



# Evolution Process and Failure Mechanisms of Rockfalls Revealed by the Integration of Ambient Seismic Noise and Multi-Source Monitoring Data

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**Abstract.** Rockfall hazards are characterized by their sudden occurrence, complex evolutionary processes, and the difficulty of identifying reliable precursory signals for early warning. Understanding their failure mechanisms and precursory characteristics remains a key scientific challenge in geohazard research. In this study, the Mogangling high-elevation rockfall, triggered by the 5 September 2022 Luding earthquake, was selected as a representative case. Based on long-term in situ observations, we developed an integrated analytical framework that combines ambient seismic noise with hydro-mechanical multi-source monitoring data to investigate the evolution and failure mechanisms of rainfall-induced rockfalls. A rockfall event detection method based on the short-term average/long-term average (STA/LTA) algorithm was established to identify rockfall events, while relative seismic velocity changes ( $dv/v$ ) were extracted from ambient seismic noise interferometry to characterize temporal variations in the internal state of the rock mass. These results were further integrated with rainfall, hydrological observations, and slope stability analyses. During the monitoring period, a total of 329 rockfall events were identified and classified into three categories: single-trigger events, short-duration event clusters, and continuous rockfall sequences. Rockfall activity was strongly associated with rainfall but exhibited pronounced nonlinear, stage-dependent, and time-lagged responses. The  $dv/v$  measurements were highly sensitive to internal structural changes within the rock mass, showing significant anomalies approximately 2 h before failure and a rapid decrease of about 3 % during the collapse, indicating the transition from progressive damage accumulation to catastrophic failure. Integrated analysis of the multi-source monitoring data revealed that the rainfall-induced rockfall process can be divided into five evolutionary stages: the baseline stage, precursory fluctuation stage, instability stage, recovery stage, and re-equilibrium stage. Hydrological, geophysical, and stability-related parameters exhibited strong consistency across these stages, revealing a progressive disaster chain of rainfall infiltration–hydraulic deterioration–stability reduction–damage accumulation–failure. The results elucidate the hydro-mechanical-seismic coupling mechanisms governing rainfall-induced rockfalls and demonstrate the potential of integrating ambient seismic noise with multi-source monitoring data for precursor identification and early warning of rockfall hazards.



## 1 Introduction

Rockfalls are among the most destructive gravity-driven geohazards in mountainous regions owing to their sudden onset, high mobility, long runout distances, and severe consequences for human life, infrastructure, and the natural environment (Brennguier et al., 2011; Ferrari et al., 2016; Volkwein et al., 2011; Yan et al., 2019; Yang et al., 2017). In recent decades, the frequency and intensity of rockfall hazards have increased under the combined influences of climate change and anthropogenic activities. More frequent extreme rainfall events, together with the rapid expansion of transportation networks, hydropower development, and other engineering activities in mountainous areas, have altered hydrological conditions and stress regimes within rock slopes, thereby accelerating rock weathering, fracture propagation, and progressive structural degradation (Huggel et al., 2012; Stoffel et al., 2024; Tetteh et al., 2025). Consequently, rainfall-induced rockfalls have become a major natural hazard affecting mountainous regions world wide China is particularly susceptible to rockfall hazards because mountainous terrain, including plateaus, mountains, and hills, covers approximately 74.9 % of its land area (Fang and Ying, 2016). Complex topography, active tectonic deformation, and intense surface erosion provide favorable conditions for the initiation and evolution of rockfalls (Korup and Clague, 2009; Korup et al., 2007). Based on the annual statistics reported in the China Statistical Yearbook 2025, we calculated that 73 263 collapse events occurred in China between 2000 and 2024, corresponding to an annual average of approximately 2931 events (National Bureau of Statistics of China, 2025). Meanwhile, the continuous expansion of large-scale linear infrastructure, including railways, highways, power transmission corridors, and oil and gas pipelines, into mountainous areas has substantially increased the exposure of critical infrastructure to rockfall hazards. Improving the understanding of the evolution and failure mechanisms of rockfalls, as well as identifying reliable precursory indicators for early warning, has therefore become a pressing scientific challenge and an essential prerequisite for effective geohazard risk mitigation.

Rockfall failure is generally the culmination of progressive crack propagation, internal damage accumulation, and continuous degradation of the mechanical properties of rock masses rather than a process directly controlled by observable surface deformation. Consequently, continuously tracking the internal state of a rock mass and identifying reliable precursory signals during the progressive damage stage are essential prerequisites for effective early warning of rockfall hazards. To achieve this objective, a variety of monitoring techniques have been developed for rockfall hazard assessment. Existing approaches can generally be classified into three categories: surface deformation monitoring, subsurface deformation monitoring, and auxiliary geophysical or mechanical monitoring. Surface deformation is commonly monitored using conventional geodetic surveys, automated displacement measurements, Interferometric Synthetic Aperture Radar (InSAR), Global Navigation Satellite Systems (GNSS), Geographic Information Systems (GIS), and terrestrial laser scanning, whereas subsurface deformation is typically characterized using inclinometer-based techniques. In addition, stress- and energy-related monitoring methods, such as anchor cable load measurements and acoustic emission monitoring, have also been applied to investigate rock mass stability (Abellán et al., 2011; Barla and Antolini, 2016; Casagli et al., 2023; Ragnoli et al., 2023; Song et al., 2025; Zaki et al., 2014). Although these techniques have substantially improved the



capability for deformation detection and hazard assessment, their application in alpine canyon environments remains  
 65 challenging. Rugged topography, limited accessibility, harsh climatic conditions, and insufficient power supply and  
 communication infrastructure often hinder instrument deployment and long-term operation. More importantly, most  
 conventional monitoring approaches primarily characterize the external deformation response of slopes after damage has  
 accumulated, while providing limited insight into the progressive evolution of internal rock mass properties before failure.  
 These limitations, together with restricted spatial coverage, insufficient temporal resolution, and limited integration of  
 70 multi-source observations, constrain their ability to provide long-term, continuous, high-resolution, and real-time early  
 warning for rockfall hazards in complex mountainous regions (Casagli et al., 2023; Ragnoli et al., 2023; Yan et al., 2019).  
 Recent years have witnessed increasing interest in microseismic monitoring as a remote, continuous, and non-contact  
 technique for geohazard observation because of its capability to detect fracture-related seismic activity in real time (Huang et  
 al., 2025; Pang et al., 2026; Wu et al., 2026; Yang et al., 2023). By recording seismic signals generated by rock fracturing or  
 75 rockfall impacts, microseismic monitoring enables the detection of rockfall events, source localization, and identification of  
 hazardous areas, providing valuable information for hazard assessment and emergency response. For example, Gracchi et al.  
 (2017) employed a microseismic monitoring network to record impact-induced seismic signals from rockfalls and  
 reconstructed the source locations and trajectories of falling blocks based on seismic wave propagation characteristics.  
 Similarly, Feng et al. (2021) developed a spatiotemporal early-warning framework for rockfalls using microseismic  
 80 observations, in which event detection, source localization, and cumulative seismic energy analysis were integrated to  
 estimate failure timing and delineate hazardous zones. These studies have demonstrated the effectiveness of microseismic  
 monitoring for rockfall detection and post-event analysis. Nevertheless, microseismic monitoring primarily relies on  
 transient seismic signals generated after crack coalescence, rock fracturing, or block detachment. As a consequence, its  
 capability to resolve the gradual evolution of internal damage before failure—including crack initiation and propagation,  
 85 progressive stiffness degradation, and changes in the mechanical state of the rock mass—remains limited. This intrinsic  
 limitation restricts its ability to identify reliable precursory information during the incubation stage of rockfall hazards,  
 highlighting the need for complementary monitoring approaches that are capable of continuously tracking subtle changes in  
 the physical properties of rock masses before catastrophic failure.

Recent advances in ambient seismic noise interferometry have provided a powerful framework for continuously monitoring  
 90 temporal variations in the physical properties of subsurface media without relying on active seismic sources (Breguier et al.,  
 2011; Sens-Schönfelder and Wegler, 2008; Wang and Yao, 2020). By cross-correlating continuous ambient seismic noise  
 recordings, empirical Green's functions can be reconstructed between seismic stations, enabling high-resolution monitoring  
 of temporal changes in the elastic properties of geological media (Campillo and Paul, 2008). Among the various observables  
 derived from ambient seismic noise, the relative seismic velocity variation ( $dv/v$ ) has emerged as one of the most sensitive  
 95 indicators of changes in rock mass conditions, as it responds to crack opening and closure, stress perturbations, fluid  
 migration, and variations in elastic properties. Owing to its high sensitivity to subtle changes in the internal state of  
 geological media, ambient seismic noise interferometry has been increasingly applied to volcanoes, active faults, landslides,



and unstable rock slopes (Brennguier et al., 2008; Colombero et al., 2021; Larose, 2017; Mainsant et al., 2012; Snieder and Larose, 2013). Previous studies have shown that  $dv/v$  derived from ambient seismic noise is capable of detecting precursory velocity anomalies prior to slope failure, providing a promising proxy for monitoring progressive rock mass damage and mechanical degradation (Xie et al., 2023). More recently, Sun et al. (2025) reconstructed the three-dimensional shear-wave velocity structure of the Brienz rock slope using ambient seismic noise tomography and revealed the spatial characteristics of the sliding surface together with its relationship to slope instability. These findings demonstrate that ambient seismic noise can continuously capture subtle changes in the internal properties of rock masses that are difficult to resolve using conventional deformation monitoring or transient microseismic observations. Consequently, ambient seismic noise interferometry offers a unique opportunity to investigate the progressive evolution of rockfall instability and to identify precursory changes preceding catastrophic failure.

