynamic response and failure processes of tilt-resistant slopes under seismic loading (Yang et al., 2012; Adhikary and Dyskin, 2007). Comparative analyses of slope models with varying materials revealed that tilt velocity governs slope instability regimes (Wolinsky and Take, 2019; Zhang et al., 2019; Chen et al., 2015). Xu et al. (2022) further demonstrated, through physical modeling, the cumulative failure mechanisms of rocky slopes in hydraulic fluctuation zones under repeated seismic loads, with experimental results aligning well with numerical simulations. These studies elucidated dynamic cumulative damage evolution and characteristic failure patterns in such environments. Wang J M et al. (2023) utilized friction tests coupled with digital image analysis to investigate slope deformation under excavation-induced unloading, identifying destabilization mechanisms involving basal traction or top thrust, followed by accelerated deformation and eventual failure. In landslide dy-

namics research, Zhang S L et al. (2023) employed a custom-designed apparatus to examine block configuration effects, enabling realistic assessment of particle fragmentation's role in energy dissipation and flow dynamics. Li et al. (2021) explored granular flow mobility over erodible substrates, demonstrating that increased basal resistance can promote stable multilayer flow development in high-mass granular systems. While these experimental approaches have advanced understanding of landslide mechanisms and addressed quantitative analysis limitations for sudden failures, field validation through physical modeling remains scarce. This study bridges this gap by integrating long-term field investigations with physical modeling experiments to verify landslide failure mechanisms.

This study examines the spatial distribution of rock mass within the Baige landslide's geo-structure and elucidates its distinctive failure mechanisms within the tectonic mélange belt. Through comparative analysis of multi-temporal slope surface displacements derived from historical remote sensing data and borehole core samples exhibiting deep shear displacement, we identify characteristic failure patterns. Physical modeling experiments successfully replicate these failure mechanisms, particularly demonstrating how brittle shear zones circumvent locked segments within the complex mélange structure. The results provide critical insights into catastrophic failure mechanisms of large-scale landslides in the Tibetan Plateau's tectonic mélange belt.

1 REGIONAL SETTING

The Baige landslide is situated on the western bank of the Jinsha River and straddles the border between Sichuan and Tibet (Figure 1a). The toe of the landslide rests on the concave bank of the Jinsha River, whereas the crown is perched on the shoulder of the river valley.

The landslide is situated within the Jinsha River suture zone, a key tectonic marker delineating paleoconvergent plate boundaries and accretionary block margins (Kawabata et al., 2021; Najman et al., 2017). This zone preserves the complete evolutionary record of the Paleotethys Ocean from Paleozoic rifting through oceanic maturation to final closure. The suture zone comprises a tectonic mélange belt featuring an accretionary wedge complex that incorporates: sedimentary cover sequences, disrupted oceanic crust fragments, *in-situ* deep-sea sediments of varying ages. These components were accreted through subduction-related tectonic processes including trench scraping, tectonic collage, and basement underplating (Kusky et al., 2013; Festa et al., 2012). Subsequent plateau uplift and neotectonic fracturing have significantly degraded rock mass integrity, critically compromising slope stability in the region.

The landslide area exhibits a northwest-southeast topographic gradient, with elevations ranging from 2 846.97 to 4 972.97 m, characteristic of a typical tectonic erosion landscape. The India-Eurasia collision orogeny has driven uplift of the Tibetan Plateau, creating signifi-

crown, while the toe remained essentially stable (Figures 3a, 3b). This apparent decoupling between crown displacement and toe stability persisted until the catastrophic failure in October 2018. We attribute this unique deformation pattern to internal geo-structural kinematics, reflecting the distinctive failure mechanism induced by the complex tectonic mélange structure.

The potential sliding surface of the landslide failure area progressively activated under prolonged environmental forcing, including rainfall infiltration, freeze-thaw cycles, seismic activity, and gravitational loading. Remote sensing analysis reveals that by March 2011, a continuous tension crack had developed at the crown, which

2.1 Geo-Structure and Deformation Process of the Baige Landslide

Multi-temporal remote sensing analysis of the Baige landslide reveals distinct deformation patterns between slope segments. The middle–upper section (3 300–3 700 m) exhibited primary deformation and failure, while the lower segment (2 900–3 300 m) showed erosion-dominated displacement (Figures 3a – 3c). Accordingly, we classified these as the failure zone and erosion zone, respectively (Figures 3a–3c). Comparative analysis of 2011 – 2017 imagery indicates ~50 m displacement at the

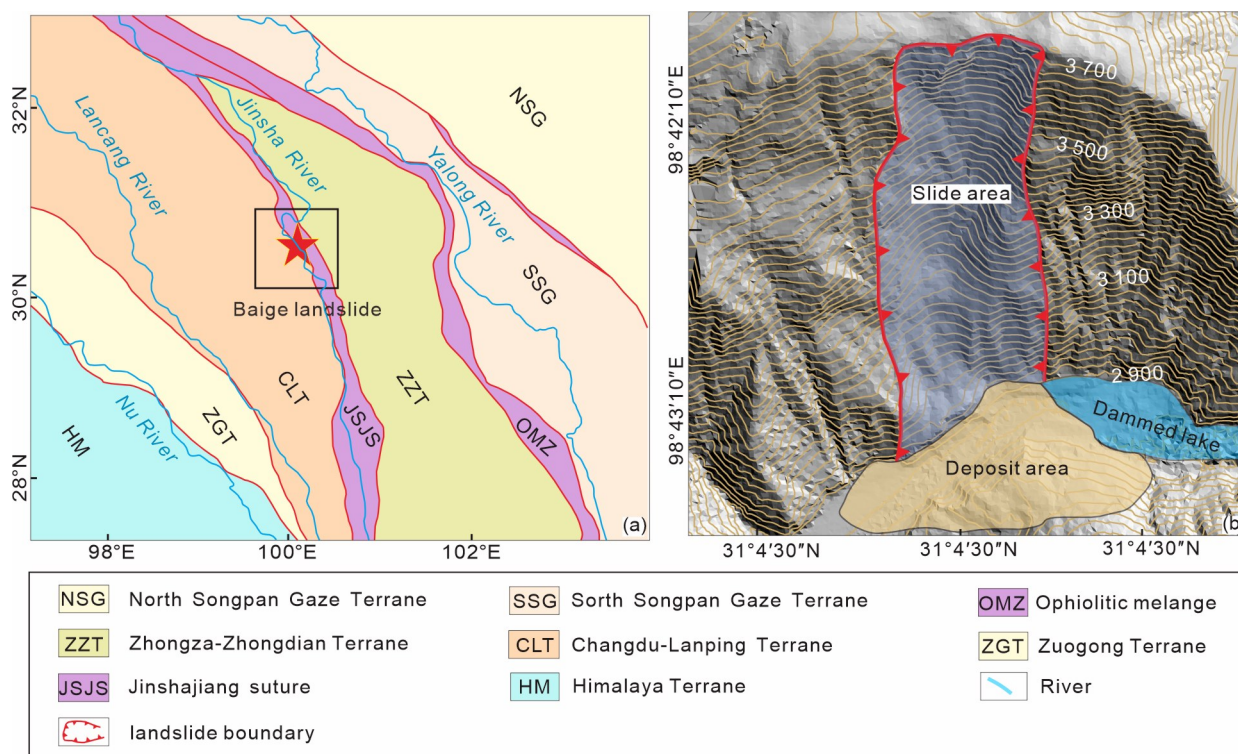


Figure 1. Location and regional background of the study area. (a) Location of the Baige landslide; (b) basic characteristics of the Baige landslide and deposit area.

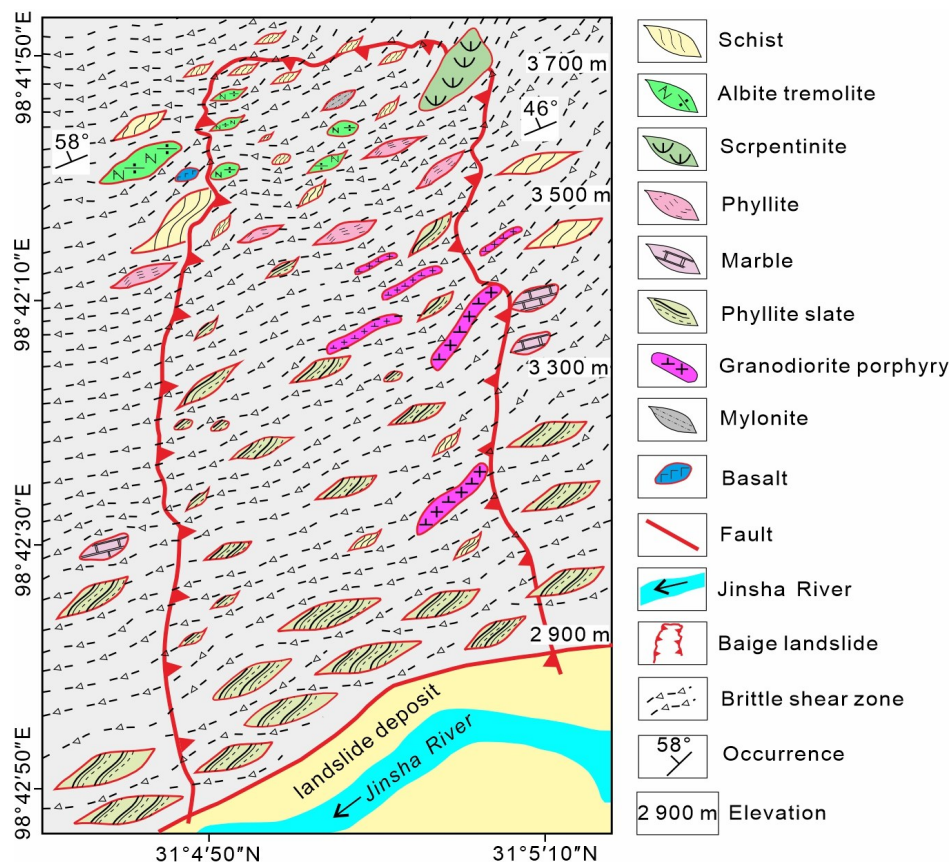


Figure 2. Geo-structural characterization of Baige landslide.

