

Article

Failure Mechanism of Sandy Soil Slopes Under High-Angle Normal Bedrock-Fault Dislocation: Physical Model Tests

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Abstract: Bedrock fault dislocation is a crucial structural factor influencing landslide movement. Accurately predicting the location and scale of rupture zones within a slope body is essential for effective slope construction design and risk mitigation. Based on an analysis of seismic damage in slope cross-bedrock faults, this article creatively realizes the physical model test of the slope and its covering layer site with soil rupture zones at the top and toe of the slope caused by the dislocation of the bedrock normal fault. Through the model test, macroscopic phenomena were observed, and microscopic analysis was obtained by deploying sensors. The main results were as follows: (i) The evolutionary process of the instability mechanism could be divided into three stages: crack damage stage (Stage I), crack expansion and penetration stage (Stage II), and slope instability stage (Stage III). (ii) Two rupture modes of the soil body in the slope under bedrock dislocation were identified, with the rupture mode at the slope crest having a greater impact on the soil slope. (iii) Inferring the position of bedrock faults through the location of the main rupture zones on the slope surface represents a feasible supplementary method for identifying seismogenic structures during field surveys. These research results provide a scientific basis for the stability assessment of cross-fault slopes and the reinforcement design of landslide disasters.



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1. Introduction

Extensive research on earthquake damage has shown that earthquake-induced slope instability and landslides are among the major geological hazards in mountainous and hilly regions [1–3]. These landslides, triggered by earthquakes, are typically characterized by their widespread distribution, high frequency, and considerable destructiveness, leading to substantial casualties and economic losses [4–8].

The spatial distribution of earthquake-induced landslides is closely correlated with the main seismogenic faults and their surface ruptures [9,10]. Jibson et al. [11] studied thousands of landslides triggered by the Mw 7.9 Denali earthquake in Alaska and found them to be concentrated within a 15 km range on either side of a surface rupture zone. Scholars have investigated the aftermath of the Mw 7.9 Wenchuan earthquake in 2008 and

found that approximately 80% of large landslides were distributed within approximately 5 km on either side of the seismogenic fault surface rupture zone, with a significantly higher density of landslides on the hanging wall compared to the footwall [12–19]. Experts and scholars have analyzed landslides triggered by the Mw 6.9 Yushu earthquake in 2010 and found that 80% of the landslides were concentrated within a 2 km width along a 95 km-long surface rupture zone, illustrating the typical characteristics of surface fault control [20–22].

The ground motion near strong seismic fault zones is associated with high energy, leading to a dense development of landslides. In particular, the damage caused by the landslide being directly “cut” by the relative dislocation of the fault or the relative motion of the two walls is more serious. For instance, Huang et al. [23] and Zhao et al. [24] studied the Wenchuan earthquake-induced Guantan landslide (Anxian County), which was traversed by the Longmenshan fault zone. They found that the relative displacement between the two walls of the fault causes the slope to be fractured and loosened, with cracks extending deeper to form tensile fractures. The landslide experienced overall instability eight hours after the earthquake, resulting in the formation of a landslide dam. The formation mechanism and development process of this landslide could be divided into three stages: compression-toppling deformation of the natural slope, post-earthquake through-going slip surface stage, and overall failure stage of the landslide. Wang et al. [25], Yin et al. [26], Wang et al. [27], and Wang et al. [28] investigated and analyzed the Donghekou landslide. The upper wall of the Shikan fault across the slope moves upward and the surface rupture zone is found at the landslide front. The rock mass at the rear of the rupture zone developed tensile cracks, causing the outer rock mass to be ejected as a whole, moving forward approximately 2 km in the form of a debris flow on impacting with the ground. Hauksson et al. [29] and Harp and Jibson [30] investigated the 1994 Northridge Mw 6.7 earthquake in the United States, and found that the Loma Verde landslide, composed of sandstone, had multiple steep scarps at its top due to the thrust fault, leading to a complete fragmentation of a ridge hundreds of meters high. Xin et al. [31] investigated the 2022 Menyuan Mw 6.7 earthquake and found that under the action of strong fault dislocation, significant displacement movement occurred in the fault zone where the tunnel was located (the subgrade was raised by 2 m), resulting in a large number of rockfall and collapse of the tunnel slope. Therefore, the instability of the cross-fault landslide is caused by the relative movement of the two sides of the bedrock fault. However, due to the different positions of the main rupture zone (tensile surface) caused by the fault dislocation, the formation mechanism of the cross-fault landslide is not clear.

At present, many researchers have explored the failure mechanism and evolution process of cross-fault slopes through physical model tests. As an important piece of equipment for simulating seismic phenomena, the shaking table is popular with researchers [32]. Most of them carried out shaking table physical model tests by giving the ground motion time history on the seismic input. Jia et al. [33] and Huang et al. [34] conducted shaking table tests and numerical simulations on loess–mudstone slopes with fault zones. They discovered that the dynamic response of slope acceleration exhibited a surface effect. The acceleration amplification effect within the fault zone was significantly greater than that on either side, with the maximum acceleration amplification factor reaching 3.5. Yu et al. [35] performed large-scale shaking table-based physical model tests and numerical simulations on loess–mudstone slopes with an anti-dip fault zone. The results showed that the acceleration amplification factor increased with elevation, demonstrating a pronounced “fault zone amplification effect” and “hanging wall effect”. Xin et al. [36] simplified the cut slope across the Xiaojiang fault zone into a stepped bedding rock slope model with weak interlayers and conducted large-scale shaking table tests. The results indicated that the acceleration amplification factor of the slope exhibited an elevation amplification effect.

The failure process comprised four stages: shallow creep, local tensile cracking, accelerated deformation, and overall instability. The deformation and failure mode of the slope could be characterized as sliding–tensile cracking. Yang et al. [37] and Cui et al. [38] conducted large-scale shaking table model tests and numerical simulations on rock slopes containing weak fault rupture zones, finding a significant acceleration amplification effect. The progressive failure mode of the model slope was identified as a tensile cracking–sliding failure, with the deformation primarily concentrated in the shear-sliding failure stage. According to the current state of research on shake table tests for fault-crossing slopes, most studies simulate fault surfaces (rupture zones) by using different materials within a model box, followed by shake table testing. However, due to the limitations of shake table equipment, it is difficult to accurately replicate the relative movement between the two fault blocks in bedrock. This results in certain flaws in simulating the damage mechanisms and evolution processes of fault-crossing slopes, as the relative dislocation between the fault blocks cannot be realized.

Therefore, in conducting cross-fault slope model tests, a model device capable of simulating the relative dislocation across the fault is essential. The primary fault dislocation devices currently used include the 1 g constant gravity fault dislocation model device and the Ng centrifuge model device. Both 1 g and Ng fault dislocation devices are capable of simulating dislocation loading on bedrock faults in model tests assessing the fracture response of buildings and their overlying soils [39–41]. For example, Fadaee et al. [42] and Fadaee et al. [43] utilized a custom-designed model box to simulate a fault slip and examined the relationship between various foundation types of three-story buildings and the surface rupture locations. Bransby et al. [44] studied the interaction between a strip foundation and a normal fault displacement in the direction parallel to the strike using centrifuge model tests. However, despite extensive slope model experiments conducted using centrifuge testing [45–53], there has been no research addressing the impact of relative dislocations between the two fault blocks in bedrock on cross-fault slope model tests.

In general, the distribution of earthquake-induced landslides is primarily controlled by the distribution of the fault rupture. The relative movement between the two fault blocks causes the location of the main rupture zone (tensile fracture surface) in the slope to vary, making the formation mechanism of cross-fault landslides unclear. Some researchers have simulated earthquake-induced damage to cross-fault slopes by setting up equivalent fault surfaces (rupture zones) in shaking table model boxes and inputting seismic motion records. However, due to the limitations of shake table equipment, it is difficult to replicate the relative dislocation between the two fault blocks. On the other hand, fault dislocation devices have become quite advanced. Whether using normal gravity or centrifuge models, there has been abundant experimental research on the rupture responses of buildings and their overburden soil sites under the bedrock fault dislocation. However, experimental studies on cross-fault slopes under bedrock fault dislocation remain quite scarce. Centrifuge model tests face challenges such as small model size, high costs, and complex testing procedures. Therefore, based on the case study of slope damage induced by bedrock fault dislocation, this paper independently developed a large-scale normal gravity bedrock dislocation device to simulate the failure mechanisms and evolution process of cross-fault slopes under bedrock fault dislocation.

At the same time, microseismic monitoring has been widely applied in the entire process of the initiation, development, and propagation of microfractures within the slope's geotechnical materials, ultimately leading to macroscopic instability and rupture [54–56]. To further validate the rationale of field site investigations and hypotheses, this study introduces microseismic monitoring technology to reveal the process and patterns of fault rupture evolution within the slope.

Based on the above research, the strong earthquake rupture zone (fault softening surface) directly affects the slope damage in the region adjacent to the strong earthquake fault and controls the failure mode and damage scale of the landslide. Therefore, this paper presents physical model tests conducted on soil slopes across normal faults using a self-developed large-scale bedrock dislocation testing platform. The research results aim to reveal the deformation patterns and instability mechanisms of slopes across faults, promote the development of dynamic theories for slopes under seismic action, and provide technical support for seismic design in practical slope engineering.

2. Experimental Investigation

2.1. Implementation of Test Equipment

The experiments in this study were conducted on a self-developed large-scale model test platform designed to simulate gravity and strong seismic surface rupture. The core components of the platform included a soil box for the slope and overlying soil layers (dimensions: 4.96 m × 1.85 m × 1.4 m), a simulated bedrock fault dislocation system, and a hydraulic synchronous drive system, as shown in Figure 1. The simulated bedrock fault dislocation system comprised high-strength ribbed double-layer steel plates to simulate the relative movement of the fault blocks, a reaction support base, and a portable angle adjustment module, enabling the simulation of fault slip between the footwall and hanging wall (active and passive blocks). A hydraulic synchronous drive system was used, comprising a PLC control console with displacement loading software, four sets of hydraulic actuators, displacement lines, and hydraulic pipes connecting the control console and actuators, allowing a precise control of the bedrock plate movement and its rate. The DHDAS V1.11 software (provided by Jiangsu Donghua Testing Technology Co., Ltd., Taizhou, Jiangsu, China) was employed as the data acquisition system.