Despite these significant advances, several important challenges remain. Most previous studies have primarily focused on rockfall event detection or the interpretation of individual monitoring parameters, while the progressive evolution of rockfall instability—from the initiation of internal damage to catastrophic failure—has received considerably less attention. Although relative seismic velocity variations ( $dv/v$ ) derived from ambient seismic noise have demonstrated high sensitivity to changes in the physical properties of rock masses, the relationships between  $dv/v$ , rainfall infiltration, hydrological processes, and the temporal evolution of slope stability remain poorly understood. Moreover, existing investigations have largely relied on single-source observations, whereas quantitative integration of ambient seismic measurements with hydrological and geotechnical monitoring data is still limited. This lack of integrated observations hinders a comprehensive understanding of the hydro-mechanical-seismic coupling processes governing progressive rockfall failure and restricts the identification of reliable precursory indicators for early warning. Therefore, an integrated analytical framework combining ambient seismic noise with multi-source monitoring data is required to systematically investigate the progressive evolution and failure mechanisms of rainfall-induced rockfalls.

To address these challenges, this study investigates the Mogangling high-elevation rockfall, which was reactivated following the 2022 Luding earthquake, using long-term continuous in situ monitoring data. An integrated analytical framework combining rockfall event detection, ambient seismic noise interferometry, and hydro-mechanical monitoring is developed to investigate the progressive evolution and failure mechanism of rainfall-induced rockfalls. Specifically, a short-term average/long-term average (STA/LTA) algorithm is employed for automatic rockfall event detection. Relative seismic velocity variations ( $dv/v$ ) are subsequently retrieved from ambient seismic noise interferometry to characterize temporal changes in the internal structure and mechanical state of the rock mass. These observations are further integrated with rainfall, volumetric water content, matric suction, suction stress, and slope stability analyses to elucidate the hydro-mechanical-seismic coupling processes governing progressive rockfall failure. By integrating geophysical observations with hydrological and geotechnical monitoring data, this study provides new insights into the precursory characteristics and progressive failure mechanisms of rainfall-induced rockfalls, and demonstrates the potential of ambient seismic noise as a complementary tool for multi-source monitoring and early warning of rockfall hazards.



## 2 Study Area and In Situ Monitoring System

### 2.1 Study Area

The Mogangling rockfall is located in Luding County, within the Dadu River valley of the Hengduan Mountains, southwestern China. Tectonically, the study area lies within the Y-shaped junction of the Xianshuihe and Anninghe fault systems, one of the most tectonically active regions on the eastern margin of the Tibetan Plateau(Xu et al., 2025). The 2022 Mw 6.6 Luding earthquake caused substantial structural damage to the monzogranitic rock mass forming the rear scarp of the ancient Mogangling landslide, significantly increasing fracture density and reducing rock mass integrity. Combined with long-term tectonic uplift, weathering, and unloading processes, the rock slope has evolved into a highly fractured and unstable rock mass characterized by well-developed subvertical joints, providing favorable geological conditions for recurrent rockfall activity.

Field investigations (Fig. 1) indicate that the study slope has a relative elevation difference of approximately 550 m and an average slope angle exceeding  $45^{\circ}$ . Under such steep topographic conditions, detached rock blocks predominantly move downslope through rolling and bouncing, generating high kinetic energy and posing substantial impact hazards. Frequent rockfall activity has been documented in the study area (Wei et al., 2024), posing a persistent threat to power transmission facilities located at the slope toe. Controlled by complex joint networks and continuously influenced by rainfall infiltration, the stability of the rock slope exhibits pronounced temporal variability. These characteristics make the Mogangling rockfall an ideal natural laboratory for investigating rockfall detection, continuous monitoring, and the progressive evolution of rock slope instability.

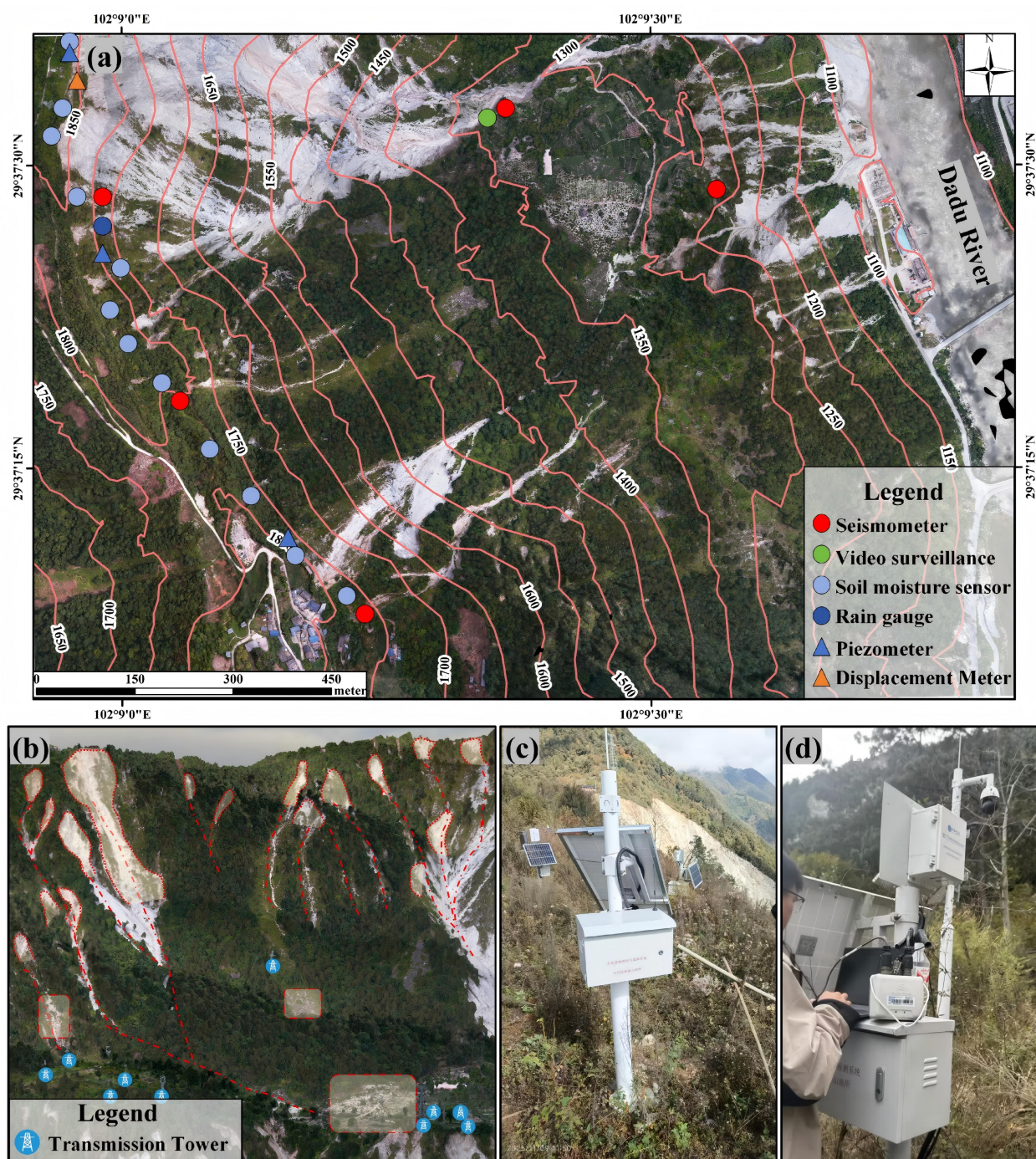


**Figure 1: Overview of the Mogangling rockfall and the in situ monitoring system. (a) Plan view of the rockfall site showing the layout of the monitoring network; (b) panoramic view of the Mogangling rockfall; (c-d) representative in situ monitoring instruments.**



155 **2.2 In Situ Monitoring System**

To investigate the progressive deformation and failure behaviour of the Mogangling rockfall, an integrated in situ monitoring system combining seismic, hydrological, geotechnical, meteorological, and optical observations was established (Fig. 1; Table 1). The monitoring network has been operating continuously since July 2025, providing long-term, high-temporal-resolution observations of the rockfall evolution under natural environmental conditions. The multi-source monitoring configuration enables simultaneous characterization of internal structural changes, hydrological responses, surface deformation, and rockfall activity.