subsequently experienced 50 m of downward displacement by February 2018, while the toe remained essentially stable (Figures 3a–3c). Field investigations of landslide remnants between the original slope and slip surface identified compacted brittle shear zones (Figure 3d), with the locked segment maintaining structural integrity. Bore-hole data from November 2019 confirmed shear deformation at 15 m depth in the left deformation body (Figures 3k, 3f) and 22 m depth in the right deformation body (Figures 3l, 3g). Notably, both remnants retained structural continuity (Figure 3e), demonstrating that slope movement occurred preferentially along pre-existing brittle shear zones while bypassing the locked segments (Figures 3i, 3j). This kinematic behavior explains the observed displacement dichotomy between the actively sliding crown and stable toe. The mechanism involves: top-down compression and compaction of the brittle shear zone, and gravitational unloading at the toe facilitating shear zone propagation around locked segments (Figure 3h). These coupled processes ultimately led to progressive slope failure, with the system currently exhibiting incipient failure characteristics.

The stability of the Baige landslide is fundamentally governed by strength heterogeneity between the brittle shear zone and locked segments. Initial failure preferentially develops within the weaker shear zone, circumventing the more competent locked segments. Progressive failure subsequently propagates along structural disconti-

nities within the locked segment rock mass. Given the pronounced lithological variability and consequent mechanical property contrasts within the locked segments, stress concentrations induce multi-directional shear failure along potential rupture surfaces. This failure mechanism typically culminates in abrupt slope collapse upon complete penetration of the failure surface.

2.2 Unique Failure Patterns of the Baige Landslide

Multi-temporal remote sensing analysis documents the evolutionary stages of the Baige landslide deformation. Pre-2011 imagery shows substantial deformation with a well-developed main scarp, while slope stability was maintained through buttressing by the locked segment, despite gravitational compaction of internal shear zones (Figure 4a). After 2011, the deformation of the slide mass accelerated. The compaction zone of the brittle shear zone developed further and was influenced by the overlying crush zone. Shear failure occurred at the toe of the brittle shear zone, bypassing the locked segment, although failure did not occur at the toe of the locked segment (granodiorite porphyry) (Figure 4b). As the toe of the brittle shear zone failed, failure progressed and accelerated. During this process, the central schist and phyllite disintegrated due to the development of lamellae and fissures, as well as their poor mechanical properties. When the failure extended to the crown of the locked segment, the structural surface of the crown (al-

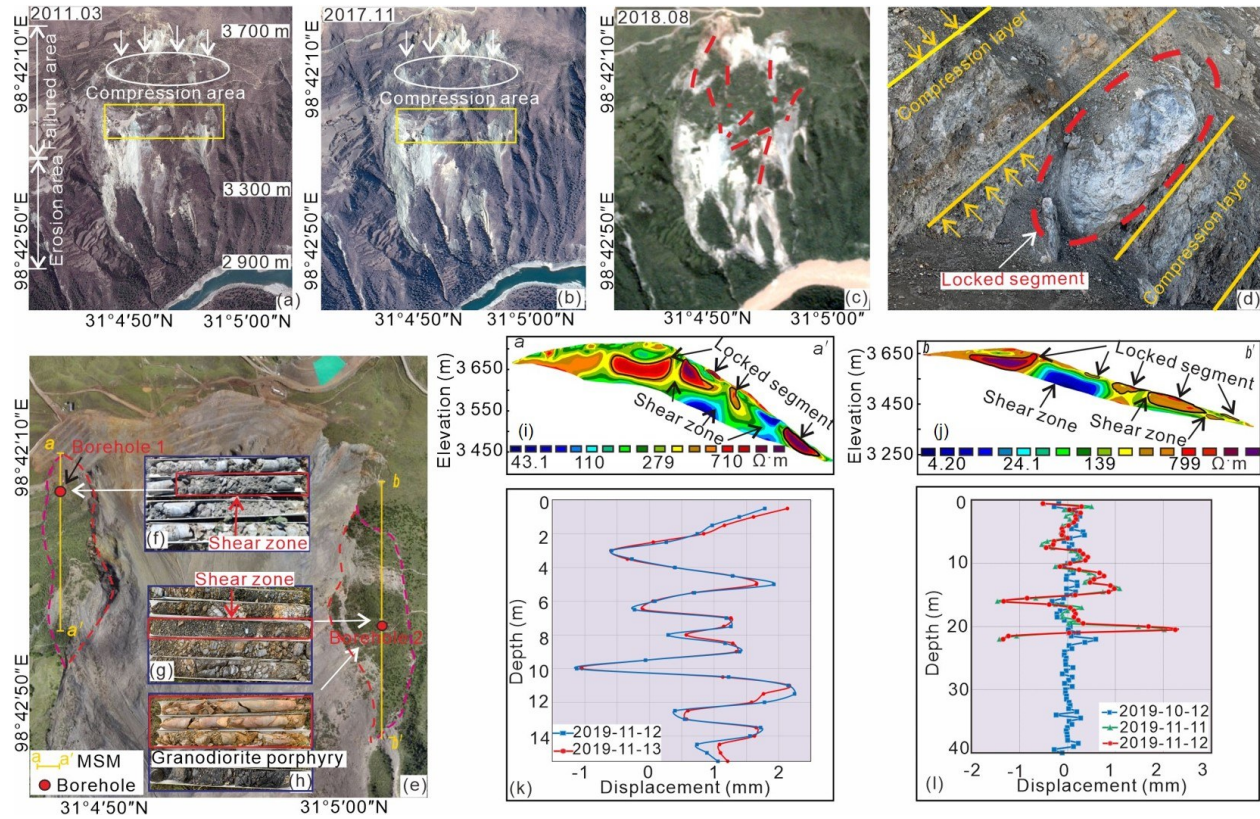


Figure 3. (a)–(c) Historical remote sensing imagery of the Baige landslide; (d) brittle shear zone compaction in these remnants; (e) layout of the boreholes and MSM profile; (f)–(g) revealing sliding zones on both sides of the deformed body; (d) drill holes reveal granodiorite porphyry; (i)–(j) multielectrode resistivity method; (k)–(l) deep displacement observation curve.

bite tremolite) was filled with debris material. This material has relatively fragile mechanical properties, making it prone to shearing under upper push pressure and its own gravitational potential energy. Following the shear failure of the crown, the entire slide mass entered a high-speed movement phase, with the crown of the locked segment being driven by particles from the brittle shear zone and gravity. Ultimately, the high-speed impact of the crown on the toe of the locked segment increased the shear stress concentration (Figure 4c). Additionally, the undulating slip section along the rupture surface, combined with shear displacement expansion forces, caused significant weakening of the granitic gneiss section in the lower part of the locked segment. This led to the complete failure of the internal structure and a catastrophic collapse of the slope. Importantly, the locked segment acts as an energy reservoir, storing substantial elastic strain energy before failure. When the segment suddenly fractures, this energy is converted into kinetic energy, resulting in the rapid onset of the landslide. Consequently, the destabilization of locked-type slopes can be highly destructive. In the case of the Baige landslide, the destabilized area experienced extremely high-speed movement, with lower materials being eroded and swept into the Jinsha River (Figure 4d).

On the basis of the studies above, we inferred that the failure mode of the Baige landslide was as follows: the weak and brittle shear zone at the toe of the failure

zone bypassed the locked segment, leading to shearing of the locked segment at the crown. This sheared crown then impacted the locked segment at the toe, resulting in the complete failure of the landslide body.