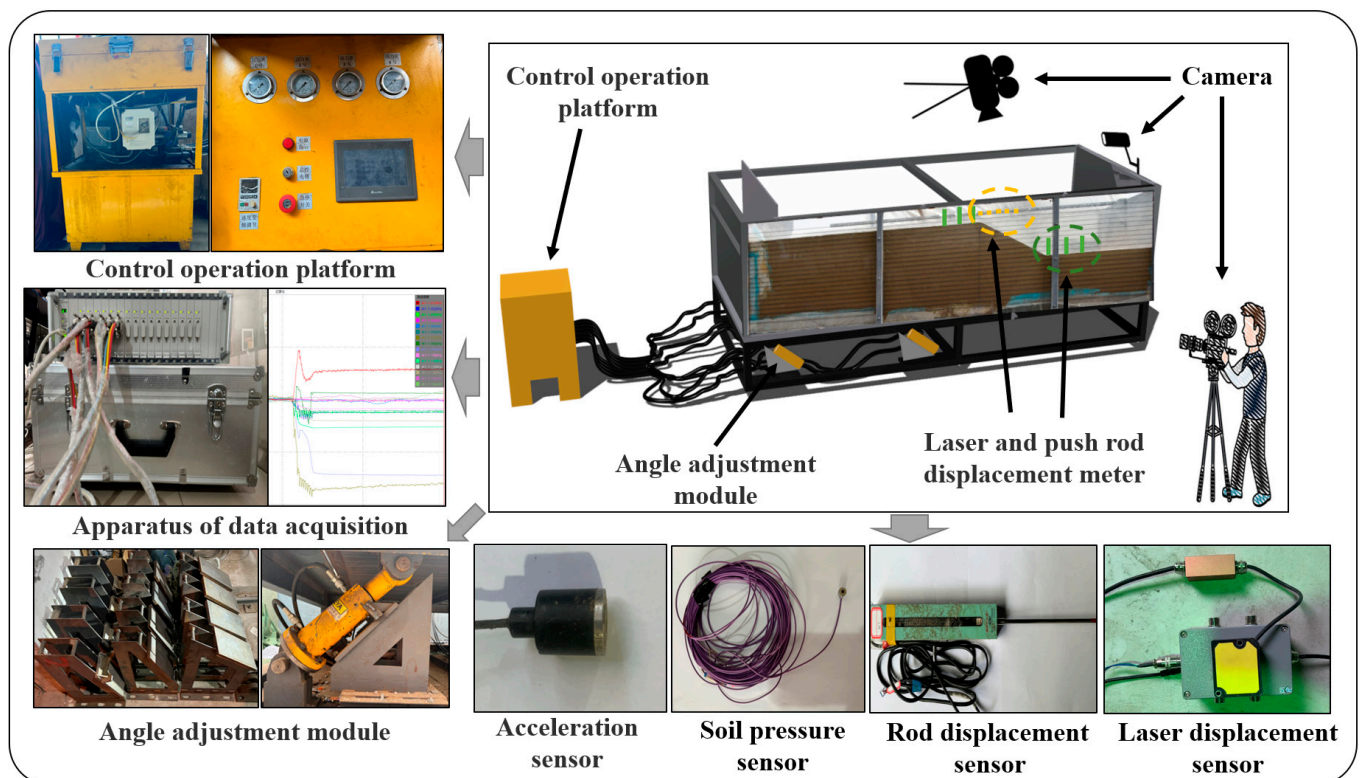


Figure 1. Implementation diagram of physical model test equipment for cross-bedrock fault slope.

The portable angle adjustment module of the test platform could help to adjust the fault slip angle and type, enabling multi-condition and simulation experiments. In this experiment, the fault slip type was a normal fault, with a slip angle of 70° . During the experiment, the actuators were controlled to simulate bedrock dislocation at an empirically set rate of 1 mm/s. At the start of the experiment, the active block steel plate began to slip. Data were recorded each time the actuators lifted by 10 mm. High-definition video recordings of the front, top, and side views of the experimental phenomena were also taken to capture a complete set of test conditions.

2.2. Similarity Relationship and Material Parameters

In this experiment, geometric dimensions, density, and gravitational acceleration were taken as the basic dimensional parameters. The geometric similarity ratio was set to 40 based on the above examples of seismic damage to bedrock fault slopes and physical model tests, as well as the loading magnitude of bedrock dislocation. The similarity constants for the other physical quantities were determined using the π theorem and dimensional analysis, as shown in Table 1.

Table 1. Similarity relationship table of a slope physical model.

Physical Quantity	Similarity Relationship	Similitude Parameter
L: Geometric dimensions	C_L	40
ρ : Density	C_ρ	1
g: Gravity	C_g	1
τ : Soil pressure	$C_\tau = C_L \cdot C_\rho \cdot C_g$	40
a: Slope acceleration	C_a	1

2.3. Preparation of Soil Slope

Referring to the international standard sand and the sand used in the typical fault dislocation model test [57–60], the standard sand of the test soil sample in this study was determined, with its particle size distribution curve obtained through a sieve analysis, as shown in Figure 2. The coefficient of uniformity (C_u) was 2.73. The internal friction angle of sand is 28° by direct shear test. Through the compaction test (vibration hammer test), the maximum dry density of sand is 1675 kg/m^3 . The relative density of sand is 67%.

The slope model was created by first compacting the soil to form a level ground and then excavating it into a slope. This process involved incrementally placing the soil sample into the model box in batches. Based on the designed tamping number determined from preliminary tamping tests, each 15 cm layer of soil was leveled and then compacted to 10 cm using a tamper (Figure 3a). This layered compaction process was repeated uniformly until the overlying soil layer reached a thickness of 100 cm (Figure 3b). The slope contour was then marked on an acrylic glass plate to ensure that the completed model slope exactly matches the dimensions of the conceptual model. Finally, the soil near the marked contour was excavated, and the slope was shaped until the preparation was complete, as illustrated in Figure 3. To minimize the boundary effects on soil deformation patterns, we specifically designed the experiment by incorporating low-friction materials—specially designed PVC films—applied to the inner side of the soil box to reduce the influence of friction on soil movement.

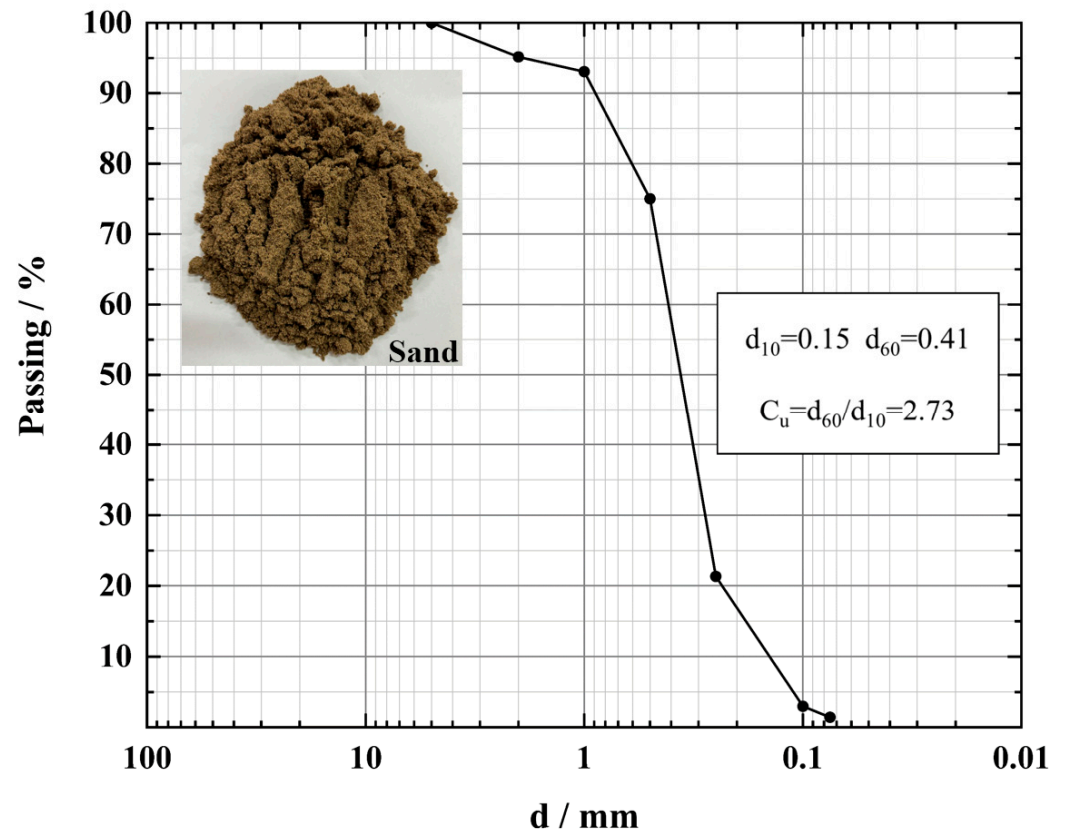


Figure 2. Particle gradation curve diagram of the procured sand.

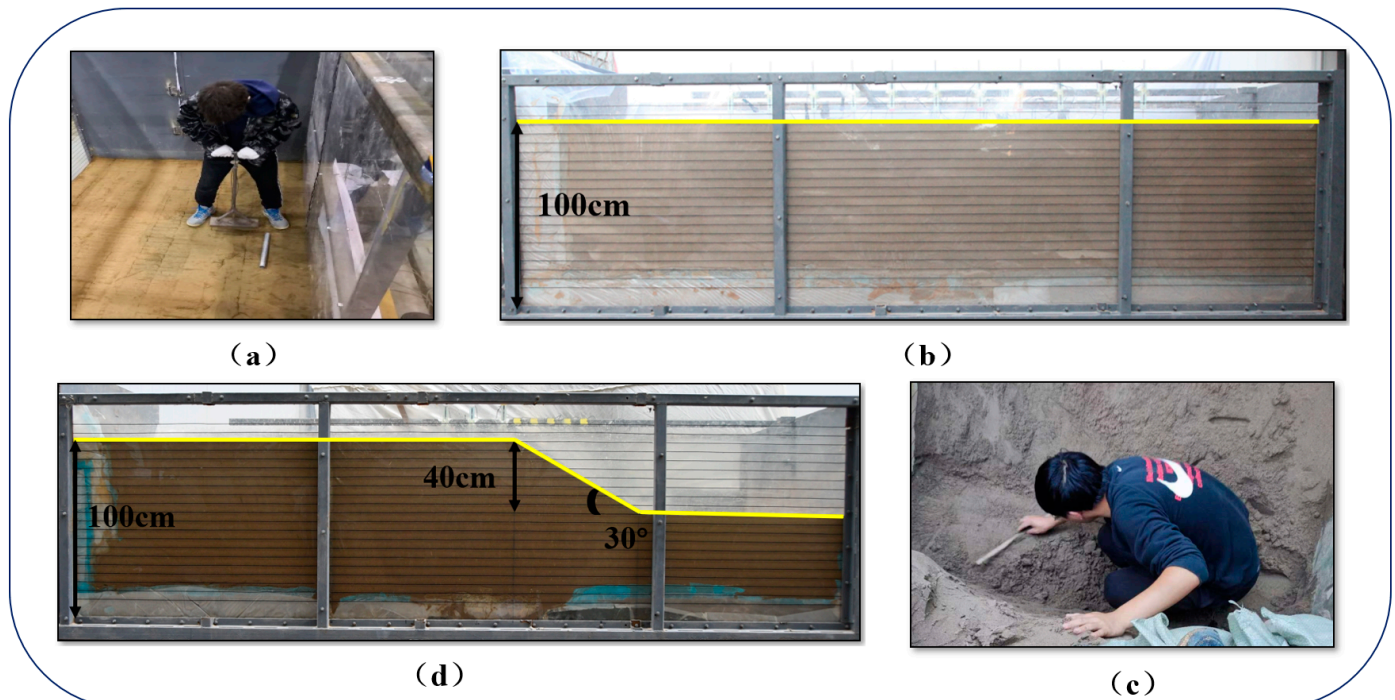


Figure 3. Preparation of a soil slope cross-bedrock fault: (a) Layered compaction; (b) Tamped to 100 cm; (c) Slope preparation; (d) Slope forming.