**Table 1: Specifications of the integrated in situ multi-source monitoring system deployed at the Mogangling rockfall site.**

| Monitoring category             | Instrument                              | No. | Specification / Model                | Sampling interval / Data transmission | Installation location                         |
|---------------------------------|-----------------------------------------|-----|--------------------------------------|---------------------------------------|-----------------------------------------------|
| Microseismic monitoring         | Three-component short-period geophone   | 5   | Natural frequency: 4.5 Hz            | 250 Hz / Near real-time               | Rockfall crest and deposit area               |
|                                 | Volumetric water content sensors        | 13  | SCA100T-D01                          | 10 min / Wireless                     | Unloading fracture zone at the rockfall crest |
| Hydro-meteorological monitoring | Tipping-bucket rain gauge               | 1   | Resolution: 0.2 mm                   | 10 min / Wireless                     | Monitoring station at the rockfall crest      |
|                                 | Pore-water pressure sensor              | 3   | Measurement accuracy: $\pm 0.1\%$ FS | 10 min / Wireless                     | Interior of the rock slope                    |
| Deformation monitoring          | Cable-extension displacement transducer | 2   | Measurement range: 1000 mm           | 5 min / Wireless                      | Main tension cracks                           |
| Video monitoring                | Video monitoring camera                 | 1   | 4G remote transmission               | Real-time / 4G                        | Location with an unobstructed view            |

A microseismic monitoring array consisting of five three-component short-period geophones (natural frequency: 4.5 Hz) was deployed across the upper part of the rock slope and the toe of the rockfall deposit. The sensors were arranged in a triangular network geometry to improve the accuracy of rockfall event detection and source localization. Continuous seismic data were acquired at a sampling frequency of 250 Hz and transmitted in near real time. These recordings were used both for automatic rockfall event detection and for ambient seismic noise interferometry to estimate temporal variations in relative seismic velocity ( $dv/v$ ). To monitor rainfall-induced hydrological processes, an integrated hydro-meteorological monitoring system was installed within the unloading fracture zone at the crest of the unstable rock mass. The system consists of one master unit equipped with a tipping-bucket rain gauge and twelve sensor nodes for continuous measurements of volumetric water content. In addition, three pore-water pressure sensors were installed to quantify subsurface hydraulic responses during rainfall infiltration and to characterize temporal variations in pore-water pressure and effective stress. Surface deformation



was monitored using two cable-extension displacement transducers installed across the main tension cracks, allowing continuous measurements of quasi-static deformation of the unstable rock mass. A video monitoring system was further deployed to continuously record rockfall activity and provide visual validation of instability events detected by the seismic monitoring network.

### 3 Methods

To achieve automated identification of rockfall events and quantitative analysis of their stability evolution processes, an integrated analytical framework of “identification–sensing–interpretation” was developed in this study by combining microseismic monitoring, seismic ambient noise interferometry, and hydro-mechanical stability analysis. Within this framework, the short-term average/long-term average (STA/LTA) algorithm was employed for automatic detection of rockfall-induced seismic events, while relative seismic velocity variations ( $dv/v$ ) were used as a sensitive proxy for temporal changes in the internal state of the rock mass. Furthermore, a hydro-mechanical coupling model under unsaturated conditions was incorporated to investigate the entire evolutionary process of rockfall instability and to reveal the associated mechanical characteristics preceding failure.

The overall methodological framework and technical workflow adopted in this study are illustrated in Fig. 2.

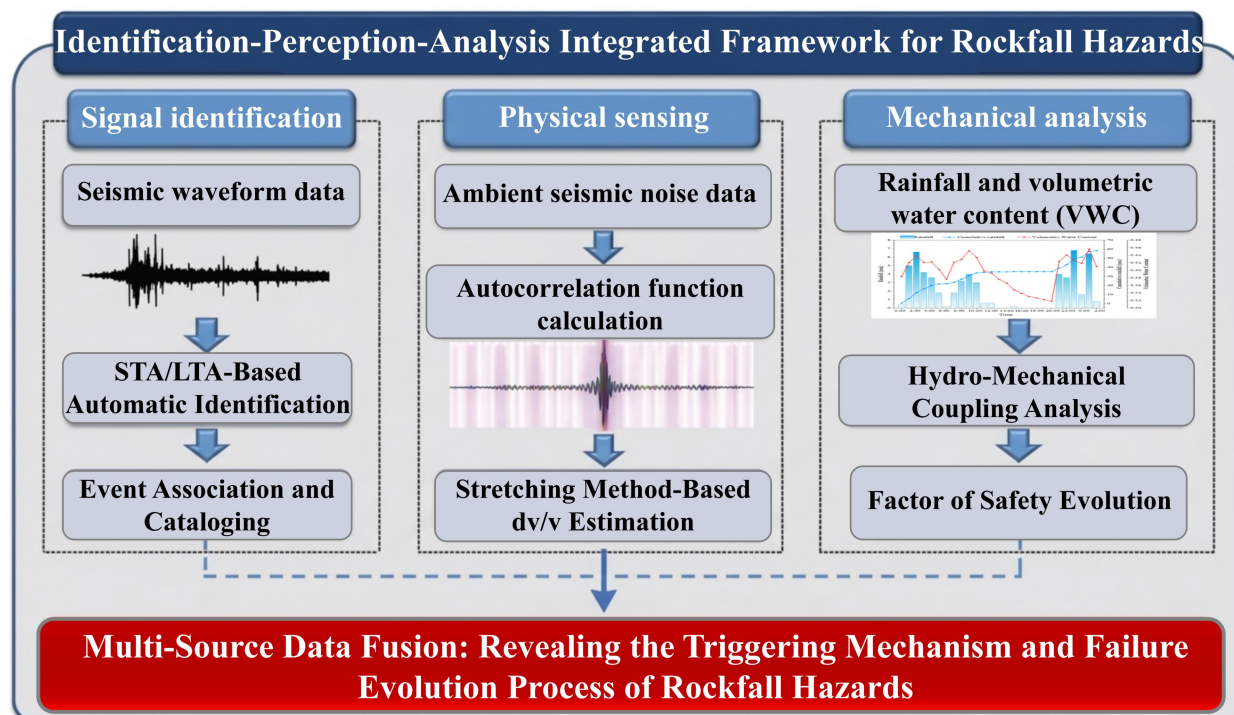


**Figure 2: Methodological framework for rockfall hazard identification, sensing, and interpretation through multi-source data fusion.**



### 190 3.1 Automatic detection of rockfall events using the STA/LTA algorithm

Accurate automatic detection and extraction of microseismic events are fundamental for investigating the evolutionary processes of rockfall hazards. In this study, the vertical-component seismic signals were selected, and the short-term average/long-term average (STA/LTA) method was employed for microseismic event detection. Originally proposed by Allen (1978) and further developed by Trnkoczy (1998), the STA/LTA algorithm has been widely applied in seismology and engineering geophysical monitoring due to its simple structure, high computational efficiency, and capability for real-time implementation.

The fundamental principle of the STA/LTA method is to continuously slide a short-time window (STA) and a long-time window (LTA) along the seismic waveform simultaneously. The STA window is designed to rapidly capture abrupt energy increases associated with transient microseismic events, whereas the LTA window provides a smoothed estimation of the ambient noise level. By comparing the short-term signal energy with the long-term background energy, a characteristic function sensitive to sudden variations in seismic amplitude can be established, enabling automatic identification and accurate triggering of microseismic events associated with rockfall processes. The STA/LTA characteristic ratio is defined as:

$$\frac{STA}{LTA}(x, n_s, n_L) = \frac{\frac{1}{n_s} \sum_{i=n-n_s}^n |x_i|}{\frac{1}{n_L} \sum_{i=n-n_L}^n |x_i|} \geq \lambda, \quad (1)$$

Where  $n_s$  and  $n_L$  represent the lengths of the short-term and long-term windows, respectively;  $x_i$  denotes the signal amplitude at time  $i$ ; and  $\lambda$  is the predefined triggering threshold.

To improve the detection accuracy of rockfall-induced seismic signals under complex ambient noise conditions, the STA/LTA parameters were systematically calibrated through a series of comparative experiments. Specifically, the frequency characteristics of long-term continuous seismic records were analyzed, and representative rockfall events were manually identified to optimize the detection performance. Based on these analyses, an optimal parameter combination suitable for the monitoring conditions of the study area was determined. During the event detection process, a dual-threshold triggering strategy, including an onset threshold and a termination threshold, was adopted to ensure reliable identification of event initiation and termination times. The specific parameters were configured as follows: the long-term window length ( $n_L$ ) was set to 120 s to characterize the background noise level and suppress low-frequency fluctuations; the short-term window length ( $n_s$ ) was set to 3 s to capture the dominant duration of impulsive signals generated by rockfall impacts. The triggering threshold ( $\lambda$ ) was set to 8, while the termination threshold was set to 2. This configuration effectively reduced false triggers caused by random noise while maintaining the integrity of detected event waveforms. Furthermore, adjacent triggering results with time intervals shorter than 5 s were merged into a single event to avoid splitting one physical rockfall process into multiple independent detections. This post-processing procedure further improved the reliability and consistency of the identified rockfall event catalog.



### 3.2 Ambient noise interferometry-based estimation of relative seismic velocity variations (dv/v)

After the automatic identification of rockfall events, continuous ambient seismic noise was further analyzed to investigate the temporal evolution of subsurface media. Following the ambient noise preprocessing workflow proposed by Bensen et al. (2007), seismic ambient noise interferometry was performed using continuous seismic records, and the relative seismic velocity variations (dv/v) were estimated using the SeisMIC toolkit (Makus and Sens-Schönfelder, 2024). This approach reconstructs noise correlation functions from continuous ambient seismic noise and quantifies temporal variations in subsurface properties by analyzing changes in the correlation functions, thereby enabling continuous monitoring of the internal state of geological media.

First, the valid waveform segments selected after STA/LTA-based event screening were processed through instrumental response removal, mean removal, linear detrending, and band-pass filtering. Subsequently, temporal normalization and spectral whitening were applied to suppress the influence of non-stationary noise sources and anomalous amplitudes on the stability of noise correlation functions. These procedures enhance the uniformity of the noise wavefield and improve the utilization of the effective frequency band.

