
**Real-time Monitoring and Analysis of Debris Flow Events: Insight
from seismic signal characteristics**

**Reconstruction of the Wenchuan debris flow process in August, 2022
by in-situ monitoring and analysis of seismic signals**

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Abstract

~~Debris flows triggered by rainfall are among the world's most dangerous natural hazards due to their abrupt onset, rapid movement, and large boulder loads that can cause significant loss of life and infrastructure. Monitoring and early warning are key strategies for mitigating debris flows. However, deploying large instruments for continuous monitoring in challenging terrains like Wenchuan, China, is difficult due to complex topography and limited access to electricity and batteries. Recognizing the effectiveness of environmental seismology in monitoring geohazards, our study aims to establish a cost-effective, reliable, and practical debris flow monitoring system based on seismic monitoring in Wenchuan, China. We analyzed seismic signals and infrared images to determine debris flow characteristics and behavior. Through a case study in Fotangba Gully, we demonstrated how seismic signals can be used to track debris flow duration and confirm rainfall as the trigger. Using the cross-correlation function, we calculated the maximum velocity of the debris flow and validated it with the Manning formula. Our analysis of infrared imagery and power spectral density showed a strong correlation between debris flow seismic energy and its frequency spectrum, supporting the accuracy of using seismic signals to reconstruct debris flow events. This study provides a foundation for real-time monitoring, analysis, early warning, and hazard assessment in debris flow monitoring systems based on seismic signals.~~

Rainfall-induced debris flows are highly destructive due to their abrupt onset, rapid movement, and high sediment transport capacity, all of which can lead to significant loss of life and damage to infrastructure. However, a comprehensive analysis of their dynamic evolution remains limited by the scarcity of in-situ monitoring data. In this study, we utilized near-field seismic data recorded by acquisition instruments deployed in Wenchuan, China, combined with images and post-event field investigations to reconstruct the second debris flow event in Fotangba Gully. Seismic signal attenuation was compensated, and time-frequency analysis and power spectral density (PSD)

calculations were conducted. The results reveal pronounced differences in signal amplitude and frequency content across stations, reflecting spatial heterogeneity in flow dynamics. We identified flow velocity and grain concentration as the dominant factors affecting the PSD curves. This research provides a framework for extracting debris flow kinematics characteristics from seismic signals and offers new insights for hazard evaluation and the design of mitigation strategies.

Keywords: Debris flow seismic; Reconstruction; Kinematic characteristics; Wenchuan (China)

Highlights:

- ~~• Real time monitoring of debris flow kinematics based on seismic signals.~~
- ~~• Extraction of debris flow characteristics (e.g., peak velocity) over space/time.~~
- ~~• Provides a framework for upscaling debris flow monitoring networks.~~
- By analyzing the characteristics of seismic signals, the study successfully reconstructed the entire process of the second debris flow event at Futangba Gully by utilizing features such as the time series, flow velocity, particle characteristics, and surge variations of the debris flow.
- The seismic signal characteristics of the debris flow showed rapid excitation and slow attenuation. Even after removing propagation effects, significant differences in amplitude and frequency were observed at different observation stations, indicating changes in the dynamic parameters of the debris flow.
- The time-frequency characteristics of seismic signals reflect the evolution process of debris flows, with a corresponding relationship between the power spectral density and debris flow characteristics.

1 Introduction

~~Landslides involve the movement of rock and soil on slopes, slipping along shear surfaces (Yan et al., 2020). In contrast, debris~~ Debris flows are solid-fluid mixtures that can create destructive surges during heavy rainfall (Iverson, 1997). Recent incidents include a debris flow in Zhouqu County, China, on August 7, 2010, which caused 1,765 deaths and damaged over 5,500 homes (Tang et al., 2011), and another in Montecito, California, on January 9, 2018, resulting in 189 casualties and damage to 408 houses (Kean et al., 2019). ~~Due to the high risk associated with debris flows, there is significant interest in disaster reduction measures, particularly seismic and flow depth monitoring systems. On-site monitoring is crucial for understanding the triggers of debris flows, such as rainfall, and for gathering key data like flow depth and velocity, which are essential for effective warning systems (Teece et al.,~~ Given the significant potential for disaster, measures to mitigate debris flows have attracted considerable attention. Existing methods for reducing debris flows include monitoring and early warning systems, risk assessment, and technical control technologies (Chen et al., 2015; Hürlimann et al., 2019; Chang et al., 2020). However, due to the complexity of debris flow dynamics and the incomplete understanding of the triggering mechanisms, these measures have certain limitations. For example, monitoring and early warning systems can trigger false alarms or overlook warnings, risk warnings can be inaccurate, and technical control measures can be either oversized or ineffective, leading to a waste of resources. Therefore, clarifying the complex process characteristics of debris flows is crucial to provide effective references for disaster management measures. ~~2003; Suwa et al., 2009; Hürlimann et al., 2019).~~