Before the formal commencement of the experiment, we conducted physical and mechanical parameter measurements of the test soil. Initially, we performed the moisture content and particle size distribution analyses of the test soil to ensure the uniformity of its

moisture content and particle gradation. Subsequently, we conducted vibration hammer tests (for sand) to obtain the maximum dry density of the test soil. Following the steps and operations of the compaction test, we poured the test soil into the soil box and leveled it to a depth of 15 cm, then compacted it with a homemade tamper to a depth of 10 cm, and compacted it in layers to a depth of 1 m. A random soil layer was sampled with a ring cutter for direct shear tests and compaction tests, since the study aims to simulate the abrupt dislocation of active faults of bedrock under strong earthquakes and analyze the seismic damage response of buildings and the deformation and destruction of the covering layer site. That is, the shear strength parameters of the test soil were determined through quick shear tests. Finally, the compaction coefficient was obtained based on the ratio of the actual measured dry density in the box to the maximum dry density obtained from indoor compaction tests. Taking into account the impact of the compaction of the upper soil layer on the lower soil layer, we sampled the lower soil layer for compaction coefficient determination after each layer was compacted. It was found that although the compaction of the upper soil layer may have some impact on the lower soil layer, this impact is within an acceptable range (0~1%), and thus the impact of the compaction of the upper soil layer on the lower soil layer can be neglected.

2.4. Experimental Design

Based on the observed seismic damage to slope soil bodies across fault lines and related experiments by the research team on the rupture of overlying soil layers during bedrock dislocation, preliminary experiments were conducted on sand slopes during bedrock fault slip. The experiments were aimed at observing and identifying the trace positions of rupture zones in the soil slopes, as shown in Figure 4. Following this analysis, physical model tests were conducted on slopes with rupture zones appearing at the crest and toe of the slope, respectively, as illustrated in Figure 5.



Figure 4. Pre-test site image of a sand slope.

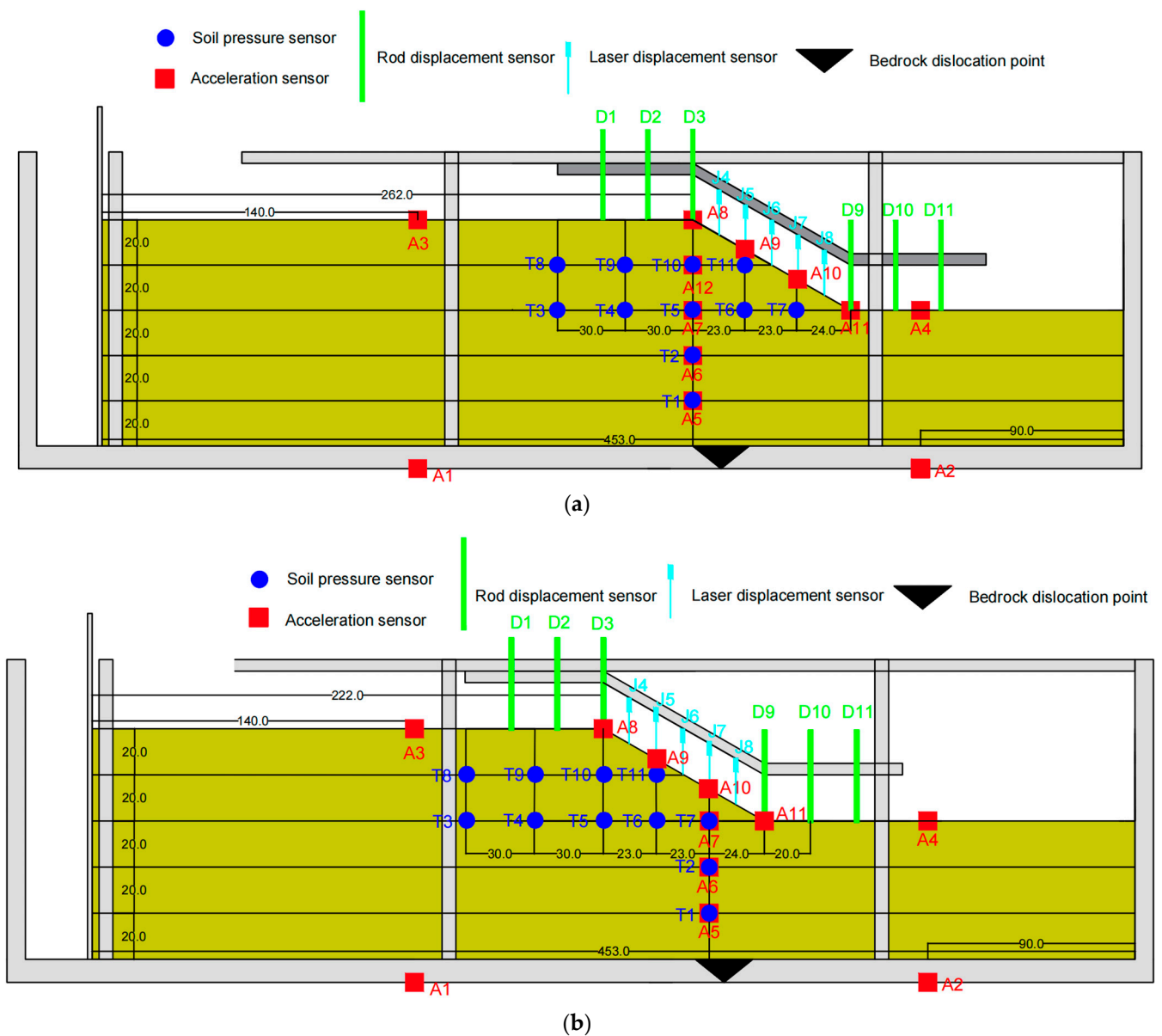


Figure 5. Model test schemes for a soil slope cross-bedrock fault: (a) Slope model test T1 layout; (b) Slope model test T2 layout.

In the experiment, the displacement of the ground surface and slope surface was monitored using displacement sensors and laser displacement sensors, respectively. Soil pressure sensors were employed to monitor changes in the soil pressure within the sand overburden layer and inside the slope. Microseismic sensors were used to monitor the dynamic responses of the bedrock base, slope surface, and internal structure of the slope. Table 2 presents the parameters of these sensors. The purpose of arranging these sensors was to comprehensively analyze the dynamic evolution process of the soil rupture in the slope and its overlying layer.

At the crest and toe of the slope, three displacement sensors (D1–D3, D9–D11) were installed at intervals of 20 cm. Five laser displacement sensors (J4–J8) were evenly distributed along the slope surface. Soil pressure sensors (T1–T11) were arranged longitudinally and transversely along the inferred main rupture zone and within the slope. A pair of microseismic sensors (A1, A2) was placed at the center of the steel plates, simulating two blocks of bedrock. Microseismic sensors (A3, A4) were positioned directly above A1 and A2 on the slope surface. Both longitudinal and transverse microseismic sensors (A5–A11 or A5–A12)

were also arranged along the inferred main rupture zone and on the slope surface. Figure 5 shows the sensor placement locations. Before each formal experiment begins, we rigorously calibrate and validate all sensors to ensure the reliability and accuracy of sensor data.

Table 2. List of sensor parameters.

Sensor Category	Model	Parameter
Rod displacement sensor	YHD-200	Range: ± 100 mm; bridge mode: full bridge or half bridge; sensitivity coefficient: 1.005
Laser displacement sensor	FTJP-1	Range: 200–1200 mm; accuracy: 0.1 mm; sampling frequency: 200–5000 Hz
Earth pressure sensor	ESP-II	Range: 50 kPa/100 kPa; accuracy: 0.5% F.S Measurement type: Voltage measurement
Microseismic sensor	DCIEM-M	Range: ± 10 g; sensitivity: 1000 mV/g; type of measurement: Voltage measurement

3. Experimental Results

3.1. Slope Failure Process and Stages

Figures 6 and 7 show the dynamic evolution of the slope morphology during soil rupture at the slope crest and toe, respectively. Panels a to j present field images showing the incremental displacement of the bedrock, ranging from 10 mm to 100 mm. These images offer a macroscopic perspective for analyzing the failure process of the soil slope and preliminarily delineating the stages of failure.

As shown in Figure 6, when the bedrock dislocation reaches 10 mm, a fine crack appears on the slope surface 15 cm from the crest, and the soil does not exhibit significant rupture (Figure 6a). At a bedrock dislocation of 20 mm, the fine crack on the slope surface extends downward (denoted by S2), while another crack (denoted by S1) propagates upward from the bedrock dislocation point (Figure 6b). Between displacements of 30 mm and 40 mm, S2 continues to extend downward, widening into a sliding surface and causing a collapse, while S1 also continues to develop (Figure 6c,d). When the bedrock dislocation is in the range of 50–70 mm, the combined action of rupture zones S1 and S2 forms the MRZ (Main rupture zone) of the slope and its underlying overburden layer. In this context, S1 and S2 within the main rupture zone are designated as MRZ-S1 and MRZ-S2, respectively. The main rupture zone extends through the soil body to the slope surface, resulting in the appearance of new fine cracks on the slope surface at a distance of 12 cm from the slope toe (Figure 6e–g). When the bedrock dislocation ranges from 80 mm to 100 mm, new cracks of the same nature as S2 appear and extend in a bundle along with the main rupture zone, forming a new main rupture zone. The soil near the main rupture zone shows evident tensile-collapse failure (Figure 6h–j).