Assuming that  $M$  waveform segments were obtained, with each segment containing  $N$  sampling points, the frequency-domain representation of the seismic signal can be expressed using the discrete Fourier transform as:

$$S_{m,k} = \sum_{n=1}^N S_{m,n} e^{-i \frac{2\pi kn}{N}}, \quad (2)$$

Where  $i = \sqrt{-1}$ ,  $m$  denotes the waveform segment index, and  $k$  and  $n$  represent the frequency- and time-domain sampling points, respectively. The autocorrelation function was then calculated in the frequency domain as

$$C_{o,k} = S_{m,k} \cdot \bar{S}_{m+j,k}, \quad (3)$$

where the overbar denotes the complex conjugate,  $o$  represents the station-pair index, and  $j=0$  corresponds to the autocorrelation of a single station. The corresponding time-domain correlation function was subsequently obtained through the inverse discrete Fourier transform:

$$C_{o,n} = \frac{1}{N} \sum_{k=1}^N C_{o,k} e^{i \frac{2\pi kn}{N}}, \quad (4)$$

The resulting time-domain correlation functions served as the basis for waveform coherence analysis and subsequent estimation of relative seismic velocity variations (dv/v). To identify stable correlation functions suitable for dv/v estimation, waveform coherence was evaluated as a quality-control criterion. The average of all correlation functions was adopted as the reference waveform, and the normalized cross-correlation coefficient between the reference waveform and each individual correlation function was calculated to quantify waveform similarity and temporal stability. Based on the coherence analysis, the effective frequency band and lapse-time window used for dv/v estimation were determined. According to the quality-control results, a frequency band of 2–4 Hz was selected for the subsequent dv/v analysis, while both the analysis window length and the sliding interval were set to 1800 s.



Within the framework of ambient noise interferometry, the stretching method was employed to continuously estimate relative seismic velocity variations ( $dv/v$ ). The average correlation function was used as the reference waveform, and its time axis was stretched using a series of candidate stretching factors. The time transformation is expressed as

$$\tilde{\tau}_j = \tau e^{-\kappa_j} , \quad (5)$$

where  $\tau$  denotes the original lapse time and  $\kappa_j$  is the  $j$ th candidate stretching factor. For each candidate factor, the stretched reference waveform was compared with the correlation function corresponding to each analysis window, and their similarity was quantified using the normalized cross-correlation coefficient. After evaluating all candidate stretching factors, the factor yielding the maximum normalized cross-correlation coefficient was selected as the optimal solution. The corresponding relative seismic velocity variation ( $dv/v$ ) was then determined from the relationship between the optimal stretching factor and seismic velocity perturbation. By repeating this procedure for all analysis windows throughout the monitoring period, a continuous time series of relative seismic velocity variations ( $dv/v$ ) and the corresponding coherence coefficients was obtained. The coherence coefficient was subsequently used to assess the stability and reliability of the  $dv/v$  estimates.

### 3.3 Hydro-mechanical stability analysis of unsaturated rock and soil masses

Building upon the automatic identification of microseismic events and the estimation of relative seismic velocity variations ( $dv/v$ ), this study further integrated multiple monitoring datasets to establish a unified time series for subsequent hydro-mechanical analysis of rock and soil stability and dynamic responses. Considering the well-developed joints and fractures within the rockfall source area, the hydro-mechanical behavior of the rock mass exhibits typical characteristics of an unsaturated geomaterial. Therefore, an unsaturated hydro-mechanical stability model was introduced to characterize the coupled hydraulic–mechanical evolution of the rock and soil mass during rainfall infiltration.

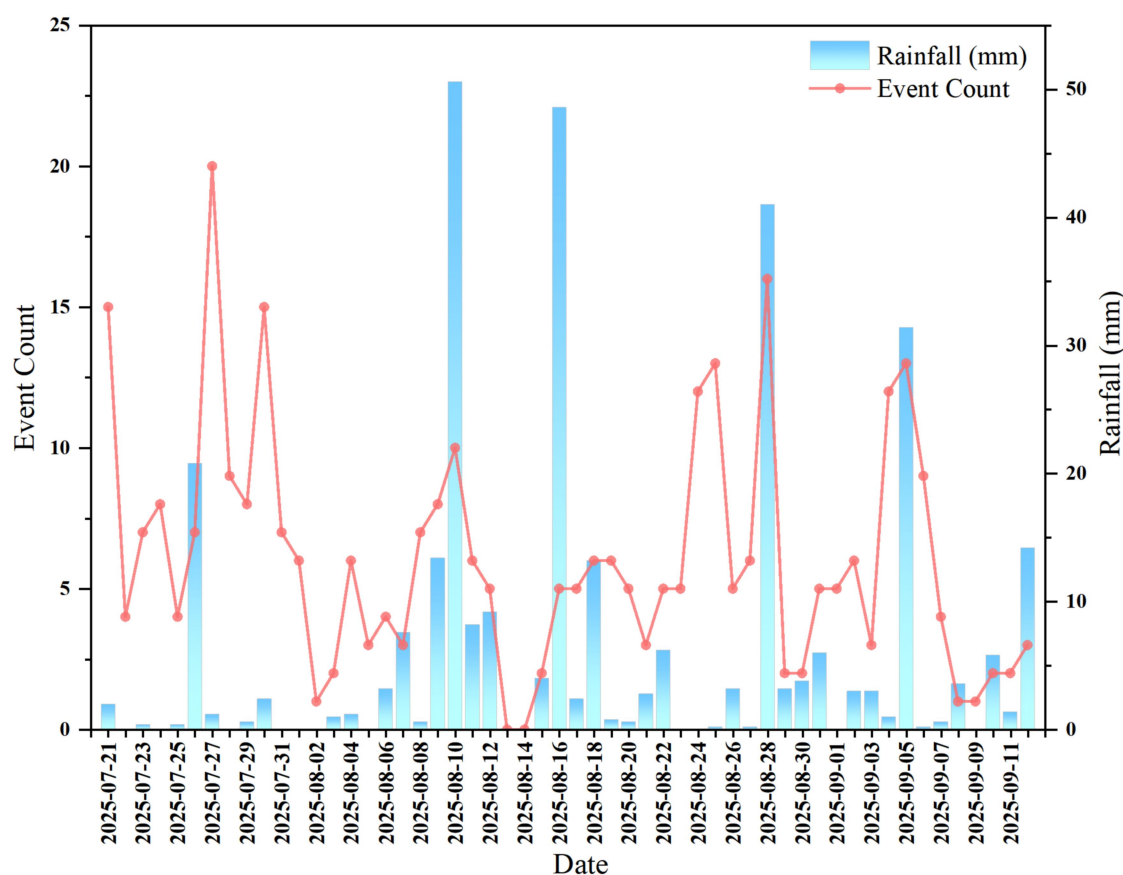
The computational framework and implementation details follow the hydro-mechanical coupling approach proposed by Yang et al. (2020) and are therefore not repeated here. Using this model, the observed temporal variations in volumetric water content were transformed into quantitative stability indicators. The model was further employed to investigate the coupled temporal evolution of matric suction, suction stress, and the factor of safety ( $F_s$ ) during rainfall infiltration, together with the corresponding geophysical response represented by relative seismic velocity variations ( $dv/v$ ). By integrating hydro-mechanical and geophysical observations within a common temporal framework, the proposed approach enables quantitative characterization of the coupling relationships among hydrological processes, mechanical stability, and seismic velocity changes, thereby providing insights into the triggering mechanisms and progressive failure evolution of rockfall hazards.



## 280 4 Results

### 4.1 Identification and classification of rockfall events

Using the STA/LTA algorithm, continuous seismic records acquired between 21 July and 12 September 2025 were automatically processed, yielding 362 candidate anomalous signals. After evaluating waveform characteristics and spectral features and manually removing false detections caused by environmental disturbances and instrumental noise, a total of 329  
 285 rockfall events were identified. Fig. 3 presents the temporal variations in rainfall and rockfall event frequency during the monitoring period. Overall, rockfall activity generally increased during rainfall events, with higher event frequencies observed during periods of continuous or intense precipitation, whereas the number of detected events decreased markedly during dry intervals. However, the response of rockfall activity differed considerably among individual rainfall episodes, indicating that not all rainfall events were accompanied by an increase in rockfall occurrence.



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**Figure 3: Temporal variations in daily rainfall and rockfall event frequency.**

Pronounced clusters of rockfall activity were observed on 27 July, 28 August, and 5 September, with the event-frequency peak on 28 August occurring almost simultaneously with the rainfall maximum. Nevertheless, rainfall amount and rockfall



frequency did not exhibit a simple linear relationship. For example, the heavy rainfall events on 10 August and 16 August  
295 were not associated with the highest rockfall frequencies, whereas several moderate rainfall episodes corresponded to  
relatively intense rockfall activity. In addition, some peaks in rockfall occurrence lagged behind rainfall events. For instance,  
a relatively high event frequency was recorded on 27 July, despite comparatively low rainfall during the same period.  
Overall, the results demonstrate a clear temporal association between rainfall and rockfall activity in the study area. However,  
the intensity of rockfall activity cannot be explained solely by rainfall amount, suggesting that the rainfall–rockfall  
300 relationship is characterized by nonlinear and time-lagged responses.

To characterize the dynamic behavior of rockfall activity, the identified events were classified into three categories based on  
their waveform characteristics, event duration, and temporal occurrence patterns (Fig. 4): single-trigger events, short-duration  
event clusters, and continuous rockfall sequences.