3 EXPERIMENTAL METHODS

3.1 Slope Mode and Similar Material

On the basis of long-term field observations, the failure mode of the Baige landslide was summarized, and physical model experiments were conducted to verify this failure mode. Currently, the selection and preparation of similar materials for rock landslide physical modeling tests are typically based on the similarity relationships between key parameters such as density, cohesion, angle of internal friction, and modulus of elasticity (Zhang et al., 2024). However, this study focused specifically on the structural surface cohesion and angle of internal friction of the locking section. In this experiment, the damage area of the Baige landslide was selected as the test prototype (Figure 5), with the slide mass length in the damage area being 400 m. On the basis of the scale of the landslide damage area and the dimensions of the experimental equipment, the geometrical similarity ratio of the model, C_L , was 285. The other similarity constants were calculated as follows.

$$C_L = L_p/L_m, C_v = \gamma_p/\gamma_m, C_c = C_p/C_m, C_\phi = \phi_p/\phi_m \quad (1)$$

$$C_\sigma = C_v C_L, C_\phi = 1 \quad (2)$$

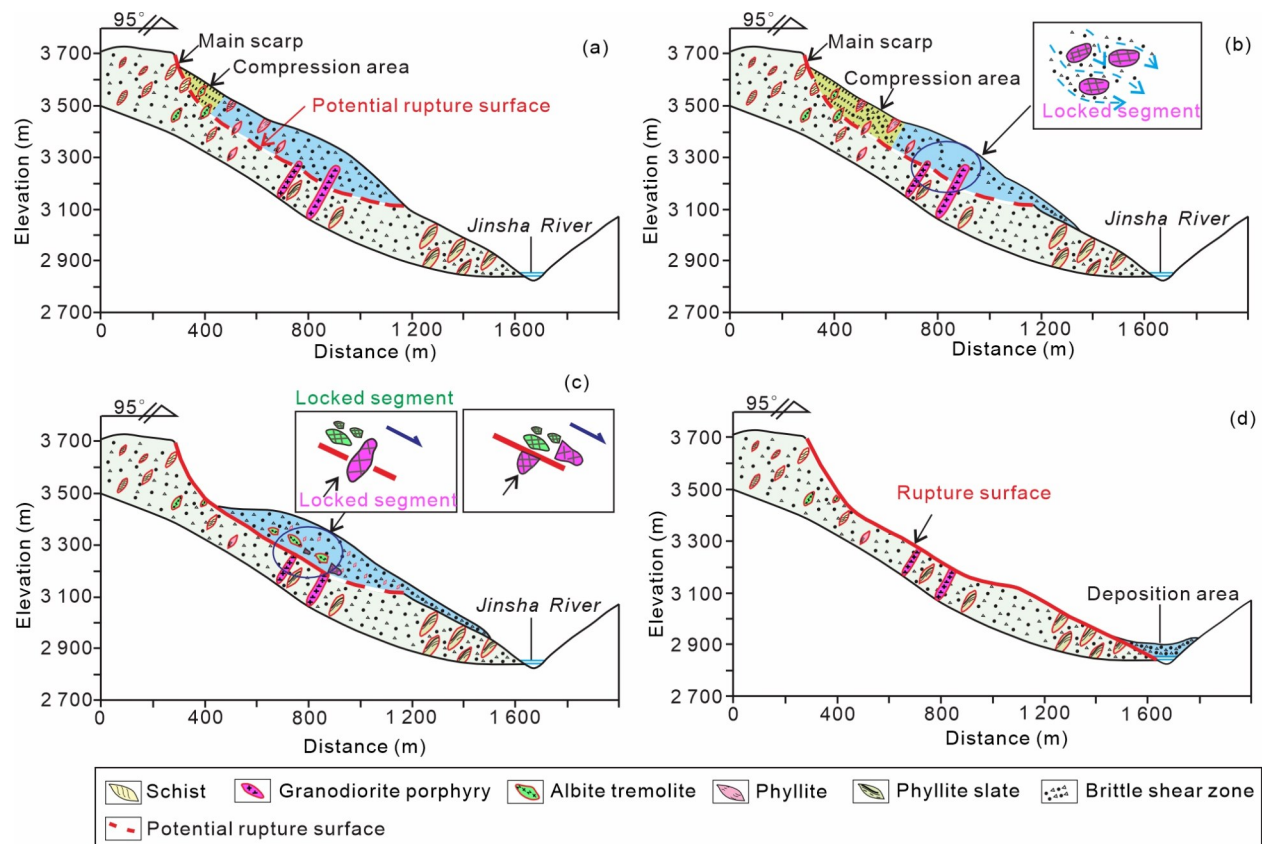


Figure 4. Process of the evolution of the Baige landslides. (a) The brittle shear zone penetration and locked segment blocking stage; (b) shear failure occurred at the toe of the brittle shear zone, bypassing the locked segment, although failure did not occur at the toe of the locked segment; (c) the failure of the upper locked segment, combined with the shear zone's impact on the lower locked segment, triggers overall slope instability; (d) the rock avalanche dynamic erosion and accumulation stage.

where C is the similarity coefficient; L , γ , σ , c , and φ are the geometry, density, stress, and cohesion, respectively; and the subscripts P and m represent the prototype and experimental models, respectively.

The Baige landslide primarily consists of a lenticular locked segment with albite tremolite, granodiorite porphyry, and brittle shear zones. In the physical model, two rock materials and stones of different grain sizes were used to simulate the rock mass of the locking section and the brittle shear zone. On the basis of mechanical tests and similarity ratio theory, the mechanical property parameters for the structural surfaces of the rock mass and the brittle shear zone in the locked section of the landslide were calculated, as shown in Table 1. Quartz sand, gypsum powder, clay, and water are commonly used as similar materials in rock landslide modeling tests. The target mechanical parameters for the modeling experiments can be achieved by adjusting the material ratios (Zhang B C et al., 2023). Cement, sand, and water mass ratios were chosen as similar materials for granodiorite porphyry and albite tremolite in the locking section on the basis of multiple sets of direct shear tests on the experimental materials (Ning et al., 2021). Importantly, field investigations of damage to these two locking segments focused on the structural surface. Therefore, gypsum powder and water mass ratios were selected as the structural face ce-

Table 1 Physical and mechanical parameters of the rock mass, similar materials

Lithology	Cohesion (MPa)	Internal friction angle (°)
Granodiorite porphyry	1.24	42.0
Target value	4.35×10^{-3}	42.0
Actual value	1.36×10^{-3}	38.0
Albite tremolite	0.69	29.0
Target value	2.42×10^{-3}	29.0
Actual value	1.81×10^{-3}	25

ment for the locking section of granodiorite porphyry. Nano-double-sided adhesive was used as the structural surface cement for sodic long diorite, which adjusts the friction angle and bond strength of the shear surface to meet the experimental similarity requirements. Owing to the complexity of similar materials, achieving perfectly consistent target values for mechanical properties is challenging. Consequently, to meet the geometric similarity theory requirements for this experiment, the strengths of the simulated materials were microadjusted to better reflect the differences in the mechanical strengths of the structural surface binder materials. The selected binder materials were suitable for this modeling experiment.

The focus of this study was to validate the failure

model of the Baige landslide to reveal its failure behavior. The physical model was based on simplified conditions derived from a generalized geological model, which slightly deviated from the prototype conditions. Additionally, the choice of experimental materials is crucial, as it affects both the selection of monitoring methods and the failure mechanism of the model. The experimental setup consisted of a simple rectangular box with dimensions of 1.4 m in length, 0.3 m in width, and 1.1 m in height. The base group included the rear sidewall of the box, which was used for sensor embedding. The slope model had dimensions of 1.1 m in height, 1.1 m in length, and 0.4 m in thickness. The slope gradient was set to 40° on the basis of the landslide prototype and geometric similarity ratio. To prevent direct sliding on the base and to replicate field conditions, a base layer of 4–5 cm thickness was applied. This layer was composed of 6 mm particles, 1 mm particles, 10 mm particles, cement, water and AB adhesive with mass ratios of 0.649, 0.185, 0.092, 0.041, and 0.022, respectively. The mixture was allowed to set at room temperature for 8 days until it solidified. The main sliding body was composed of particles with mass ratios of 0.9, 0.06, and 0.04 for the 6, 1, and 10 mm sizes, respectively. The sliding body had a gravity force of 14.50 kN/m^3 and a friction coefficient of 0.6. The spacing of the locked segments of rock was determined on the basis of field investigations and similarity criteria. The distance between identical locked segments was 4–6 cm, with a 48 cm gap between the upper and lower locked segments. The lower locked segments were placed only on the right side and in the center, with no locked segments on the left side. This arrangement reflected the natural conditions where the granodiorite porphyry in the Baige landslide was absent from the left side and did not extend into that area.

3.2 Sensor Position and Modeling Test Procedure

The experimental sensor configuration is illustrated in Figure 6. A GoPro camera, mounted on a rigid frame, was positioned parallel to the slope surface with a 1.2-m working distance to the slope center. For comprehensive 2D imaging, both high-speed and smartphone cameras were deployed on the model's frontal aspect at an average distance of 2 m, ensuring complete image overlap. Four acoustic emission fiber-optic probe sensors were embedded and secured on the rear side of the model. These sensors, labeled AE1, AE2, AE3, and AE4, were arranged sequentially from the lower to the upper part of the model to monitor the acoustic signals at different locations.

First, the slope model was secured via rod support plates. Acoustic emission fiber-optic probes were then installed. Uniformly mixed particles were added to create a heap along the marking line delineated on the sidewall of the glass, forming the slope. For the slope portion, compaction was carried out every 5 cm along the direction of the slope to ensure a uniform slope model. Achieving consistent relative density and compaction is critical for physical model tests. When the lower locking section was reached, a mixture of 8 grams of gypsum with 3.8 grams of water was prepared and applied to bond the structural surface of the locking section of the rock mass. After 10 minutes of consolidation, the slope was stacked and compacted sequentially. The upper locking section of the rock mass was then added using 3MVHB adhesive for effective bonding. After 5 min of bonding, the slope was consolidated, and stacking continued until the entire slope was completed. Once the slope model was prepared and all the instruments were installed, the fixed support plates were removed, and the slope was left to fail.