As shown in Figure 7, when the bedrock dislocation reaches 10 mm, a fine crack appears on the slope surface 20 cm from the slope toe, accompanied by a small upward-inclined crack originating from the bedrock dislocation point (Figure 7a). At a bedrock dislocation of 20 mm, the crack on the slope surface extends downward (denoted by S2), while the inclined crack (denoted by S1) propagates upward toward the slope toe (Figure 7b). When the bedrock dislocation reaches 30 mm, S2 gradually expands into a sliding surface with a collapse width of approximately 3 cm, while S1 continues to develop (Figure 7c). At displacements between 40 mm and 50 mm, the rupture zone evolves into a “Y” shape, and a new crack appears on the slope surface 10 cm from the lower side of the slope toe (Figure 7d,e). When the bedrock dislocation reaches 60 mm, the combined action of rupture zones S1 and S2 forms the main rupture zone (MRZ) of

the slope and its overlying layer, penetrating the soil to the slope surface (Figure 7f). As the bedrock dislocation ranges from 70 mm to 100 mm, the main rupture zone extends toward the active block, gradually widening. The soil on both sides of the main rupture zone exhibits evident tensile–shear failure (Figure 7g–j).

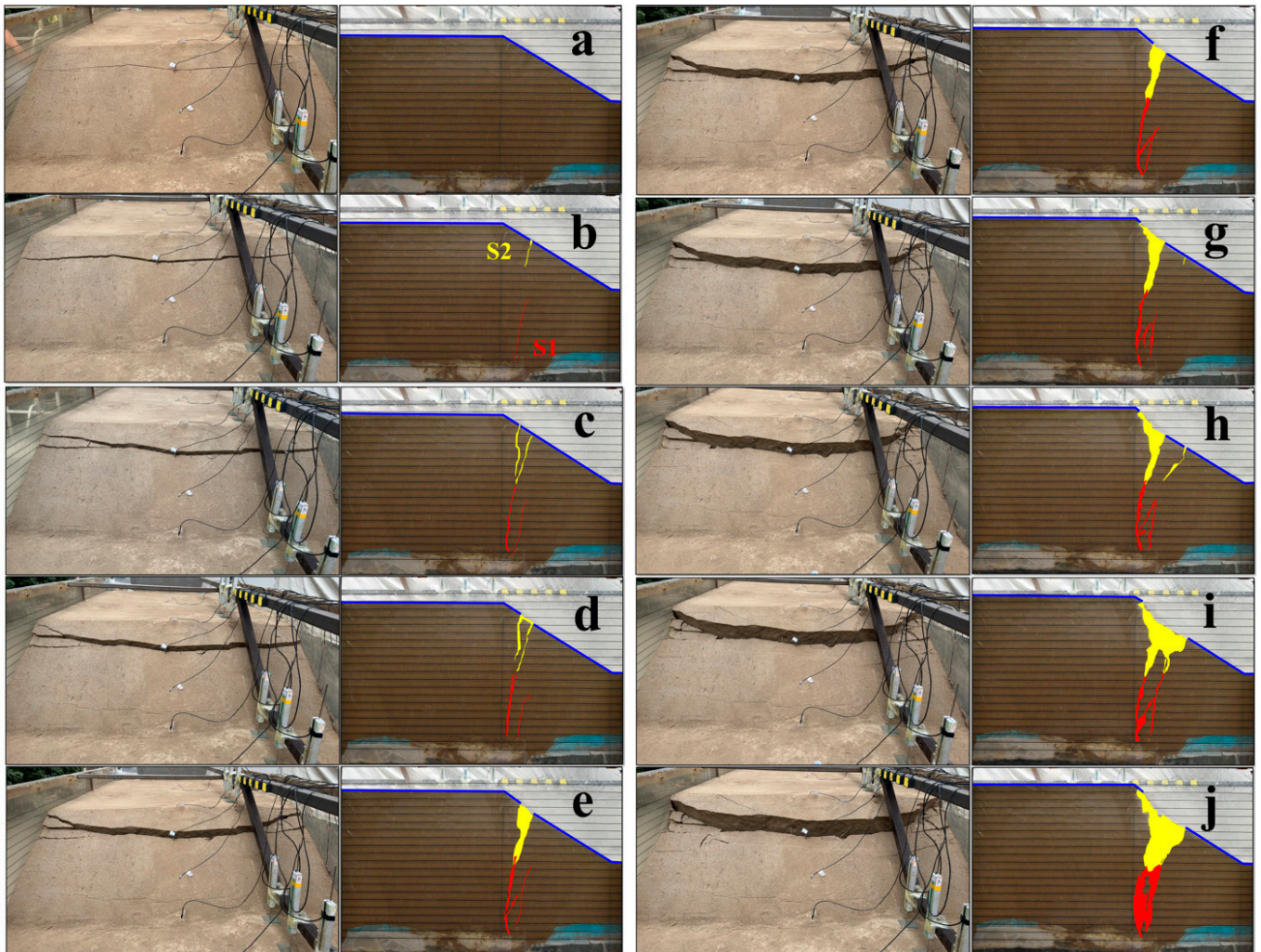


Figure 6. Failure process diagram of sandy soil slope during soil body rupture at the slope crest (T1): (a–j) refers the bedrock dislocation ranging from 10 mm to 100 mm.

From a macroscopic comparison of the failure processes, it is evident that the slope failure in the soil rupture test of the slope crest was more severe, with a wider collapse range. The MRZ was bundle-shaped and affected a larger area. In both the tests, the initial failure stage involved the appearance of small cracks on the slope surface, followed by the development of an upward rupture zone (S1) from the bedrock dislocation point and a downward rupture zone (S2) from the surface cracks on the slope. With an increase in the bedrock dislocation, the rupture zones S1 and S2 developed into the MRZ in both the tests. However, in the soil rupture test of the slope crest, S1 penetrated through the overlying layer, causing S2 to penetrate the slope body and leading to severe overall slope instability. In contrast, in the soil rupture test of the slope toe, S1 extended upward to a certain extent within the overlying layer and then terminated, while S2 penetrated the slope body and extended into the overlying layer. This explains why the soil rupture at the slope crest was more severe than that at the slope toe.

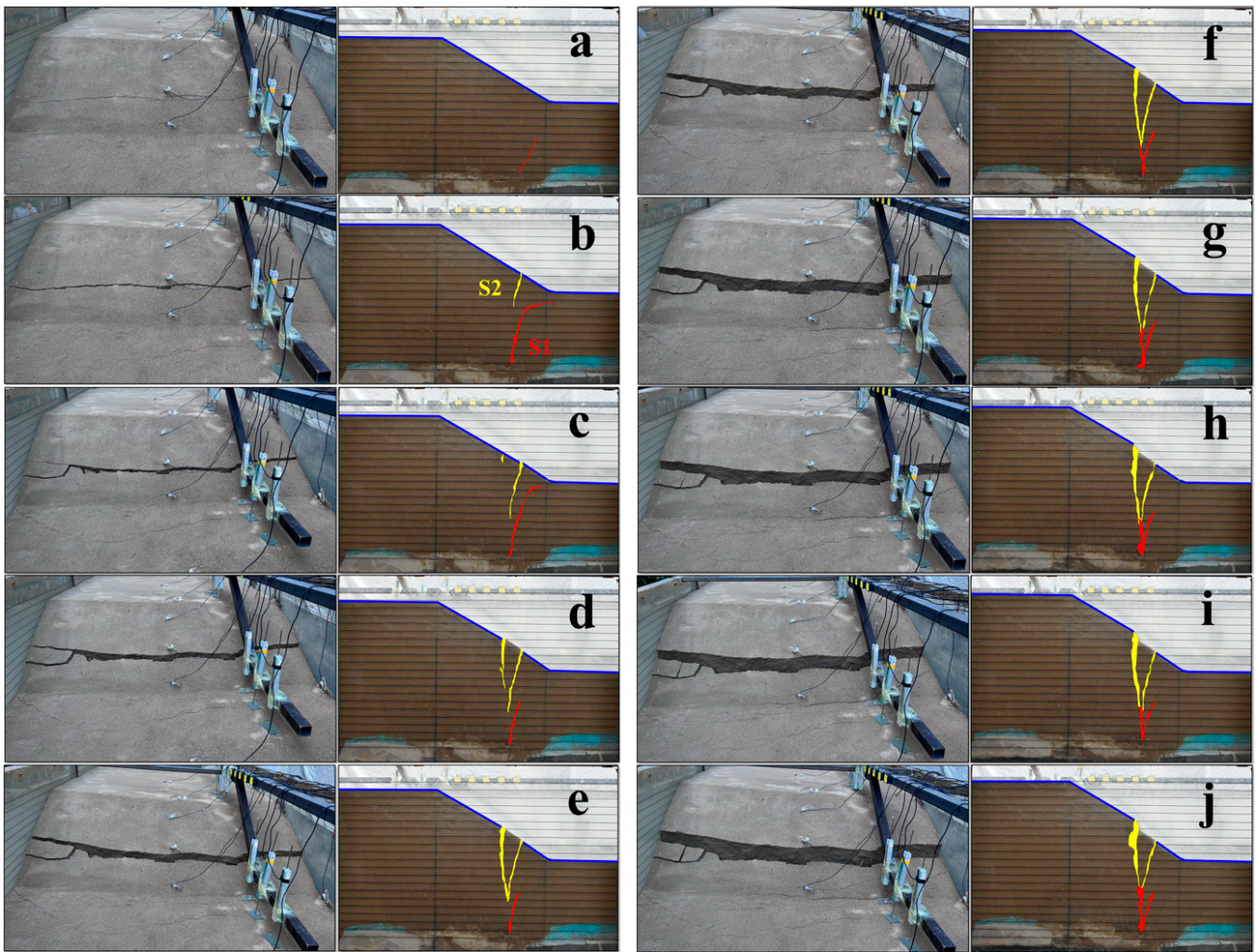


Figure 7. Failure process diagram of sandy soil slope during soil body rupture at the slope toe (T2): (a–j) refers the bedrock dislocation ranging from 10 mm to 100 mm.

Based on the above observations, the failure process of soil slopes across bedrock faults can be preliminarily divided into three stages: Crack damage stage (I), crack expansion and penetration stage (II), and failure and stabilization stage (III).