Single-trigger events (Fig. 4a) are characterized by isolated, short-duration impulsive signals with abrupt onset, rapid  
305 attenuation, and a stable background before and after the event. Short-duration clustered events (Fig. 4b) consist of multiple  
impulsive signals occurring within a relatively short period and exhibiting a clustered temporal distribution. Although  
individual sub-events remain distinguishable, the increased event density indicates enhanced rockfall activity over a short  
timescale. In contrast, continuous rockfall events (Fig. 4c) are characterized by prolonged, high-density energy release, with  
continuously varying amplitudes and no distinct quiescent intervals. Their energy envelopes exhibit a typical pattern of  
310 progressive amplification, peak energy release, and gradual decay. Similar continuous rockfall signals have also been  
reported by Lévy et al. (2010), who associated this type of seismic signature with sustained rockfall activity.

The three event types exhibit distinct characteristics in terms of duration, waveform complexity, and energy-release patterns.  
Single-trigger events constitute the majority of the identified events and are dominated by instantaneous energy release.  
Short-duration clustered events are characterized by multiple successive triggers within a limited time interval, whereas  
315 continuous rockfall events exhibit the longest durations and the most intense energy release. Overall, the observed waveform  
characteristics reveal pronounced multi-scale dynamic behavior of rockfall activity in the study area, reflecting different  
stages of slope destabilization under rainfall conditions.

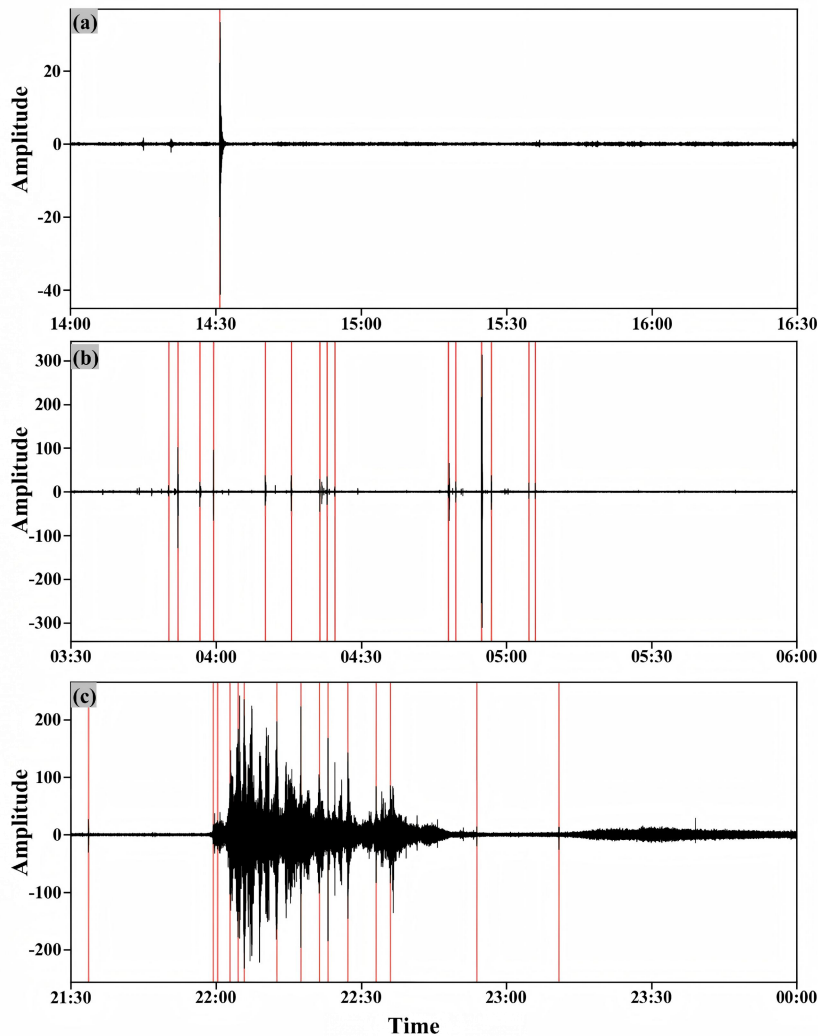


**Figure 4: Representative waveforms of rockfall events identified using the STA/LTA algorithm: (a) single-trigger event; (b) short-duration clustered event; and (c) continuous rockfall event.**

#### 4.2 Response of relative seismic velocity variations ( $dv/v$ ) during rockfall evolution

The preceding analysis revealed a clear temporal association between rockfall activity and rainfall in the study area. However, event statistics primarily describe the external manifestation of rockfall activity and provide limited information on the evolution of the internal structural state of the rock mass. To further investigate the response of the rock mass before, during, and after failure under rainfall conditions, a representative continuous rockfall event that occurred on 10 August 2025 was selected for detailed analysis. Ambient noise monitoring data were integrated with hydro-mechanical monitoring observations following the analytical framework illustrated in Fig. 2.



The time series of relative seismic velocity variations ( $dv/v$ ) estimated using the stretching method are shown in Fig. 5. Based on the temporal evolution of  $dv/v$ , the rockfall process can be divided into five successive stages: the baseline stage, the precursory fluctuation stage, the instability stage, the recovery stage, and the re-equilibration stage. During the baseline stage,  $dv/v$  fluctuated slightly around zero and remained relatively stable, indicating little temporal variation in the internal state of the rock mass. Approximately 2 h before the rockfall event, the amplitude of  $dv/v$  fluctuations increased noticeably, marking the transition from the baseline stage to the precursory fluctuation stage. Subsequently,  $dv/v$  decreased rapidly as the rock mass entered the instability stage. At the time of failure,  $dv/v$  exhibited an abrupt reduction of approximately 3 %. Following the rockfall event,  $dv/v$  gradually increased during the recovery stage and approached a stable level approximately 2 h later, indicating the onset of the re-equilibration stage. It should be noted that this stage does not imply recovery of the rock mass to its initial condition; rather, it reflects post-failure structural readjustment and the establishment of a new mechanical equilibrium. Overall, the  $dv/v$  time series continuously captured the progressive evolution of the rock mass from the baseline stage through the precursory fluctuation, instability, recovery, and re-equilibration stages, demonstrating its capability to characterize temporal changes in the internal structure of the rock mass before, during, and after rockfall failure.

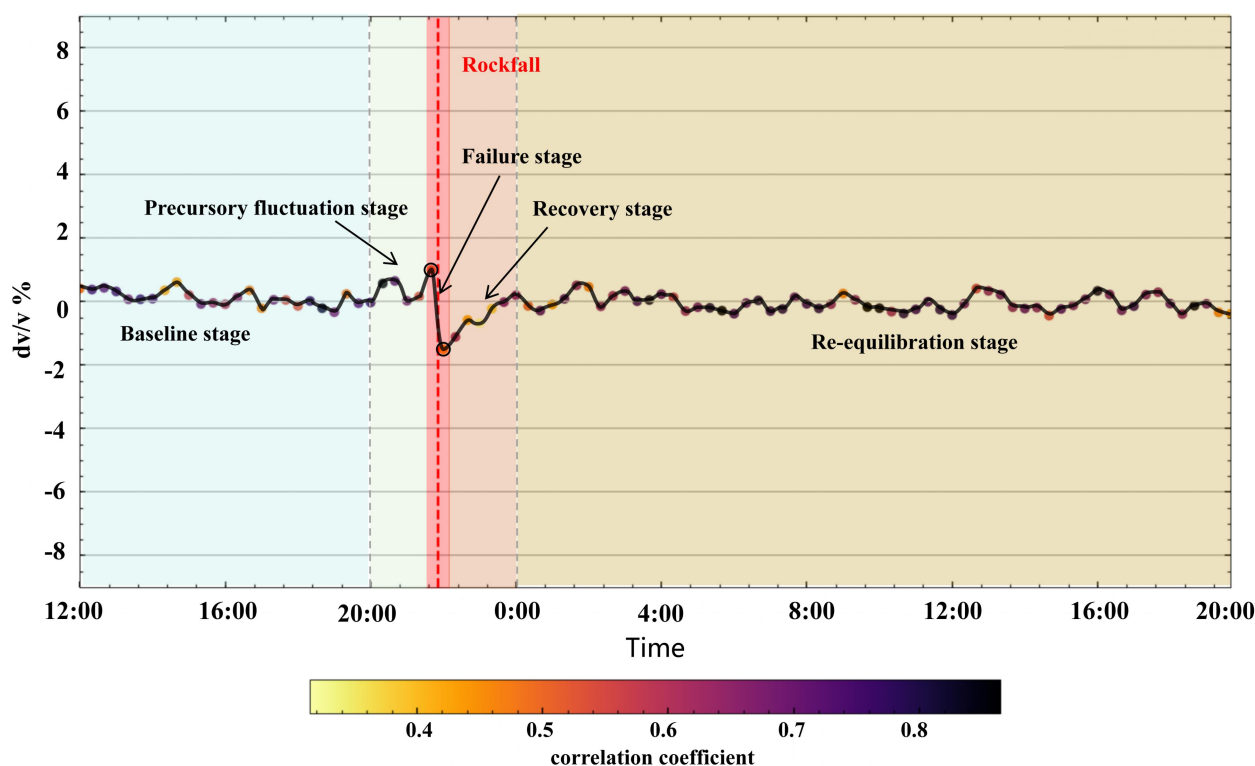


**Figure 5: Temporal evolution of relative seismic velocity variations ( $dv/v$ ) during the rockfall event.**

### 4.3 Coupled hydro-mechanical-seismic responses during rockfall evolution

The rainfall process in the study area during August 2025 exhibited an overall pulse-like pattern (Fig. 3). Before the occurrence of the rockfall event on 10 August 2025, the study area had already experienced several consecutive days of rainfall. As shown in Fig. 6, the period from 00:00 to 12:00 corresponds to rainfall process I, during which continuous precipitation resulted in an increase in volumetric water content from approximately 0.38 to 0.45, indicating significant rainfall infiltration into the rock and soil mass. The interval from 12:00 to 20:00 was characterized by rainfall interruption, during which the volumetric water content decreased to approximately 0.32. After 20:00, rainfall process II began, and renewed precipitation caused the volumetric water content to rapidly increase and remain at a relatively high level. Meanwhile, the  $dv/v$  time series exhibited a pronounced increase in fluctuation amplitude approximately 2 h before the rockfall event (Fig. 5), suggesting that changes in the internal state of the rock mass had occurred prior to failure. The concurrent variations in volumetric water content and  $dv/v$  indicate a close temporal relationship between rainfall-induced hydrological changes and seismic velocity responses during the pre-failure stage.