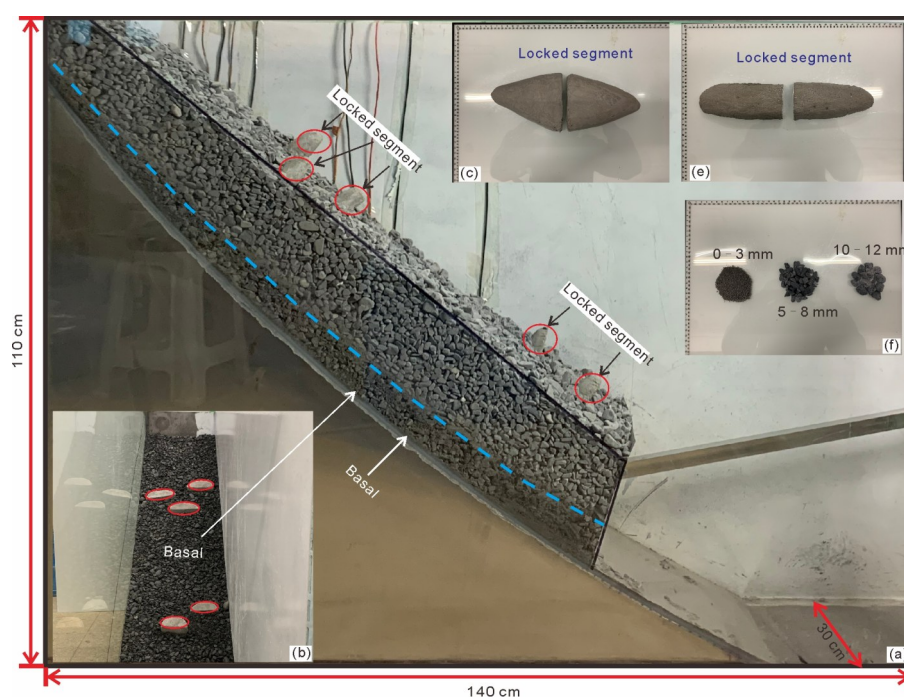


Figure 5. (a) Overview of the physical model; (b) basal; (c)–(e) upper locked segment and lower locked segment; (f) particles of different sizes.

4 RESULTS

4.1 Deformation and Failure Characteristics

In this experiment, a GoPro camera was used to record the damage characteristics of the slope model (Figure 7). Six key frames were extracted via PR software to analyze failure progression. Initially, the particles at the base of the slope failed by gravitational unloading around the locked segment, which remained stable and effectively blocked movement in the upper section. As the particles accelerated their movement, the failure zone gradually extended toward the middle, where it experienced shear failure due to traction and pushing action at the crown of the locked segment. Following this, the crown of the locked segment accelerated due to gravitational potential energy and particles until it failed at the slope base.

4.2 Evolution of the Displacement Field in Model Tests

The top-view 2D surface displacements of the model were obtained through image processing analysis via particle image velocimetry (PIV). To emphasize significant

changes in displacement during the failure of the locked segments, simulations were performed for the horizontal and vertical displacements of the model, as well as the total displacement vectors for various failure stages. The horizontal displacement represented the movement in the transverse direction, whereas the vertical displacement reflected the movement in the slope direction.

The particles in the slope model were influenced by the locked segments during their movement. The particles shifted from the left and right sides, resulting in negative horizontal displacements on the left and positive displacements on the right. Initially, the vertical displacement of the slope model was negligible and measured less than 1 mm. As failure progressed at the base of the slope, the area of horizontal displacement increased (Figure 8a). The displacement on the right side became significantly larger than that on the left, with a maximum positive displacement of 5 mm and a maximum negative displacement of 4 mm. However, the locked segment at the base remained stable (Figure 8b). As damage continued to spread, the upper locked segment experienced minor

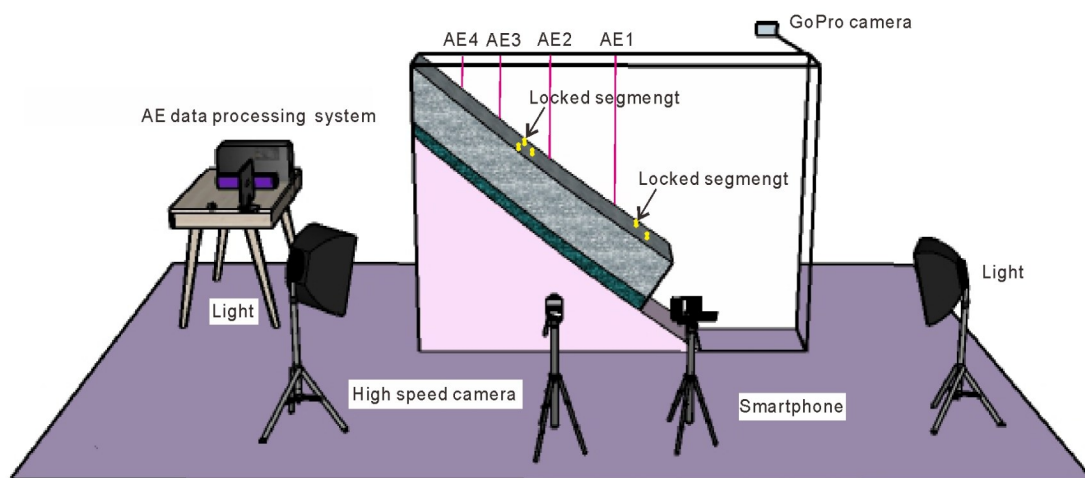


Figure 6. Location and distribution of the monitoring instruments.

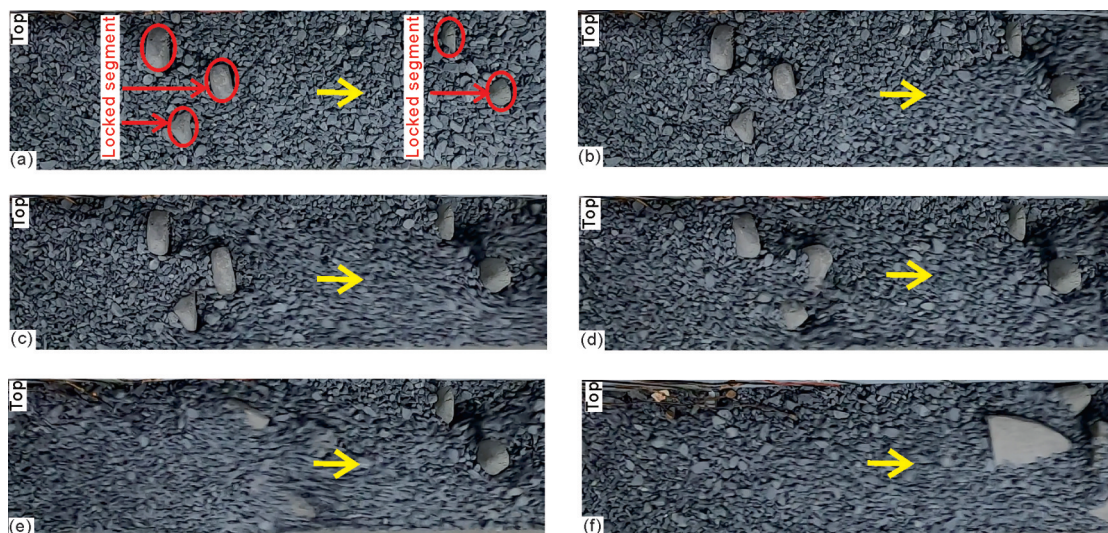


Figure 7. Deformation and failure characteristics of the slope model.

deformation, with a maximum displacement of approximately 7.5 mm (Figure 8d). Eventually, when the upper locked segment completely failed, it impacted the lower locked segment, causing it to shear off. This led to substantial horizontal displacement of the slope, with a maximum displacement of approximately 12 mm (Figure 8f). However, the horizontal displacement along the slope was much smaller than the vertical displacement.

In the vertical displacement map, downward displacement was considered positive. At the initial stage, the particles at the base of the modeled slope exhibited minimal movement, with a maximum displacement of 2.4 mm, whereas the lower locked segment remained stable (Figure 9a). As failure progressed, the affected area expanded significantly, with the maximum displacement reaching 14 mm. At this point, failure primarily involved particles bypassing the lower locked segment (Figure 9b). As the failure zone grew, the upper locked segment began to deform, extending toward the upper part of the slope model, with a maximum displacement of 32 mm (Figure 9d). When the upper locked segment completely failed and accelerated under the influence of gravitational potential energy, the maximum displacement increased to 220 mm, whereas the lower locked segment remained stable (Figure 9e). Ultimately, the vertical displacement region of the slope extended from the base to the top. The lower locked segment was sheared off due to high-speed impacts from particles, leading to the complete collapse of the slope, with a maximum vertical displacement of 440 mm (Figure 9f).

The analysis of the total displacement vector field revealed the destructive kinematic characteristics of the slope. Arrows of varying lengths illustrate the direction and magnitude of slope movement. The failure motion in the model was driven primarily by vertical displacement.

Initially, the vertical displacement on the left side was significantly greater than that on the right side because of the influence of the lower locked segment, resulting in uneven initial accelerated motion of the particles in the slope model (Figures 10a, 10b). As the failure zone expanded, the particles exhibited accelerated motion. Furthermore, failure to the upper locked segment accelerated this motion, although the lower left side remained localized in its initial acceleration state, which was influenced primarily by the left locking segment (Figures 10c, 10d). In the final stage, the displacement at the middle front reached its maximum because particles from the upper locked segment accelerated and impacted the lower locked segment, causing slope instability (Figures 10e, 10f). On the basis of the changes in landslide displacement over time, the slope model behavior can be generally divided into two stages: the initial acceleration phase and the accelerated deformation phase.