3.2. Deformation Analysis of Main Rupture Zone

In the soil rupture test of the slope crest, the MRZ formed by bedrock dislocation had a width of approximately 25 cm and a displacement difference of 8.5 cm (see Figure 8a). In the soil rupture test of the slope toe, the MRZ formed by bedrock dislocation had a width of approximately 15 cm and a maximum displacement difference of 5.5 cm (see Figure 8b).

As shown in Figure 9, during Stage I, the depth of the MRZ (main shear zone) in the slope crest and toe soil rupture tests was approximately 3 cm and 20 cm, respectively, with slight variations observed, indicating early signs of slope instability and the onset of soil rupture. In Stage II, the maximum MRZ depth in the slope crest soil rupture test reached 92 cm, with a maximum width of 25 cm. With the depth of the MRZ increasing rapidly at first and then leveling off. This suggests that the soil rupture penetrates and fully develops, with minimal changes thereafter. In contrast, the MRZ depth in the slope toe soil rupture test reached a maximum of 60 cm, with a maximum width of 15 cm. The depth of the MRZ increased steadily, indicating that the soil rupture did not fully develop. In both the tests, the width of the MRZ experienced a sudden change on entering Stage III, marking an intensification of slope instability. During Stage III, The maximum width and depth of

the MRZ during slope crest soil rupture were 35 cm and 95 cm, respectively, while during slope toe soil rupture, the maximum width and depth of the MRZ were 15 cm and 70 cm. The width and depth of the MRZ in both the tests tended to stabilize with minimal changes, indicating that the slope had fully lost its stability.

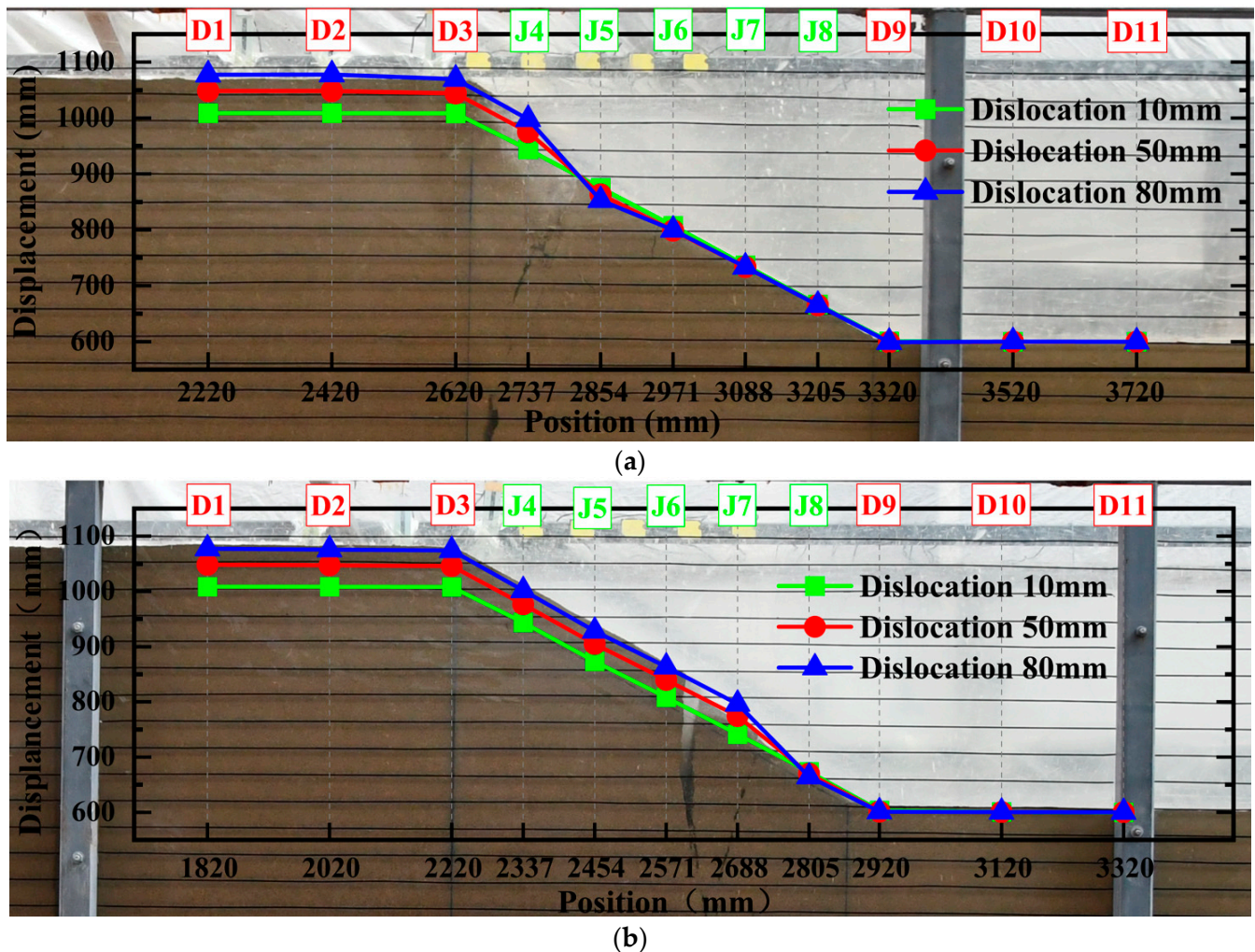


Figure 8. Slope surface deformation under soil slope cross-bedrock fault. Slope surface deformation of sandy soil slope during soil body rupture at (a) slope crest (T1) and (b) slope toe (T2). The base figs show the on-site damage photos of the bedrock after a dislocation of 80 mm.

During the stage of MRZ penetration and development, the damage caused by the slope crest soil rupture test was more severe. In the slope crest soil rupture test, by the time Stage II was reached, the soil in the slope underwent a thorough rupture, resulting in the formation of small overhanging faces. In Stage III, these overhanging faces become more pronounced, leading to the formation of a double-sided slope. Due to the steepness of the overhanging faces, there is a risk of secondary landslides under seismic activity and other conditions. In the slope toe soil rupture test, after reaching Stage II, the ruptured shear rupture zone near the slope toe caused the upper slope body to lose support. This can trigger secondary landslides under the influence of self-weight and other forces such as seismic activity. This process is more likely to occur after Stage III. Therefore, regardless of whether it is the slope crest or slope toe soil rupture test, secondary landslides are likely to occur once the slope soil undergoes thorough rupture. The slope crest soil rupture test required a greater amount of bedrock dislocation to reach Stage III, resulting in a wider and deeper MRZ and a greater extent of damage.

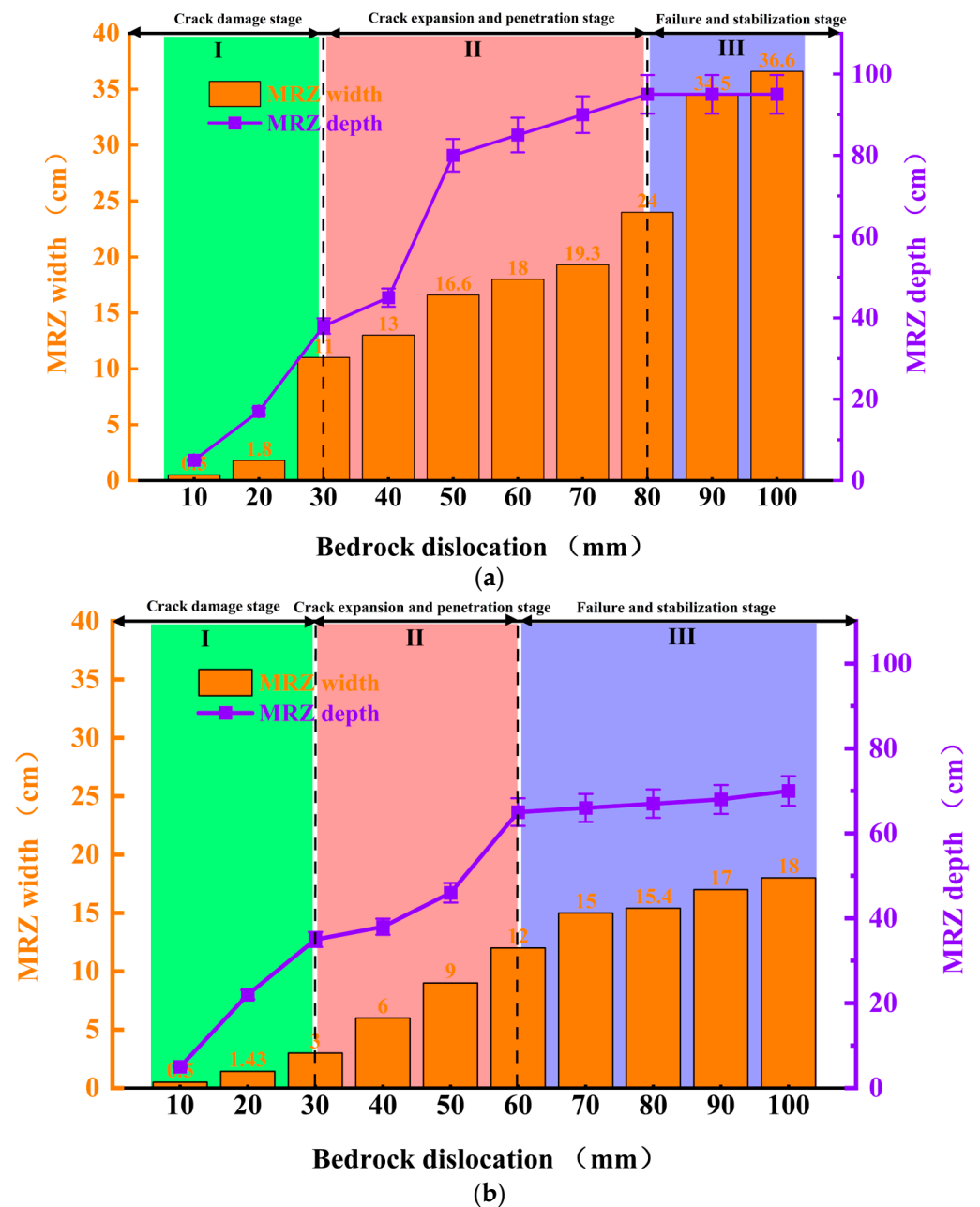


Figure 9. MRZ width and depth trend diagram of bedrock dislocation: Changes in the width and depth of the MRZ during soil body rupture (a) at the slope crest (T1) and (b) at the slope toe (T2).