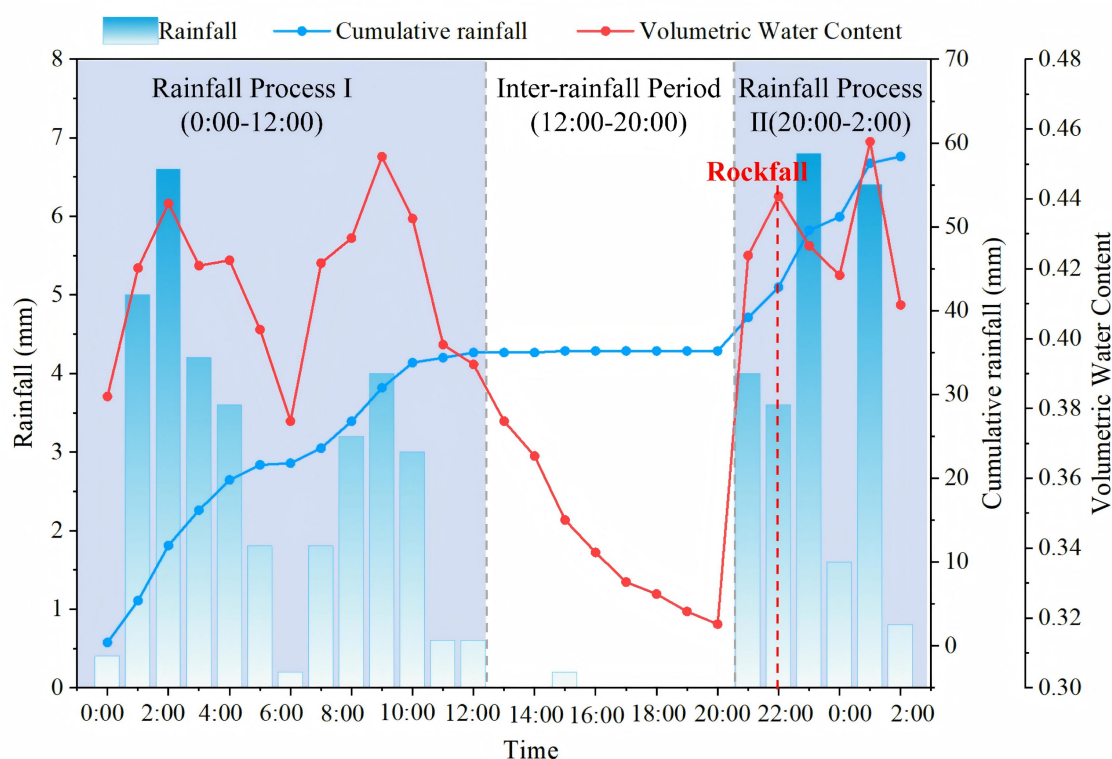
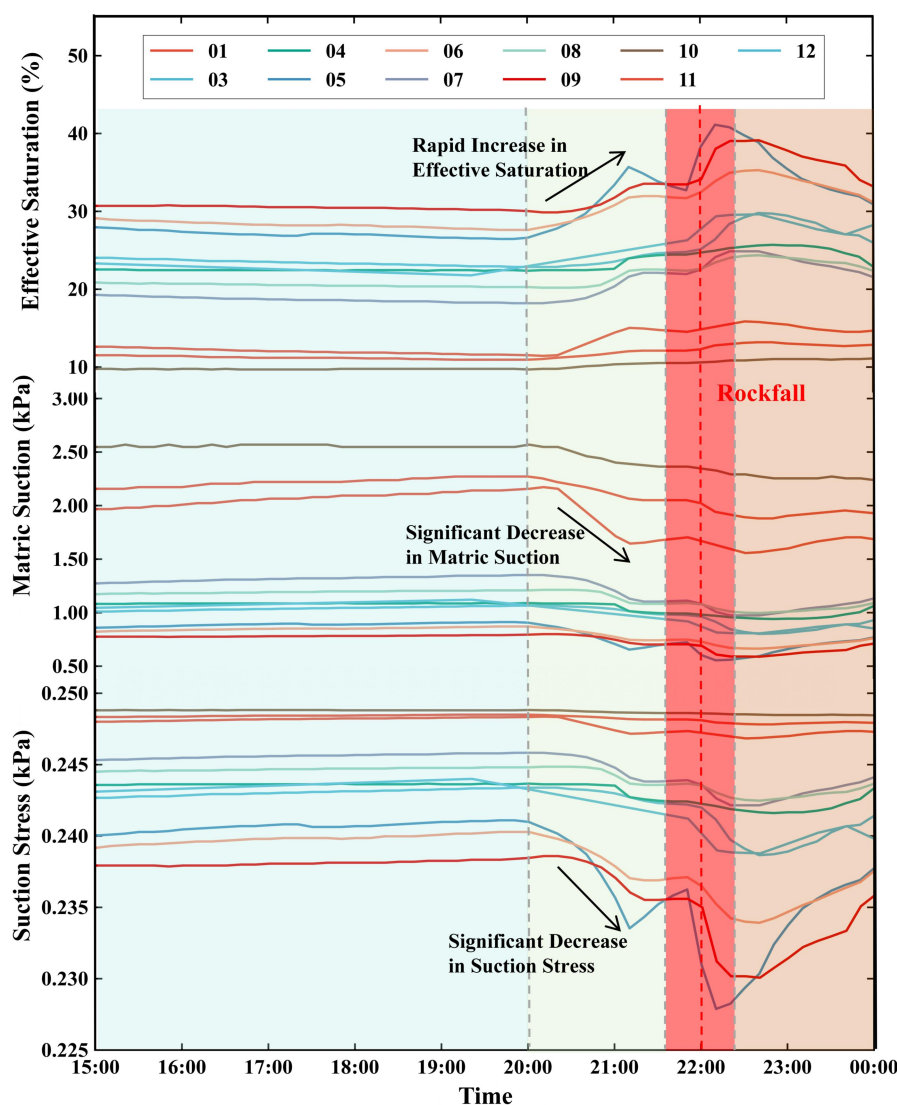


**Figure 6: Temporal variations in rainfall and volumetric water content during the rockfall event.**

During the preceding period of continuous rainfall, the volumetric water content remained at a relatively high level, and the subsequent rainfall episode caused a further rapid increase. Meanwhile, the  $dv/v$  time series exhibited pronounced anomalous fluctuations approximately 2 h before the rockfall event. Following the onset of rainfall process II, the effective



360 saturation continued to increase, with the value at monitoring point No. 5 increasing by approximately 15% compared with the preceding period. Correspondingly, matric suction and suction stress decreased simultaneously. The temporal evolution of these hydro-mechanical parameters showed good agreement with the five-stage evolution pattern identified from the  $dv/v$  variations, indicating a strong temporal consistency between hydrological responses and seismic velocity changes during the rockfall development process.



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**Figure 7: Temporal evolution of hydro-mechanical parameters during rainfall infiltration, including effective saturation, matric suction, and suction stress.**

As shown in Fig. 8, continuous rainfall infiltration resulted in a progressive decrease in the factor of safety ( $F_s$ ) due to the reduction in matric suction and suction stress. A pronounced inflection point occurred at approximately 20:00, which



coincided with the evolution of the rainfall process and the anomalous fluctuations in  $dv/v$ . At approximately 22:00, the  $F_s$  values at monitoring points No. 5 and No. 9 approached or decreased below 1.0, accompanied by a rapid decline in  $dv/v$ , indicating that the unstable rock mass had transitioned from a critically stable state to a failure stage. Following the rockfall event, the  $F_s$ , hydro-mechanical parameters, and  $dv/v$  all exhibited recovery trends. However, several monitoring points did not return to their initial levels, suggesting that the re-equilibration stage represents the establishment of a new post-failure equilibrium state associated with internal structural readjustment rather than a complete recovery of the original rock mass structure.