4.3 Characterization of Velocity Field Evolution in Slope Models

The 2D surface velocities of the model were obtained via high-speed camera recordings and particle image velocimetry (PIV) image processing. The velocity field information was calculated by dividing the displacement of the model between adjacent frames (L) by the time interval between these frames (T). For the analysis, the frame interval was set to 22 frames, corresponding to a time period of 0.105 seconds at a frame rate of 210 FPS. At $T_0 + 0.105$ s, influenced by the lower locked segment, the failure velocity of the toe particles was approximately 0.21 m/s (Figure 11a). As the damage zone expanded, at $T_0 + 0.315$ s, the failure extended to the upper locked segment, with the failure velocity of the particles reaching approximately 0.7 m/s (Figure 11c). By $T_0 +$

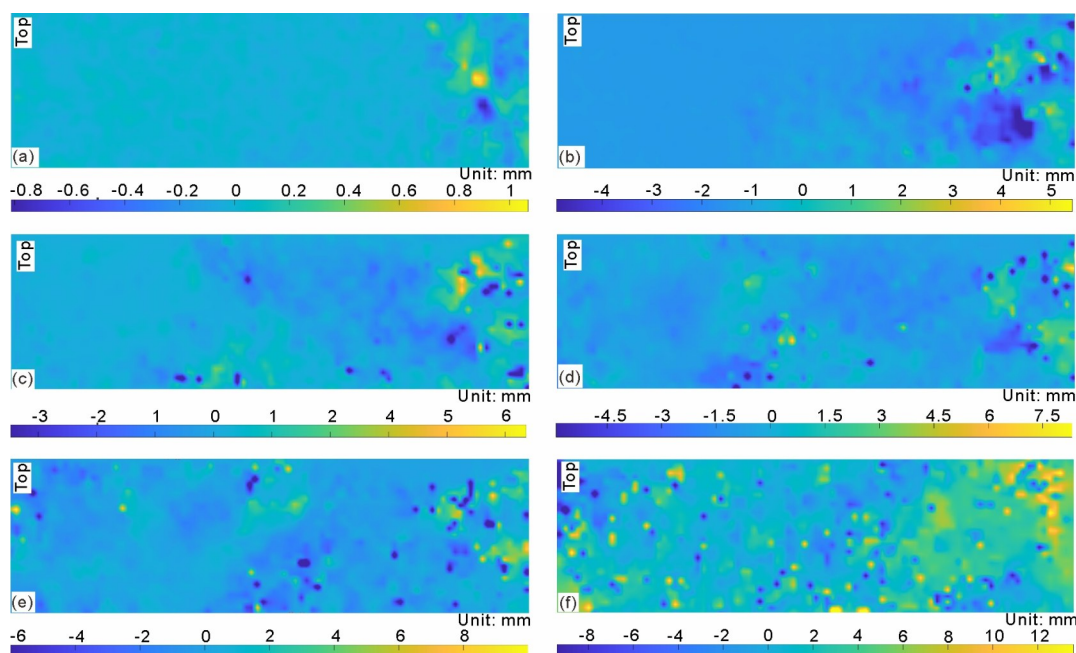


Figure 8. Horizontal displacement of the slope model.

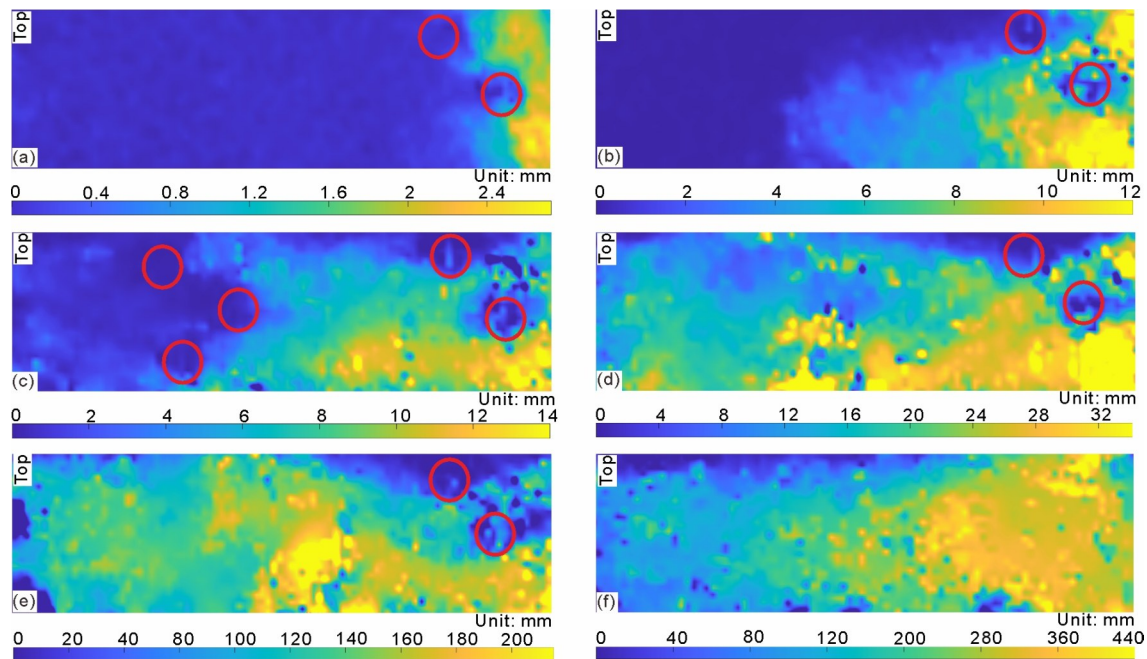


Figure 9. Vertical displacement of the slope model.

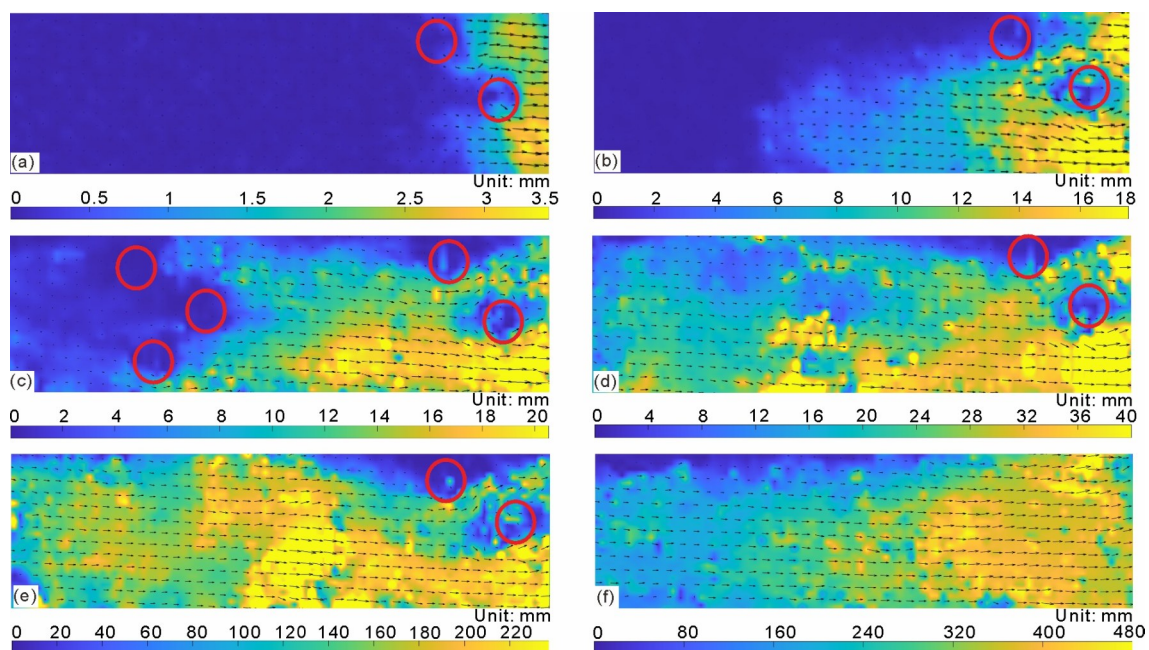


Figure 10. Displacement vectors of the slope model.

0.525 s, damage to the upper locked segment increased the particle velocity further to approximately 0.82 m/s (Figure 11e). Notably, the front part, influenced by the locking section, moved at a lower central velocity. Additionally, the localized velocity at the crown reached 0.82 m/s because of the destruction of the upper locked segment. At $T_0 + 0.63$ s, the velocity of the anterior part reached 0.85 m/s, and at this stage, the impact of particles from the upper locked segment on the lower locked segment led to the complete collapse of the slope (Figure 11f).