The MRZ developed from small cracks in Stage I to a sliding surface (rupture zone) in Stage II, ultimately forming a zone that penetrated the soil to the slope surface. During this process, the formation of the MRZ was influenced by the width and depth of the rupture zone, the uneven deformation zone on the surface, and the internal slope rupture.

3.3. Slope and Overburden Stress Analysis

Soil pressure monitoring can help comprehensively characterize and reveal the plastic zone and fracture mechanisms of the slope soil body during stress changes. Based on the range of soil pressure sensors arranged in the slope and covering layer (from T3 and T8 on the left, to the toe of the slope on the right), representative analysis was conducted on the data obtained from one displacement in each of the three stages. The stress change cloud maps during soil fracture in the two experiments were drawn using the contour map of

Origin2024 software, as shown in Figures 10 and 11. The range of significant soil pressure changes in the figures roughly represents the plastic zone.

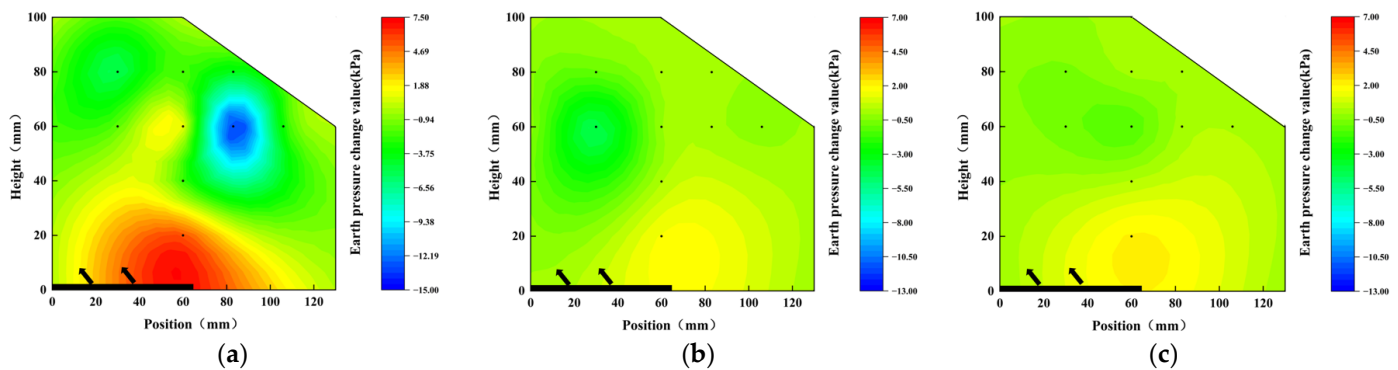


Figure 10. Stress variation cloud diagram during soil body rupture at the slope crest (T1) under different dislocation: (a) 10 mm, (b) 50 mm, and (c) 80 mm.

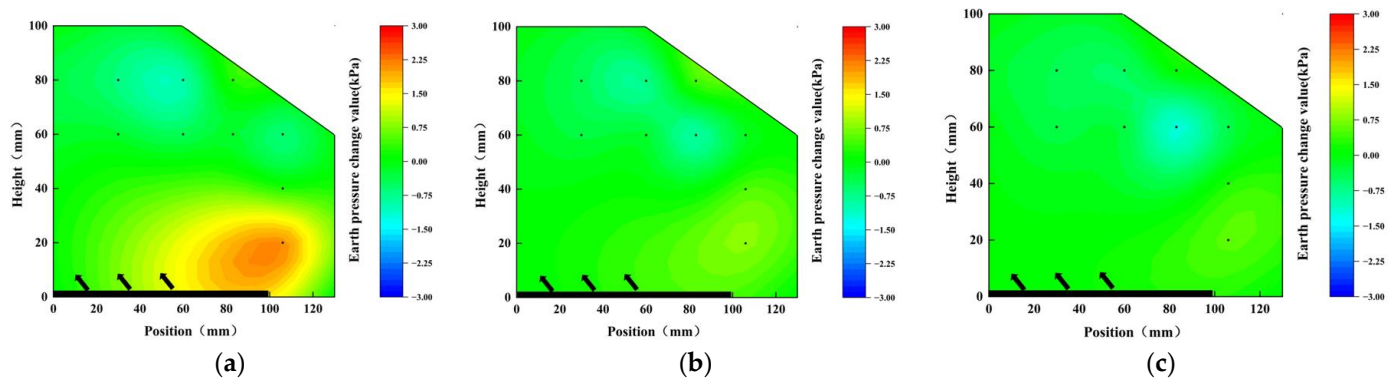


Figure 11. Stress variation cloud diagram during soil body rupture at the slope toe (T2) under different loading: (a) 10 mm, (b) 50 mm, and (c) 80 mm.

As shown in Figures 10 and 11, the local soil stress concentration caused by changes in the soil pressure contributes to the further development of the MRZ by accumulating plastic or stress boundary zones. In the crack damage stage (Stage I, 10 mm), both the tests showed distinct plastic zones in the overlying soil near the bedrock dislocation point, a plastic zone also developed within the slope, corresponding to the crack development observed at the site. However, the plastic zone range in the slope crest soil fracture test was wider, and the damage was more significant, with the maximum soil pressure change reaching -11 kPa. In the expansion and penetration stage (Stage II, 50 mm), the plastic zone of the overlying soil in the slope crest soil fracture test still changed, indicating the transition of the crack into a rupture zone. Indicating the expansion and widening of MRZ-S1. The plastic zone within the slope body continued to change, and the interaction between MRZ-S2 and MRZ-S1 caused the main rupture zone to penetrate the soil body, which is roughly consistent with the location of the main rupture zone. The changes in the slope toe soil fracture test were not as significant as those in the slope crest test. The location of the rupture zone dislocation at the slope toe has changed. In the failure and stabilization Stage (Stage III, 80 mm), the plastic zone of the overlying soil in the slope crest soil fracture test continued to change, indicating that MRZ-S1 was expanding and widening and that it continued to extend upward, while there was no change in the slope toe soil fracture test, nor within the slope body. The final rupture area is consistent with the location of the main rupture during the experiment.

From the above, it can be seen that the damage was more severe in the slope crest soil fracture test. Moreover, a stress analysis of the slope body and its overburden layer reflected the macroscopic rupture development characteristics of the MRZ.

3.4. Microseismic Monitoring Damage Analysis

The bedrock fault dislocation caused the soil to rupture, releasing a significant amount of energy instantaneously and generating microseismic events (microseisms). These microseismic elastic wave signals were inputted into the acquisition system, enabling a real-time monitoring of the occurrence and development of soil rupture. The following analysis primarily focused on the peak acceleration indices in the collected microseismic waveforms.

In the slope crest soil rupture test, the acceleration showed a gradually increasing trend with elevation. The maximum acceleration peak occurred at MRZ-S2 (locations A8 and A9). During Stage I, the soil at A9 ruptured and deformed, releasing a large amount of energy, resulting in a maximum acceleration of 0.013 g. In Stage II, as MRZ-S2 developed up to the slope crest, the peak acceleration at A8 became significant, while A9 showed minimal changes due to the completed rupture at this location. In Stage III, the presence of overhanging faces at the MRZ-S2 led to a decrease in the peak acceleration (Figure 12a). In the slope toe soil rupture test, the acceleration at various points on the slope surface initially increased, and then decreased with elevation. The maximum acceleration peak was located at MRZ-S2 (location A10). The soil at A10 remained active throughout all the three stages, deforming and releasing a large amount of energy, resulting in a maximum acceleration of 0.015 g. The closer to MRZ-S2, the more pronounced the acceleration response (Figure 12b). In the slope crest soil rupture test, the peak acceleration near the MRZ in the vertical direction within the slope body increased with the gradual displacement of the bedrock. The peak acceleration in the middle part of the soil was significantly greater than those at the top and bottom (Figure 13a). In the slope toe soil rupture test, the peak acceleration near the MRZ in the vertical direction within the slope body amplified with increasing height. When the bedrock dislocation was small, the acceleration response in the middle part of the soil was significantly greater than those at the top and bottom, indicating a gradually developing main rupture zone, with soil rupture occurring near the MRZ. As the bedrock dislocation increases, the acceleration response becomes less pronounced. The maximum acceleration response occurs near the slope toe (main rupture zone) when the bedrock dislocation reaches 10 mm. (Figure 13b).

A comparative analysis indicates that the acceleration along the slope surface elevation exhibited an amplification trend, particularly when a significant amount of energy was released during soil rupture near the MRZ, resulting in the most pronounced peak acceleration. For the acceleration within the slope body and its overlying layer, the peak acceleration at MRZ-S1 was the most significant, elucidating the dynamic rupture development process of MRZ-S1 in the overlying layer site. In conclusion, microseismic monitoring demonstrated that the soil slope exhibited a clear elevation amplification effect, while both the soil slope and its overlying layer exhibited a surface rupture zone amplification effect.

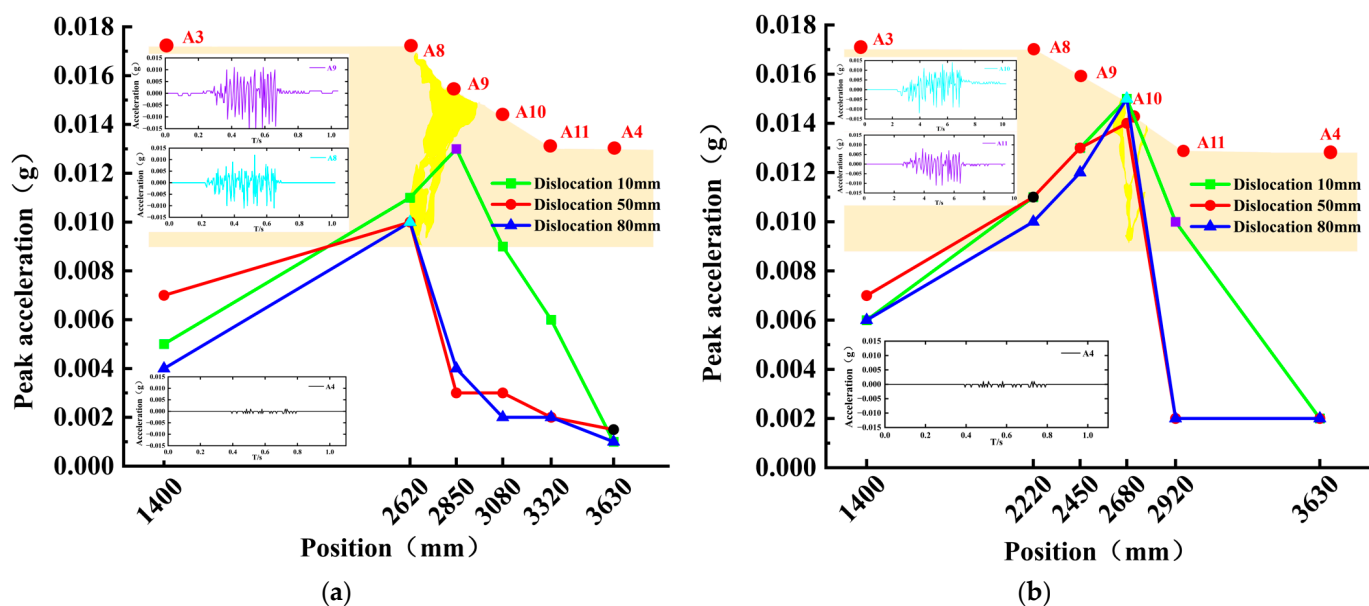


Figure 12. Peak microseismic variation diagram of the slope surface. Peak microseismic variation on the slope surface during soil body rupture (a) at the slope crest (T1) and (b) at the slope toe (T2).