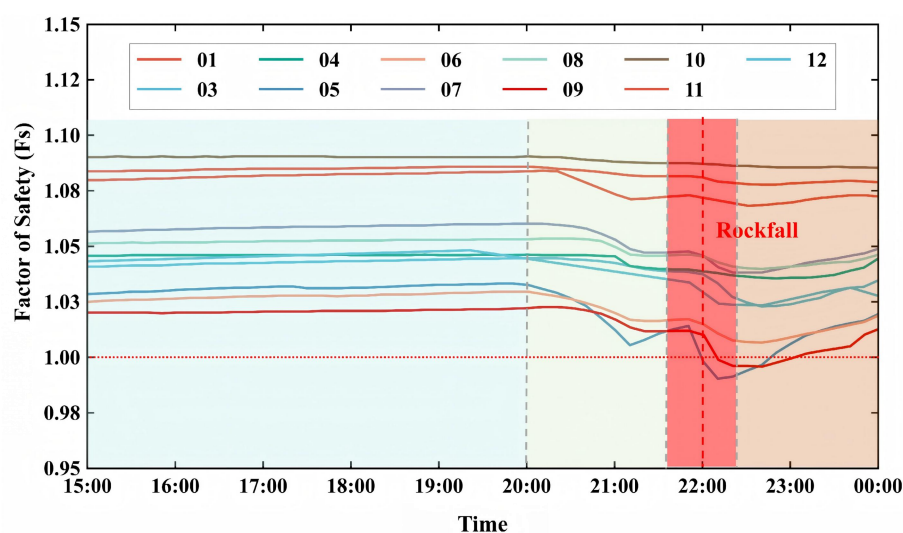
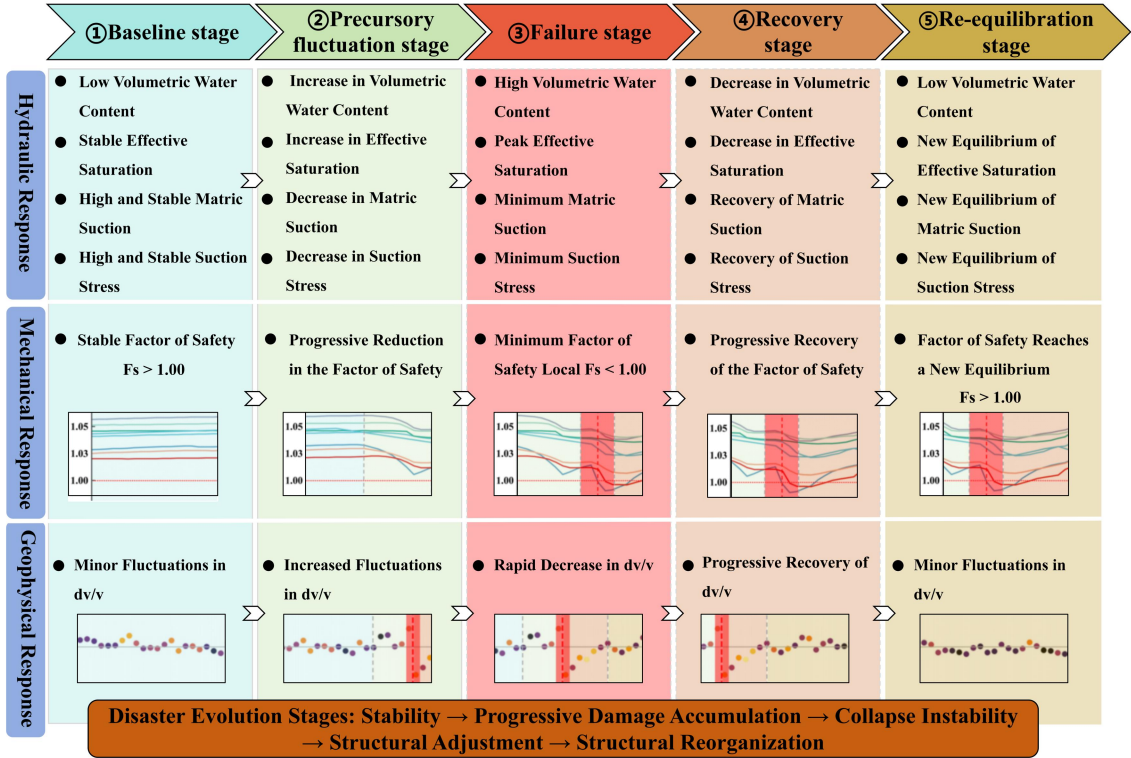


**Figure 8: Temporal variations in the factor of safety ( $F_s$ ) at different monitoring points during rainfall-induced rockfall instability.**

A comprehensive analysis of Figs. 5–8 demonstrates that the hydro-mechanical-seismic monitoring parameters exhibited similar temporal evolution patterns before and after the rockfall event. The entire failure process can be divided into five successive stages: the baseline stage, precursory fluctuation stage, instability stage, recovery stage, and re-equilibration stage (Fig. 9). The relative seismic velocity variations ( $dv/v$ ), effective saturation, matric suction, suction stress, and factor of safety ( $F_s$ ) showed coordinated variations throughout these stages. As shown in Fig. 9, all monitoring parameters remained relatively stable during the baseline stage. During the precursory fluctuation stage, the fluctuation amplitude of  $dv/v$  increased significantly, accompanied by a continuous increase in effective saturation, gradual decreases in matric suction and suction stress, and a progressive reduction in  $F_s$ . At the time of rockfall occurrence,  $dv/v$  exhibited an abrupt decrease, while  $F_s$  approached its minimum value, effective saturation remained at a high level, and matric suction and suction stress further declined. After the completion of the rockfall event,  $dv/v$ , hydro-mechanical parameters, and  $F_s$  gradually recovered and stabilized, marking the transition into the recovery and re-equilibration stages. However, several parameters did not return to their initial levels, indicating post-failure structural readjustment and the establishment of a new equilibrium state. The different monitoring parameters exhibited consistent temporal responses before and after the rockfall event. In particular,  $dv/v$  showed pronounced anomalous fluctuations approximately 2 h before failure, with a clear temporal correspondence to



395 Overall,  $dv/v$ , hydro-mechanical parameters, and  $F_s$  exhibited a consistent five-stage evolutionary pattern, with strong temporal correspondence among different monitoring indicators at critical stages of rockfall development. Notably, the anomalous variation in  $dv/v$  occurred earlier than the reduction of  $F_s$  to the critical state and the occurrence of macroscopic rockfall failure, highlighting the potential of seismic velocity variations as an early indicator of internal structural changes preceding instability.



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Figure 9: Five-stage hydro-mechanical-seismic evolution of the rockfall failure process based on multi-source monitoring.

## 5 Discussion

### 5.1 Hydro-mechanical mechanism governing rainfall-induced progressive rockfall instability

405 This study demonstrates that rainfall does not act as the direct trigger of rockfall occurrence; rather, it indirectly governs slope stability by regulating the evolution of hydro-mechanical conditions within the unstable rock mass. Although rockfall activity generally shows a clear temporal association with rainfall processes, substantial differences exist in event activity intensity among individual rainfall episodes, and some event peaks occur after rainfall maxima. These observations indicate that rockfall activity is controlled by the progressive evolution of internal rock mass conditions rather than by a simple linear



response to rainfall variations. Therefore, rainfall should be regarded as an external boundary condition driving the long-term evolution of unstable rock masses rather than as a direct failure trigger.

The integrated multi-source monitoring results further reveal the hydro-mechanical mechanism underlying rainfall-induced rockfall instability. Continuous rainfall infiltration modifies the internal hydraulic conditions of the unstable rock mass, resulting in the degradation of matric suction and suction stress. This process reduces the shear strength of the rock mass and causes a progressive decrease in the factor of safety (Fs), thereby promoting the accumulation of internal damage. Once the damage evolution exceeds a critical threshold, global instability occurs. This mechanism provides a reasonable explanation for the nonlinear, staged, and time-lagged responses observed in rockfall activity, suggesting that failure is governed by the combined effects of rainfall accumulation and progressive internal damage evolution rather than by an individual rainfall event alone. Accordingly, hydraulic processes serve as a critical physical bridge linking rainfall infiltration to mechanical instability. Conventional rainfall thresholds essentially represent external manifestations of critical internal damage states rather than direct controlling conditions for rockfall initiation.

Based on these findings, we propose that rainfall-induced rockfall failure is fundamentally a progressive evolutionary process driven by hydro-mechanical coupling, in which internal damage accumulates continuously until a critical threshold is exceeded, rather than an instantaneous failure triggered by a single external factor. Accordingly, a progressive failure chain of “rainfall infiltration - hydraulic degradation - stability reduction - damage accumulation - instability failure” is established, providing a unified physical interpretation of the relationships among rainfall forcing, hydraulic weakening, mechanical degradation, and macroscopic failure. This perspective extends the understanding of rainfall-induced rockfall hazards from traditional external triggering mechanisms toward internal state evolution mechanisms, providing a physical basis for developing process-oriented monitoring and early-warning approaches based on internal damage evolution and multi-source information integration.

## 5.2 Physical mechanism of $dv/v$ precursory anomalies and their implications for rock mass damage evolution

The results demonstrate that the relative seismic velocity variation ( $dv/v$ ) derived from ambient seismic noise interferometry does not merely respond to the occurrence of rockfall failure, but continuously captures the evolution of internal structural conditions and progressive degradation of rock mass stability. The anomalous fluctuations observed approximately 2 h before failure and the rapid decrease during instability indicate that  $dv/v$  reflects the continuous evolution of the physical properties of the medium rather than a transient response to the occurrence of macroscopic rockfall events.