4.4 Characterization of the Acoustic Signal Evolution for Slope Models

4.4.1 Statistical analysis of the acoustic emission characteristic parameters

In recent years, acoustic emission technology has become a widely used method for studying slope failure processes, proving effective in landslide research. This study employed acoustic emission monitoring to observe the deformation and failure processes of slopes simultaneously in model experiments. The aim was to uncover the patterns in the acoustic emission characteristics related to the deformation and failure of slopes, as well as to

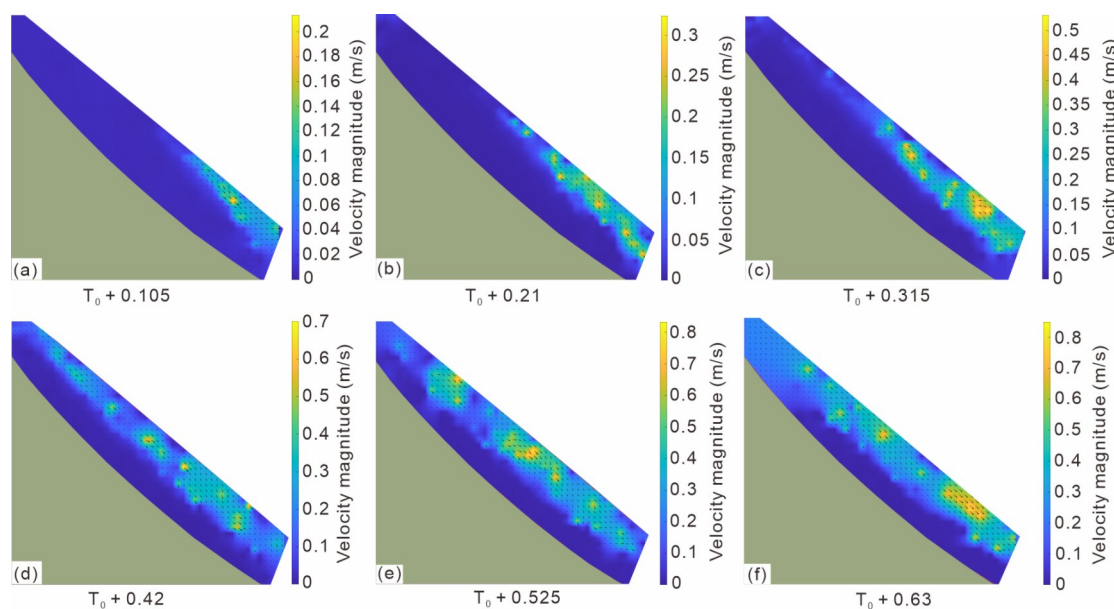


Figure 11. Velocity vectors of the slope model during slope failure.

examine the impact of different locked segments on slope failure. The acoustic emission energy represents the elastic energy released by the acoustic emission source, providing a direct indication of internal rupture changes within the slope. The acoustic emission count refers to the number of ringing pulses in which the acoustic emission signal exceeds a certain threshold during testing, offering insights into the rupture mechanisms of rock materials. Moreover, the acoustic emission amplitude indicates the magnitude of energy released during these acoustic emission events.

During the test, four acoustic emission (AE) sensors were used to sequentially measure the AE characteristic parameters of slope damage from top to bottom. AE1 was positioned near the lower locked segment. The cumulative energy, amplitude, and counts at the AE1 monitoring point began to rise during the initial failure of the particles at the toe. As failure progressed, the acoustic emission activity within the slope model intensified, with a sharp increase in counts and amplitude observed between 4 and 4.5 s. This indicated that the upper locked segment failed at that time, leading to a significant increase in acoustic emission activity. At 6.4 s, there was a dramatic increase in the acoustic emission count and amplitude, exceeding 25 000, which suggested that the upper locked segment had impacted the lower locked segment, causing it to fail and leading to overall model failure. Additionally, the cumulative energy increased progressively until 6.4 s, after which it stabilized, indicating that slope failure was nearly complete following the failure of the lower locked segment (Figure 12a). AE2 was positioned near the upper locked segment. Between 3.8 and 5.6 s, there was a notable increase in the acoustic emission counts and amplitudes, with counts peaking at 10 000. This indicated that the upper locked segment had failed and begun to slide. At 6.6 s, the acoustic emission counts and amplitudes rapidly increased to their

maximum values, primarily because of the collision of the upper locked segment with the lower locked segment. Although the recorded acoustic signal intensity was somewhat affected by the distance between the sensor and the locked segments, it was still accurately monitored (Figure 12b). AE3 and AE4 were primarily positioned at the crown of the slope. The counts and amplitudes at these points began to rise during the initial failure and surged abruptly, reaching their maximum at 4.4 s. This peak was likely related to the failure of the upper locked segment, as AE3 and AE4 were close to it. After 5 s, the counts and amplitudes gradually decreased as the major disruption of the posterior margin completed over time (Figures 12c, 12d).

4.4.2 Time-frequency domain characterization of seismic signals

To characterize the seismic signals generated during the simulation of locked segments and particle failure in detail, we use the continuous wavelet transform (CWT) to obtain a time-domain distribution. The wavelet transform provides information about the frequencies of the signals and the moments at which these frequency components occur. The expression for the CWT is given as

$$W(a, b) = \int_{-\infty}^{\infty} x(t) \cdot \varphi\left(\frac{t-b}{a}\right) dt \quad (3)$$

where $W(a, b)$ are the wavelet coefficients, $x(t)$ is the original signal, $\varphi(t)$ is the wavelet basis function, a is the scale parameter, and b is the translation parameter.

These signals effectively illustrate the dynamic processes of failure on the modeled slopes (Li et al., 2023; Yan et al., 2020). The acoustic signals primarily reflect localized failure events, as the granular material significantly attenuates high-frequency signals. Observations from the spectrogram at AE1 revealed a substantial increase in signal energy at 5.02 s, with a peak frequency exceed-

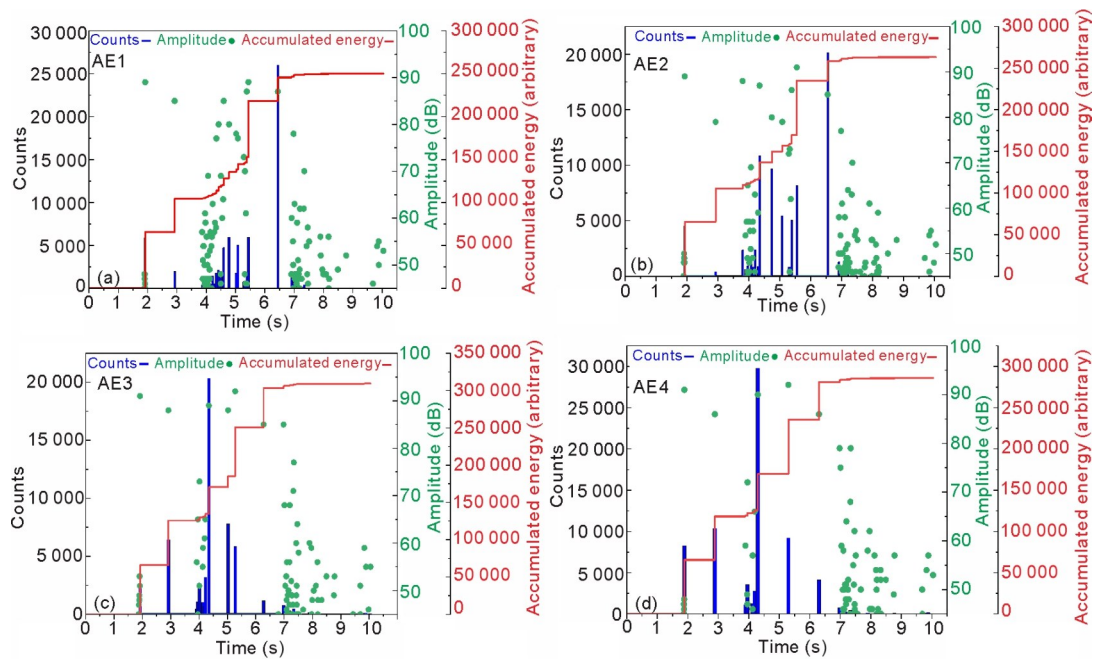


Figure 12. (a) AE1 acoustic signal characteristics; (b) AE2 acoustic signal characteristics; (c) AE3 acoustic signal characteristics; (d) AE4 acoustic signal characteristics.

ing 600 kHz. This likely resulted from multiple strong oscillations following the destruction of the upper locked segment and the subsequent movement of the particles. A further increase in signal energy was noted at 7.08 s, indicating that these oscillations occurred during the destruction of the lower locked segment (Figure 13a). At AE2, the spectrogram revealed a high-frequency signal at approximately 5.27 s, with a frequency reaching approximately 700 kHz. This was attributed to the closer proximity of the AE2 transducer to the upper locked segment, allowing for effective detection of the failure vibrations. The signal intensity was more pronounced between 7.19 and 7.32 s, suggesting that these vibration events were associated with kinematic collision following the destruction of the anterior locked segment (Figure 13b). Despite variations in the transducer position and distance from the locked segment, the timing of damage detected through the time-frequency spectrograms of AE1 and AE2 generally aligned. Spectrograms from AE3 and AE4 revealed a notable increase in signal intensity at approximately 7 s, which may have been associated with higher frequency and energy vibrations between particles in the later stages of failure. The signal frequency at this stage persisted until approximately 7.46 s, when it reached a peak of approximately 680 kHz (Figures 13c, 13d). The acoustic emissions exhibited similar frequency and energy characteristics, with frequencies and energies associated with particle slip being lower than those generated by the destruction of the locked segment.

5 DISCUSSION

5.1 Failure Mechanism of the Baige Landslide

Extensive research has advanced our understanding of failure mechanisms in large landslides occurring within

complex geological settings. The Vaiont Reservoir landslide exemplifies these dynamics, displaying characteristic morphological features with steep upper slopes transitioning to gentler basal sections, where the toe maintains direct contact with the underlying strata (Paronuzzi and Bolla, 2017; Müller-Salzburg, 1987). Systematic investigations of large rock slope failures have yielded three principal geomechanical models: the sliding-pulling-shearing three-stage model, the retaining wall collapse model, and the “super tamping” model. These frameworks collectively emphasize the mechanical significance of locked segments in slope stability regulation (Huang et al., 2013; Huang, 2012). Scholars have focused on predicting the instability of locked-segment landslides, formulating a theory to forecast their instability. They also introduced a classification system for locked-segment landslides, constructed a disaster model to illustrate their evolution, and established a critical displacement criterion for two disaster modes: the fast-unlocking sudden-onset type and the slow-unlocking gradual-onset type of locked-segment landslides (Chen et al., 2018; Xue et al., 2017). These landslide models are highly valuable for understanding the failure mechanisms of Baige landslides within the tectonic mélange belt.