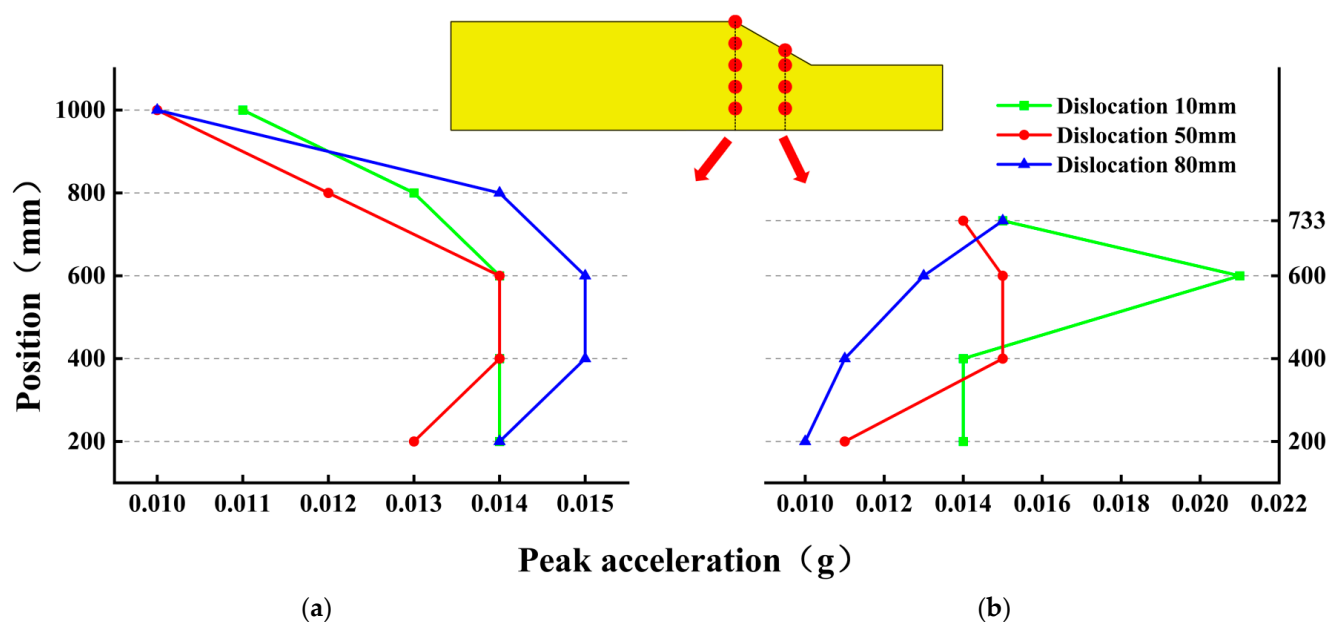


Figure 13. Peak microseismic variation diagram of the slope body. Peak microseismic variation within the slope body during soil body rupture (a) at the slope crest (T1) and (b) at the slope toe (T2).

4. Discussion on Failure Mechanism

The cross-bedrock fault-induced landslide is influenced by both the relative movement of the two fault blocks during fault slip and the significant plastic deformation of the overlying layer and slope soil, leading to the formation of the main rupture zone. This results in a severe degree of landslide damage and a complex evolution process and failure mechanism. By analyzing the previously summarized macroscopic slope failure characteristics, main rupture zone deformation analysis, slope body and overlying layer stress analysis, and microseismic monitoring damage analysis, the slope body failure can be divided into three stages: crack damage stage (I), crack expansion and penetration stage (II), and slope instability stage (III). Ultimately, the forms of soil failure and instability are tensile-collapse or tensile-compressive shear failure, as illustrated in Figure 14.

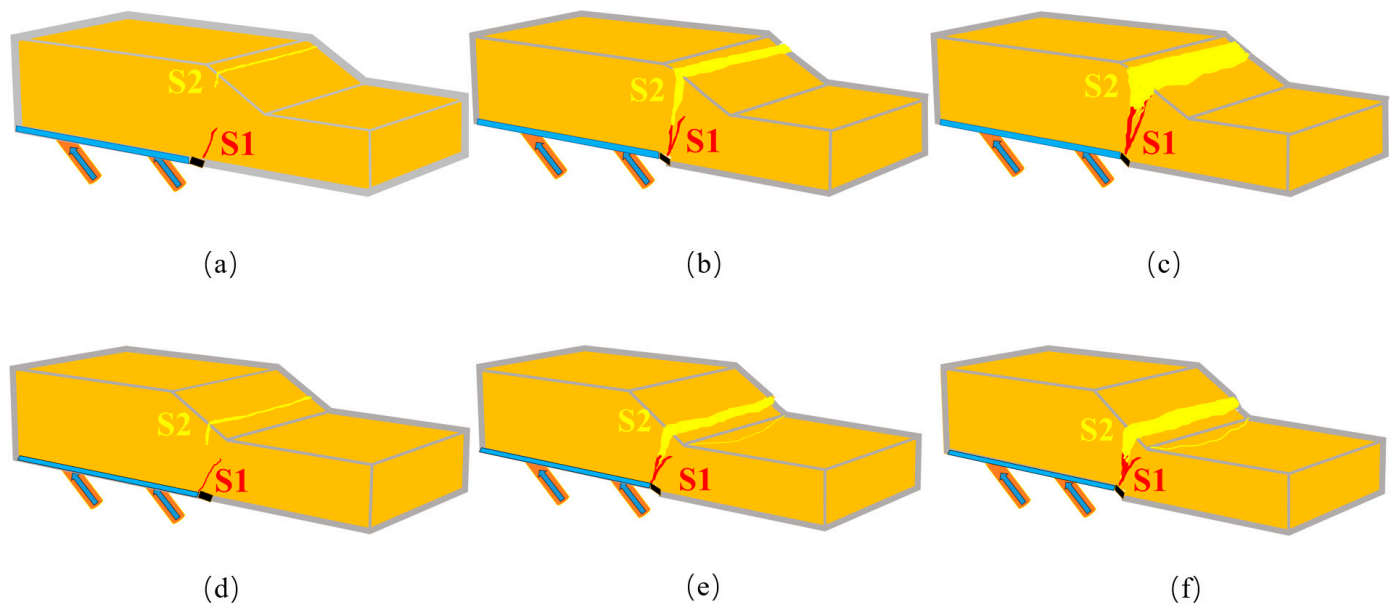


Figure 14. Failure mode diagram of slope cross-bedrock fault ((a–c): soil body rupture at the slope crest, (d–f): soil body rupture at the slope toe).

In Stage I, both the slope crest and slope toe soil rupture tests exhibited the development of cracks in the overlying soil layer. These cracks extended upward from the bedrock fault (approximately parallel to the fault dip angle) and downward from the slope surface. The slope surface cracks developed into narrow collapse zones, and the soil, under shear stress, began to exhibit plastic deformation zones (Figure 14a,d). It can be observed that during Stage I, by utilizing the predicted crack location, placing crack gauges and microseismic sensors allows for early warning of cross-fault slope failure.

In Stage II, in the slope crest and slope toe soil rupture tests, with an increase in the bedrock dislocation, the main rupture zone penetrated the soil and the slope body to the slope surface. The slope surface cracks widened, and the collapse zone expanded. The soil near the collapse zone underwent compression and plastic deformation, showing more pronounced tensile cracking deformation within the slope body, further expanding until forming a through-soil tensile crack surface. After the rupture penetrated the soil, the slope crest soil rupture test showed small overhanging faces in the main rupture zone, while the slope toe soil rupture test showed distinct ruptured shear rupture zones near the slope toe (Figure 14b,e). It can be observed that in the later part of Stage II, the slope's structure changes, and an overall sliding surface (the known through-rupture zone) appears. This enables the prediction of potential slope instability risks and provides a scientific basis for taking appropriate engineering measures.

In Stage III, both the slope crest and slope toe soil rupture tests showed minimal changes in terms of the failure morphology despite the gradual increase in the bedrock dislocation. This indicates that the slope was already fully unstable, characterized by large deformation zones. The increase in bedrock dislocation caused the overhanging face in the main rupture zone in the slope crest soil rupture test to expand, resulting in the formation of a double-sided slope. Due to the steepness of the overhanging face, secondary landslides are likely under seismic activity and other conditions. In the slope toe soil rupture test, the severely ruptured shear rupture zone near the slope toe caused the upper slope body to lose support, leading to secondary landslides under the effect of self-weight and seismic activity (Figure 14c,f). In summary, the slope crest soil rupture mode had a greater impact on soil slopes. It can be observed that during Stage III, the slope's structure undergoes significant changes, with the overall sliding surface intensifying further and the free face

fully forming. This allows for the prediction of the potential hazards and scale of cross-fault slope instability. At the same time, the sliding surface and free face of the slope form the existing slope structure, providing a geological conceptual model for subsequent numerical simulations and model tests under loads such as rainfall and earthquakes, which can be used for comparative analysis and validation.

In summary, at different stages, mitigation measures such as early warning, stability safety calculations, and subsequent disaster experiments and simulation analyses can be applied. By implementing these scientific mitigation strategies, a monitoring system for cross-fault slopes can be established to promptly detect and provide early warning of safety hazards. In slope design, the impact of the sliding surface and its geometric characteristics on slope stability should be thoroughly considered. In the analysis of slope-induced disasters, real geological conceptual models provide essential data for subsequent experiments and numerical simulations. These effective prevention and control measures can significantly enhance slope stability and reduce the risk of instability.