From a physical perspective, rainfall infiltration modifies the water content conditions within the unstable rock mass and promotes the initiation, propagation, and coalescence of microcracks. These processes lead to progressive degradation of medium stiffness and a reduction in seismic wave velocity, manifested as a decreasing trend in  $dv/v$ . Once internal damage accumulation exceeds a critical threshold, the rapid development and coalescence of fracture networks result in an abrupt change in medium stiffness, producing a step-like decrease in  $dv/v$  that corresponds to macroscopic rockfall failure. The occurrence of  $dv/v$  anomalies approximately 2 h before failure suggests that stiffness degradation and internal damage



evolution precede macroscopic structural collapse, enabling the detection of early-stage structural changes that may be difficult to identify using conventional displacement-based monitoring approaches. This observation is consistent with the findings of Colombero et al. (2021), who demonstrated that water infiltration can induce stiffness reduction and decreases in relative seismic velocity, further indicating that negative  $dv/v$  variations fundamentally reflect changes in structural integrity and stiffness degradation of the medium.

Overall,  $dv/v$  primarily characterizes the temporal evolution of internal stiffness and structural integrity within the unstable rock mass and can therefore be regarded as a key geophysical parameter linking hydraulic degradation, mechanical weakening, and macroscopic instability. This study suggests that  $dv/v$  does not directly represent the rockfall event itself, but rather the progressive evolution of internal damage states within the unstable rock mass; the observed rockfall represents the external manifestation after this evolutionary process exceeds a critical threshold. This perspective extends the conventional interpretation of  $dv/v$  as a response indicator of rockfall activity and provides a theoretical basis for internal damage monitoring and physically constrained identification of rockfall precursors using ambient seismic noise interferometry.

### 5.3 A unified hydro-mechanical-seismic framework for the five-stage evolution of rockfall instability

The results of this study demonstrate that the five evolutionary stages of unstable rock mass development, including the baseline stage, precursory fluctuation stage, instability stage, recovery stage, and re-equilibration stage, are not empirically defined based on a single monitoring indicator. Instead, these stages are consistently identified from multiple observations, including relative seismic velocity variations ( $dv/v$ ), hydro-mechanical parameters, and the factor of safety ( $F_s$ ). The different monitoring parameters exhibit strong temporal correspondence during stage transitions, indicating that the five-stage evolution model represents an intrinsic characteristic of multi-field coupled evolution within the unstable rock mass rather than the response behavior of an individual monitoring parameter.

The integrated monitoring results further reveal that rainfall infiltration continuously modifies the internal hydraulic conditions of the unstable rock mass, inducing hydraulic degradation and progressive stability reduction, accompanied by structural deterioration and continuous accumulation of internal damage. Once the accumulated damage exceeds a critical threshold, overall instability occurs. Although  $dv/v$ , hydro-mechanical parameters, and  $F_s$  characterize variations in structural properties, hydrological conditions, and mechanical states, respectively, their evolutionary trends exhibit highly consistent stage-dependent patterns. This consistency indicates that these parameters collectively capture the progressive evolution of internal damage within the unstable rock mass and reveal the coupled interactions among hydraulic processes, mechanical responses, and geophysical signatures.

These findings further suggest that rockfall hazards are not instantaneous failures triggered by a single external factor, but rather progressive instability processes driven by continuous internal damage accumulation under coupled hydro-mechanical-seismic effects. The proposed five-stage evolution model provides a unified interpretation of the interactions among rainfall forcing, hydraulic degradation, mechanical weakening, and structural evolution of the rock mass. Furthermore, it establishes a physical linkage between internal damage states and multi-source monitoring responses,



475 extending rockfall monitoring from conventional event detection toward continuous observation of internal state evolution.  
This framework provides a new physical basis for developing process-oriented monitoring and early-warning approaches  
based on multi-source data integration and damage evolution mechanisms.

#### 5.4 From event detection to process-oriented early warning: implications of the five-stage evolution model

The five-stage evolution model proposed in this study provides a new theoretical framework for establishing a  
480 process-oriented monitoring and early-warning system based on internal damage state evolution. Compared with  
conventional empirical criteria based on single indicators, such as rainfall thresholds, displacement rates, or event frequency,  
this framework takes internal damage evolution as the primary pathway and characterizes the progressive stability changes  
of unstable rock masses through the coupled variations of hydraulic, mechanical, and geophysical parameters. This provides  
a physically based foundation for multi-source data integration and hierarchical early-warning strategies.

485 Among the five stages, the precursory fluctuation stage shows potential as an operational window for early-warning  
initiation, while the recovery and re-equilibration stages may provide valuable information for post-failure stability  
assessment and secondary hazard monitoring. However, it should be noted that the proposed five-stage evolution model was  
established based on a representative case study, and its applicability under different geological conditions, as well as the  
critical thresholds of key parameters, require further validation using long-term continuous monitoring datasets.

490 Future studies should integrate physically constrained machine learning approaches and digital twin technologies to establish  
quantitative relationships between internal damage states and failure probabilities. Such developments may facilitate the  
transition of rockfall hazard monitoring from conventional event detection toward process-based monitoring and risk  
prediction.

#### 6 Conclusions

495 Based on the integrated analysis of multi-source monitoring data from the post-earthquake Mogangling high-elevation  
rockfall site, this study revealed the hydro-mechanical-seismic coupling mechanism governing rainfall-induced progressive  
instability of unstable rock masses and established a five-stage failure evolution model based on internal damage evolution.  
The main conclusions are summarized as follows:

(1) Continuous ambient seismic noise monitoring combined with the STA/LTA automatic detection method enabled efficient  
500 identification and dynamic classification of rockfall events. A total of 329 rockfall events were detected and classified into  
three categories: single-trigger events, short-duration event clusters, and continuous rockfall sequences. Although rockfall  
activity was generally associated with rainfall processes, the event occurrence exhibited pronounced nonlinear, staged, and  
time-lagged responses, indicating that rainfall primarily influences rockfall activity by regulating the evolution of internal  
hydro-mechanical conditions rather than acting as a direct failure trigger.



505 (2) Relative seismic velocity variations ( $dv/v$ ) obtained from ambient seismic noise interferometry effectively captured the temporal evolution of internal structure and stiffness within the unstable rock mass. The results demonstrate that  $dv/v$  detected precursory anomalies approximately 2 h before failure, associated with progressive microcrack development and internal damage accumulation, and exhibited an abrupt decrease of approximately 3 % at the failure moment, reflecting rapid structural degradation. The evolution of the unstable rock mass was further divided into five stages: the baseline stage, precursory fluctuation stage, instability stage, recovery stage, and re-equilibration stage. The  $dv/v$  time series successfully captured the entire process from damage initiation and accumulation to final failure and post-failure structural adjustment, demonstrating that  $dv/v$  primarily reflects the evolution of internal stability and damage state rather than the rockfall event itself.

515 (3) Multi-source observations revealed the hydro-mechanical-seismic coupling mechanism underlying rainfall-induced rockfall instability. Rainfall infiltration increased effective saturation and reduced matric suction and suction stress, resulting in progressive degradation of rock mass stability and continuous accumulation of internal damage. This process establishes a progressive failure chain of “rainfall infiltration - hydraulic degradation - stability reduction - damage accumulation - instability failure”, highlighting hydraulic processes as the critical link connecting rainfall forcing, mechanical weakening, and geophysical responses.

520 (4) The proposed five-stage evolution model was consistently supported by multiple monitoring indicators, including effective saturation, matric suction, suction stress, factor of safety ( $F_s$ ), and  $dv/v$ . This model provides a unified interpretation of the coupled hydraulic, mechanical, and geophysical responses of unstable rock masses and establishes a physical linkage between progressive internal damage evolution and macroscopic failure. The results indicate that rainfall-induced rockfall is fundamentally a multi-field coupled evolutionary process driven by continuous damage accumulation beyond a critical threshold, rather than an instantaneous failure caused by a single external factor. This study provides a new physical framework for developing process-oriented monitoring and early-warning approaches based on internal damage evolution.

### Code and data availability

530 The datasets used in this study, including continuous seismic records, hydro-mechanical monitoring data, and field observations from the Mogangling rockfall monitoring site, are not publicly available because of confidentiality restrictions associated with the monitoring project. Following publication of this article, access to the data may be requested from the corresponding author and will be considered on a case-by-case basis, subject to approval by the data owners.

535 The custom codes developed for data processing and analysis, including the STA/LTA-based rockfall event detection workflow and the parameter configurations used for the  $dv/v$  calculations, are not publicly available at present. Following publication of this article, interested researchers may contact the corresponding author to request access to the relevant codes. Such requests will be considered according to their intended use and subject to applicable project restrictions. The  $dv/v$



analysis was implemented using the open-source SeisMIC package described by Makus and Sens-Schönfelder (2024), available at <https://doi.org/10.26443/seismica.v3i1.1099>.

### Author contributions

540 PC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. ZY: Conceptualization, Funding acquisition, Project administration, Supervision, Formal analysis, Writing – review and editing. ZH: Formal analysis, Investigation, Writing – review and editing. BP: Formal analysis, Investigation, Writing – review and editing. ZW: Formal analysis, Investigation, Writing – original draft. All authors contributed to the interpretation of the results and approved the final version of the manuscript.

### 545 Competing interests

The contact author has declared that none of the authors has any competing interests.

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