The abnormal climate, intricate geo-structure, and complex geomorphology characterized by gradual upward and steep downward slopes have created favorable conditions for landslide deformation and sliding failure. In the Jinsha River suture zone of eastern Tibet, the violent collision of tectonic plates rapidly uplifted the Earth's crust, leading to significant new tectonic activity. For the geological formations within the landslide zone, the persistent activity of fractures serves as a continuous source of destructive force, providing substantial energy for the

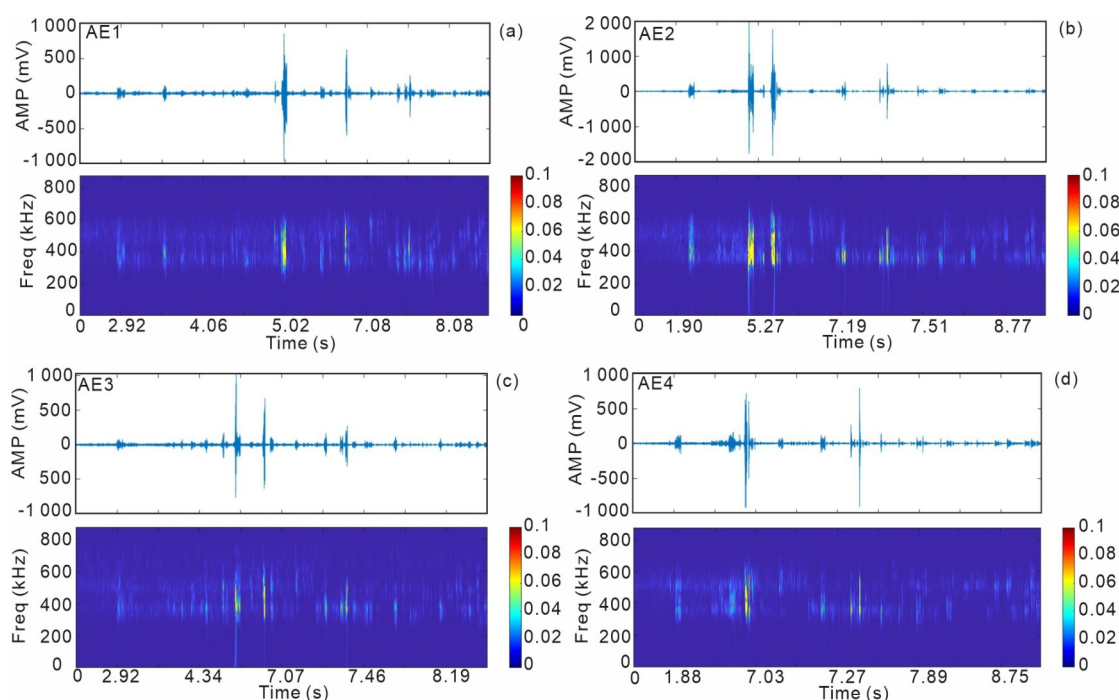


Figure 13. (a) AE1 spectrum and waveform of the collision test; (b) AE2 spectrum and waveform of the collision test; (c) AE3 spectrum and waveform of the collision test; (d) AE4 spectrum and waveform of the collision test.

failure and destruction of these geological bodies. Intense fracture activity not only contributes to the formation and progression of large landslides but also causes misalignment, which easily leads to local tectonic stress concentrations. This, in turn, results in significant variations in the stress and displacement fields of the regional slopes, ultimately disrupting the continuity and integrity of the slope. The geological bodies of the landslides experience severe fracturing, leading to internal ruptures along brittle shear zones that extend to the slope surface, producing longitudinal shear cracks and tensile cracks. Under the combined influences of internal and external dynamics, the crown of the sliding mass experiences significant subsidence deformation and develops a tensile crack surface. However, during this stage of sliding, the brittle shear zone undergoes compaction, and the locked segments within this zone remain intact, effectively maintaining their locking function (Figure 14a). Only when the upper extrusion generates shear stress that propagates to the toe do the locked segments around the brittle shear zone at the toe fail first. As this failure extends to the locked segment of the crown, it shears along the surface structural plane in the direction of proximity (Figure 14b). Following the failure of the crown's locked segment, the particles are rapidly driven into the toe's locked segment, ultimately resulting in slope failure. This study elucidated the relationship between landslide deformation and failure, which is controlled by complex geological structures within the tectonic mélangé belt (Figure 14c). This failure phenomenon has not been documented in previous research. Through physical modeling experiments, we reproduced the observation in which the brittle shear zone ruptures around locked segments during

landslides, followed by the breakage of the upper locked segment and its impact on the lower locked segment. Notably, displacement maps from the model experiments revealed uneven displacement changes influenced by the lower locked segment, with smaller displacements occurring closer to this segment. Additionally, velocity field maps revealed a sharp velocity increase after the destruction of the upper locked segment, indicating high-speed movement during this phase. These findings strongly resemble the actual deformation observed in the Baige landslide. Although it is not possible for model tests to perfectly replicate the precise deformation and damage characteristics of actual landslides, they do provide valuable insights into the deformation and failure patterns of this type of landslide. Furthermore, these experiments offer an experimental foundation for understanding the failure mechanisms of such landslides.

5.2 Acoustic Emission Characterization Based on Model Test Damage

Acoustic emission monitoring provides novel insights into experimental slope failure processes. Spectral analysis reveals distinct frequency components corresponding to specific failure mechanisms: low-frequency signals indicate low-energy dissipation events, while high-frequency components correlate with localized deformation and micro-fracturing. Ultrahigh-frequency emissions predominantly result from particle collisions and intergranular friction (Hu et al., 2022; Taylor and Brodsky, 2017). Although signal attenuation complicates absolute energy quantification, accumulated acoustic energy maintains proportionality with physical deformation processes (Hu et al., 2023; Feng and Chen, 2021). Thus, multi-transducer

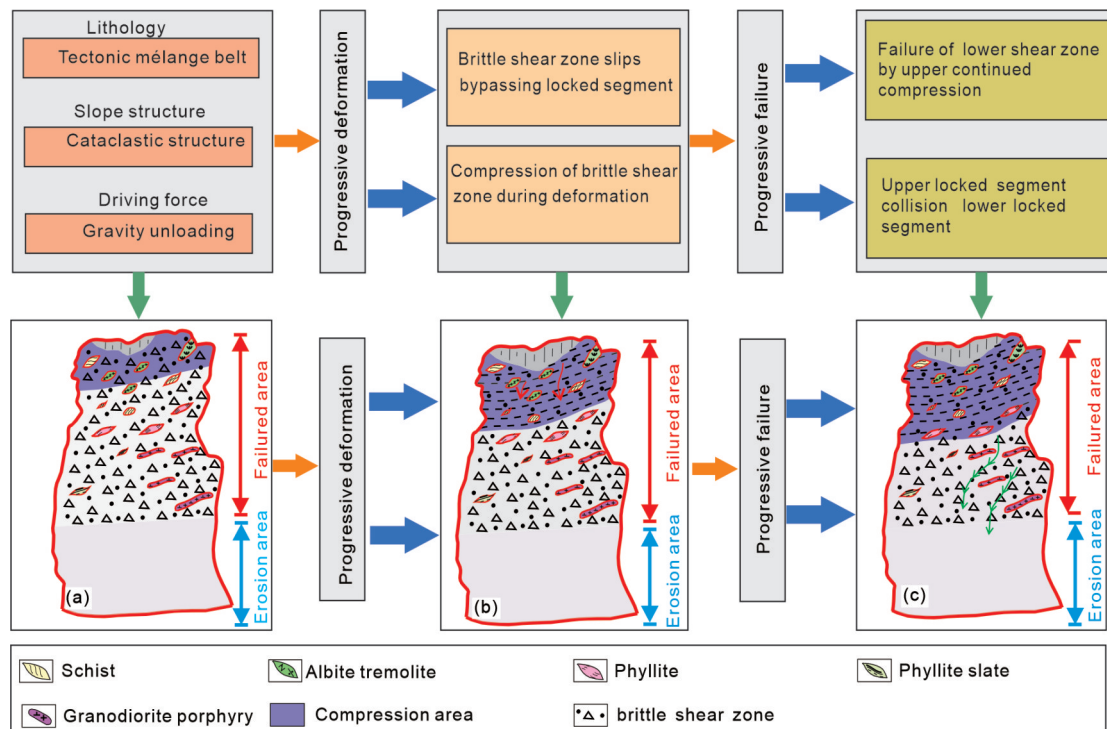


Figure 14. Failure mechanism of the Baige landslide.

measurements under controlled conditions yield valuable quantitative data for analyzing slope failure mechanisms. Although this study focused on the results of locked segment shearing and particle motion under controlled laboratory conditions, it demonstrated a correlation between collision events and acoustic signals during locked segment and particle destruction, allowing for a preliminary estimation of potential destruction modes from locked segments to particles.