This study investigated and analyzed real cases of seismic damage caused by landslides across normal bedrock faults, with typical examples including the Dongmiaojia landslide and the Lianhuasi ancient landslide. The Dongmiaojia landslide was influenced by the displacement of the main fault bedrock. The fault traversed the top of the landslide, forming the rear cutting and separation surface. This caused the appearance of a fault rupture zone and steeply inclined cracks at the slope crest, which extended into the mountain, resulting in tensile cracking damage. With significant fault displacement, the rupture zone and cracks continued to develop and penetrate toward the slope body, deepening and enlarging the rear tensile crack surface. Over time, the combined effects of the weight of the slope and other loads caused the local weak zones to become fully penetrated, leading to the formation of the Dongmiaojia landslide [61–63], as shown in Figure 15.

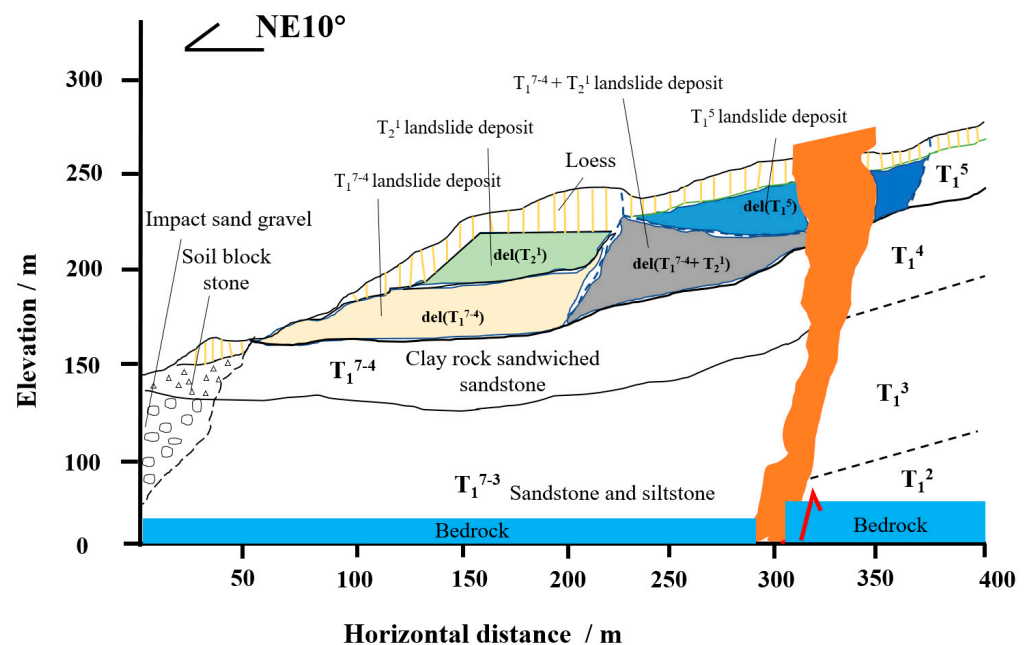


Figure 15. Geological profile of Dongmiaojia landslide.

The Lianhuasi ancient landslide is the oldest reported high-speed long-runout landslide in China. The Huashan Mountain front fault displacement directly cut through the toe of the landslide, resulting in a significant height difference and the formation of the main rupture zone (potential slip surface). Due to the weight of the mountain, continuous sliding occurred along the main rupture zone (shear rupture zone), eventually causing

the rupture surface to penetrate and shear out. Under inertia, the landslide continued to slide. According to Li et al., the large cracks caused by bedrock dislocation lead to the accumulation of a substantial amount of rock blocks due to the weight of the slope and the collapse of the overlying rock and soil mass. Subsequent secondary landslides occur under the influence of the weight of the slope and heavy rainfall, compounded by additional geological disasters, such as collapses [64–67], as shown in Figure 16.

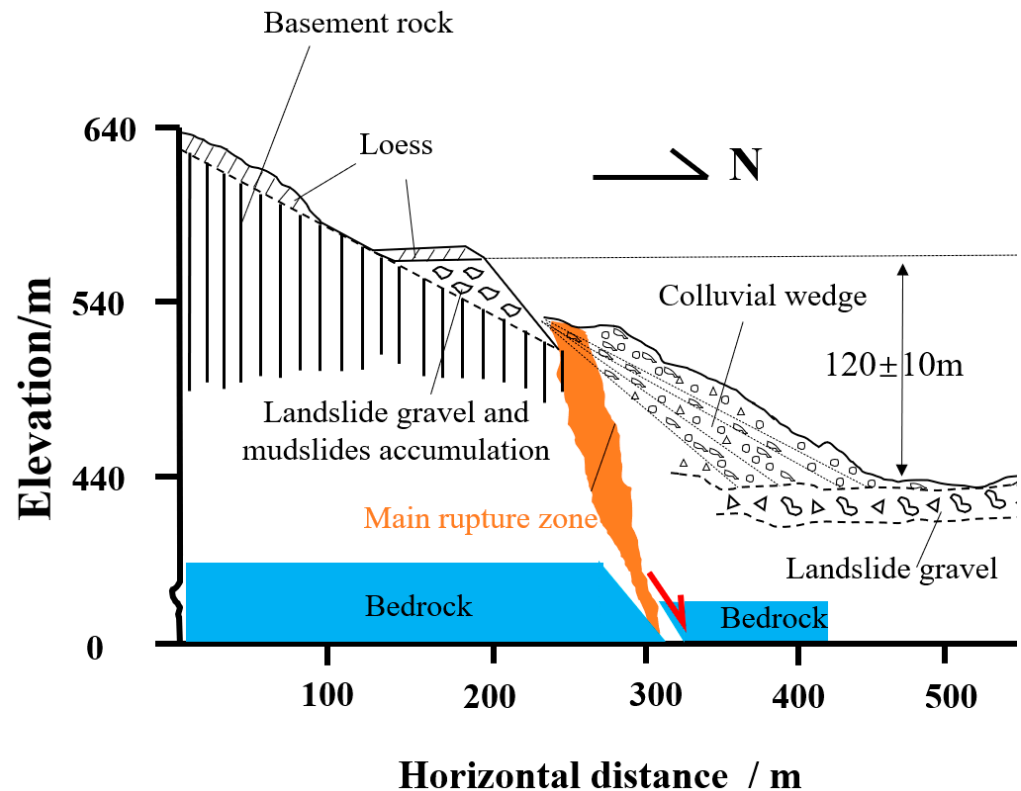


Figure 16. Geological profile of Lianhuasi ancient landslide.

An analysis of these typical seismic damage cases indicates that the causative mechanisms and failure processes of cross-bedrock fault slope models are generally consistent with actual seismic damage scenarios. Both can be characterized by the formation of a main rupture zone or a penetrative sliding surface in the slope due to fault displacement in the bedrock, leading to instability. This initial instability is then exacerbated by secondary landslides triggered by earthquakes, rainfall, and the weight of the slope itself. A further analysis of these seismic damage cases revealed that the locations of the main rupture zones in the slope models and the actual seismic damage closely correspond to the positions of the faults. Thus, the position of the main rupture zone can help effectively indicate the presence and location of bedrock faults.

5. Conclusions

Bedrock fault dislocation is a crucial structural factor influencing the movement of landslides. Accurately predicting the location and scale of rupture zones within slopes is essential for effective slope construction design and risk mitigation. In this study, microseismic sensors, surface deformation monitoring, and soil pressure sensors were deployed on slopes and their overlying soil layers affected by bedrock fault dislocation for a micro-level analysis of the soil rupture. This was combined with a macro-level analysis of field slope rupture to predict landslide acceleration and potential catastrophic events. This approach can help researchers identify active slopes with ongoing soil rupture and damage pro-

cesses due to bedrock dislocation, gain a better understanding of the mechanical properties of landslides, and provide a scientific basis for landslide risk management and disaster mitigation. The following are our conclusions:

(1) Based on the characteristics of cross-fault landslides/slope seismic damage, this study summarizes the current research status and advantages and disadvantages of cross-fault slope model tests conducted by scholars. A large-scale gravity bedrock dislocation device was developed, creatively enabling physical model tests simulating the relative movement of the two bedrock blocks causing cross-fault slope failure. This provides scientific evidence for the stability assessment of cross-fault slopes and the reinforcement design to prevent landslide disasters.

(2) The causative mechanism of the instability of a sandy soil slope, due to the dislocation of a normal fault crossing the bedrock, can be divided into three stages in its evolutionary process: crack damage stage (Stage I), crack expansion and penetration stage (Stage II), and slope instability stage (Stage III). Ultimately, the failure and instability of the soil body manifested as either tensile-collapse or tensile-compressive shear failure. The instability mechanism and evolution process obtained from this model test correspond to the field seismic damage of cross-fault slopes.

(3) A comparative analysis of the results of the soil body rupture tests at the slope crest and slope toe indicated that, under intense fault dislocation, the rupture mode of the soil body at the slope crest had a greater impact on the soil slope. Under specific bedrock dislocation conditions, when the soil body at the slope crest ruptured, a wide plastic zone was formed in the overlying layer, resulting in a distinct MRZ-S1 at this location, as verified by microseismic monitoring signals. Moreover, a significant plastic zone was observed within the slope body, and MRZ-S2 at this location also produced clear microseismic signals. With an increase in the bedrock dislocation, the plastic zone in the overlying layer continued to undergo significant changes when the soil body at the slope crest ruptured. This indicated that the main rupture zone at this location was still enlarging and extending upward. At different stages, mitigation measures such as early warning, stability safety calculations, and subsequent disaster experiments and simulation analyses can be applied. A monitoring system for cross-fault slopes should be established, and preventive measures should fully consider the impact of the sliding surface and its geometric characteristics on slope stability. These measures can significantly enhance slope stability and reduce the risk of instability.

(3) Model tests and field seismic damage cases showed that the positions of the main rupture zones on the slope surface were projected directly below the locations of coseismic dislocations of the bedrock fault. Therefore, when investigating landslide seismic damage caused by fault dislocation, the position of the bedrock fault can be determined by identifying the main rupture zones on the slope surface. This provides critical evidence for identifying seismogenic structures (faults) during field seismic surveys.

Of course, this experiment primarily investigates the dynamic failure process of cross-bedrock normal fault sandy slopes caused by bedrock dislocation. The standard sand used in the model test has certain limitations. In fact, cross-fault slopes with different soil properties are also an important research direction for our team, and extensive research work is still needed.

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