This study systematically analyzed acoustic emission (AE) waveforms and their time-frequency characteristics during particle collisions and locked segment failure. Through Fourier and continuous wavelet transformations of amplified AE signals, we quantitatively characterized slope failure patterns. As the failure area increased, both the amplitude and cutoff frequency increased. The strength of collisions within the particle assemblage was semi-quantitatively assessed on the basis of the cutoff frequency and amplitude of the AE1 bursts. Frequency-domain plots revealed components at 40 and 60 kHz, with a cutoff frequency of 200 kHz, indicating varying intensities of these intermittent collisions. Additionally, stronger signal energy was observed at 5 022.7 and 6 980.1 ms with high-frequency spectra of 400 and 600 kHz, respectively, suggesting that significant oscillations during the destruction of the rim-locked segment, moving with the particles, generated high-frequency spectra (Figure 15a). The AE2 signal had a similar frequency amplitude distribution, with high-frequency signals at 5 022.5 and 7 341.9 corresponding to spectra of 700 and 500 kHz, respectively, indicating strong collisions at these points (Figure 15b). AE3 exhibited higher intensity signal energy at 6 980.1 and 7 342.1 ms, with high-frequency

spectra of 600 and 500 kHz, respectively. The frequency-domain plots for AE3 had signal energies of 80 and 40 kHz, with cutoff frequencies of 600 and 500 kHz, respectively (Figure 16a). AE4 had a higher intensity signal energy at 6 979.8 and 7 341.8 ms, with high-frequency spectra at approximately 600 kHz. The frequency-domain plots for AE4 had components at 40 kHz, with peak frequencies of approximately 200 and 140 kHz (Figure 16b). Significant variations in signal intensities for AE3 and AE4 suggested strong activity in the upper part of the model. Therefore, using acoustic emissions in modeling experiments to monitor slope failure is valuable because it can quantitatively reflect the intensity of model failure from a specific perspective. Although this study only examined the results of the acoustic emission characteristic parameters under controlled laboratory conditions, it effectively demonstrated the correlation between slope failure and the acoustic signals.

5.3 Limitation

The use of a geometric similarity ratio of 285 in the physical model introduces significant scale effects that can impact the accuracy and reliability of the results. These scale effects primarily manifest in the following aspects. Firstly, in small-scale models, particle interactions and movements may not accurately represent those in large-scale landslides. The reduced size of particles and the model itself can lead to an overestimation of cohesive forces and an underestimation of inertial effects. Secondly, the transmission of forces, such as shear stress and normal stress, can be distorted in small-scale models. To mitigate the scale effects and improve the accuracy of the physical model, the following corrections

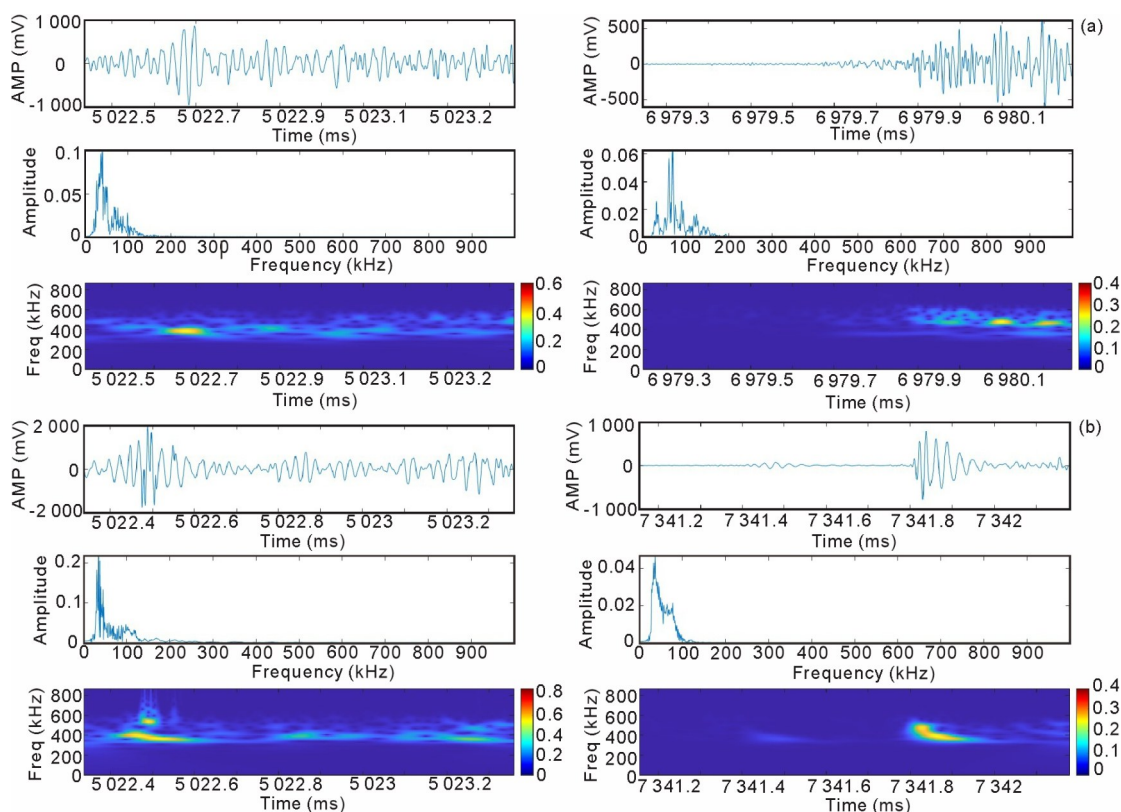


Figure 15. (a) AE1: amplitude of the original signal, fourier spectrograms, and time-frequency spectrum; (b) AE2: amplitude of the original signal, fourier spectrograms, and time-frequency spectrum.

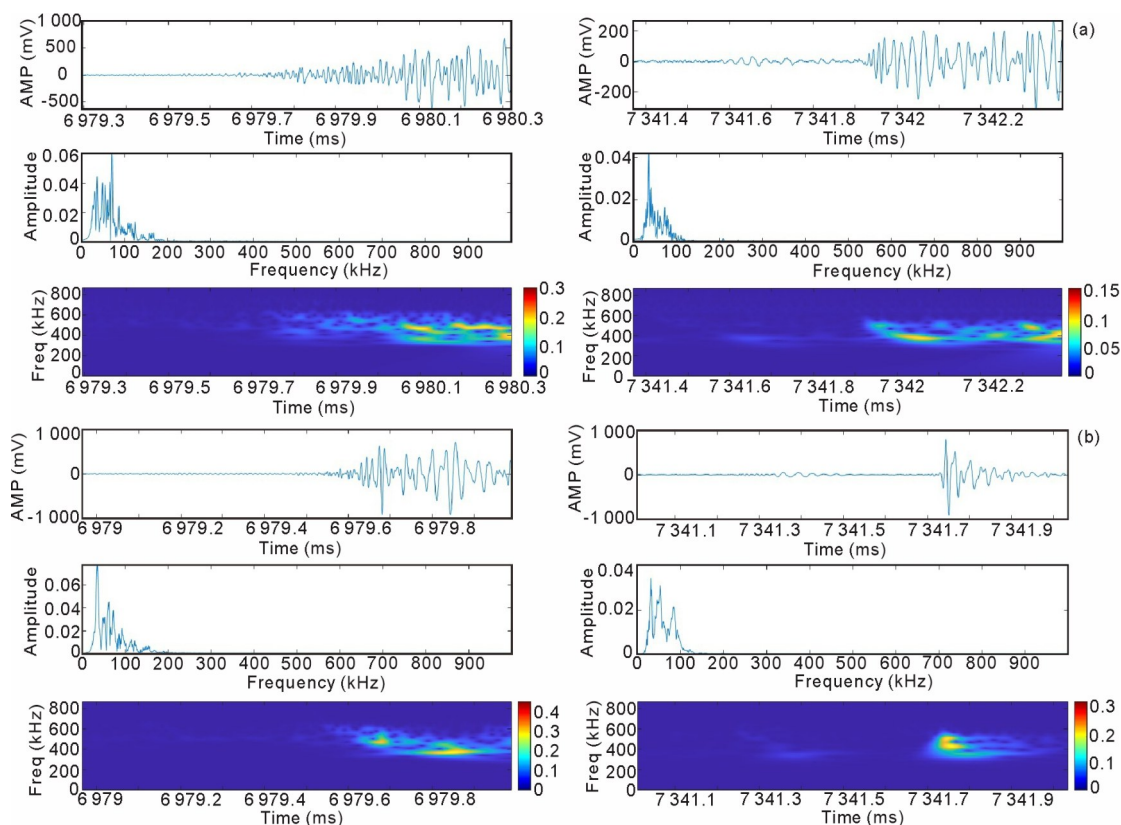


Figure 16. (a) AE3: amplitude of the original signal, fourier spectrograms, and time-frequency spectrum; (b) AE4: amplitude of the original signal, fourier spectrograms, and time-frequency spectrum.

and considerations can be proposed: introduce corrections to account for the increased cohesive and viscous forces in small-scale models. This can be achieved by scaling down these forces based on the cube of the geometric similarity ratio (i.e., H^3), where H is the thickness of the moving mass. Conduct experiments at the largest feasible scales to minimize the scale effects. Larger models will better capture the inertial and gravitational forces that dominate in real landslides.

6 CONCLUSIONS

This paper reveals the failure mechanism of the Baige landslide through field investigations and model experiments, leading to the following conclusions.

(1) The failure mode of the Baige landslide involves the brittle shear zone initially bypassing the lower locked segment destroying. This is followed by the failure of the upper locked segment combined with the shear zone impacts the lower locked segment, resulting in total destruction of the broken segment.

(2) The deformation displacement in the model is characterized primarily by vertical movement. The destruction rate of the slope transitions from an initial acceleration phase to a later acceleration stage, with the maximum movement speed reaching 0.85 m/s.

(3) This study provides valuable insights into the formation mechanisms and distinct failure patterns of large rock landslides, which contribute to catastrophic events in tectonic suture zones.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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