Current research on debris flow processes is primarily based on laboratory experiments, in situ monitoring, and field investigations (Marchi et al., 2002; Iverson, 2015; Hürlimann et al., 2019; Yang et al., 2021; He et al., 2022; Zhang et al., 2022). Although laboratory experiments allow various parameters (flow rate, slope, and

material composition) to be controlled in order to simulate different debris flow movements and investigate their dynamic properties, they are limited by spatial and technical constraints (Yan et al., 2025). Therefore, these experiments cannot fully replicate the complexity and variability of natural environments, making it difficult to accurately reflect the actual dynamic processes of debris flows in the field. Field investigations of debris flows consist of pre- and post-event investigations. Pre-event investigations are primarily used to assess debris flow risk, while post-event investigations provide valuable first-hand data to understand the specific impacts of the disaster, assess damage, analyze the extent and movement of debris flows, and investigate the underlying mechanisms of their occurrence. Field investigation methods include drone surveys, remote sensing images, and field investigation (Crowley et al., 2003; Liang et al., 2022; Turbessi et al., 2025). However, field investigations rely primarily on comparing traces before and after the debris flow to draw conclusions about the movement process. This requires preliminary investigations and, in addition, the disaster site must remain undisturbed after the event. Since debris flows occur suddenly and are often hidden, it is difficult to ensure that investigations were carried out before the event. Furthermore, without continuous data collection throughout the debris flow, there are no reliable data sets to validate the derived results, making it crucial to collect comprehensive data on the entire debris flow process. On-site monitoring plays a crucial role in understanding the triggering factors of debris flows (precipitation) and collecting important data (flow depth and velocity). This data is essential for clarifying and reconstructing the entire movement process of debris flows (Tecca et al., 2003; Suwa et al., 2009; Hürlimann et al., 2019).~~Current monitoring and early warning systems focus on factors that trigger and evolve debris flows, primarily rainfall, with early warning thresholds based on rainfall intensity or duration (Chien-Yuan et al., 2005; Chen et al., 2007; Hürlimann et al., 2014, 2019; Cui et al., 2018; Liu et al., 2021). Hürlimann et al. (2014) suggest using a combination of average rainfall~~

~~intensity and duration to define thresholds. Cui et al. (2018) proposed a method to differentiate debris flows from floods based on rainfall data. However, relying on historical rather than real-time rainfall data complicates threshold determination and reduces the transferability of these systems.~~

~~Alternative approaches use flow velocity and depth as primary indicators for monitoring and early warning (Marchi et al., 2002; Kogelnig et al., 2014; Hürlimann et al., 2019). These measurements can be combined with section geometry to estimate discharge and analyze characteristics like grain size (Arattano and Marchi, 2008; Hürlimann et al., 2019). Radar and ultrasonic instruments effectively measure flow depth and velocity (Arattano and Moia, 1999; Kogelnig et al., 2014), allowing for easy determination of early warning thresholds. However, installing ultrasonic sensors above channels can be challenging. Berti et al. (2000) noted changes in hydrological characteristics over time in Acquabona Creek, while Hürlimann et al. (2003) observed varying properties among different debris flows in the Swiss Alps, showcasing the effectiveness of ultrasonic and radar devices for monitoring.~~

~~It is critical to assess sites for monitoring systems in advance to ensure proper instrumentation. A~~

Existing monitoring methods mainly involve installing instruments in debris flow channels to monitor hydrological parameters, such as water flow and water level, a variety of instruments, including infrasound sensors (Marchetti et al., 2019), LiDAR (Aaron et al., 2023), fiber optic sensors (Huang et al., 2012; Schenato and Pasuto, 2021), pressure sensors (Berti et al., 2000; Kean et al., 2012), and stress sensors (McArdell et al., 2007; McCoy et al., 2010; Nagl and Hübl, 2017), are increasingly utilized to capture a wide array of parameters. However, existing monitoring methods face challenges when it comes to collecting comprehensive data throughout the entire debris flow process. They require accurate identification of debris flows and the prior installation of monitoring instruments, as well as ensuring that these instruments remain intact

during the debris flow. The sudden occurrence and violent impact of debris flows can damage nearby monitoring equipment and make data collection difficult. In addition, some existing methods for monitoring debris flows are limited to collecting data from a specific cross-section rather than providing continuous data for the entire debris flow process. Belli et al. (2022) found that physical parameters of debris flows correlate positively with seismic signal amplitudes. However, the sudden and intense nature of debris flow surges can damage close-range monitoring instruments, complicating data collection.

New monitoring methods are urgently needed to enhance debris flow monitoring, and recent advancements in environmental seismology provide a promising approach (Hibert et al., 2011; Moretti et al., 2012; Ekström and Stark, 2013; Barrière et al., 2015; Dammeier et al., 2016; Cook and Dietze, 2022). This field can detect ground vibrations from natural hazards as seismic signals, which In order to gain a more comprehensive understanding of the entire debris flow process and to collect more accurate and comprehensive data, it is essential to improve the monitoring capabilities for debris flows. There is an urgent need to develop new monitoring methods. Environmental seismology have been applied to monitor various geological events, including landslides (Li et al., 2017; Fuchs et al., 2018), rockfalls (Deparis et al., 2008; Vilajosana et al., 2008), avalanches (Schneider et al., 2010; Van Herwijnen and Schweizer, 2011), as well as debris flow (Arattano, 1999; Burtin et al., 2009; Schimmel and Hübl, 2016; Walter et al., 2017; Lai et al., 2018). The main benefits of environmental seismology are long-distance monitoring capabilities and detailed event dynamics (Arattano and Marchi, 2008; Hübl et al., 2013; Kogelnig et al., 2014). Belli et al. (2022) found that physical parameters (front velocity, maximum flow depth and density) of debris flows correlate positively with seismic signal amplitudes. Seismic monitoring can capture detailed event evolution, vital for analyzing movement debris flow characteristics and issuing warnings. Walter et al. (2017) successfully detected a debris flow half an hour

before it reached a critical point, while Lai et al. (2018) proposed a method for calculating flow velocity and distance from seismic signal characteristics. Farin et al. (2019) introduced a model for estimating parameters related to debris flow dynamics, and Andrade et al. (2022) found a linear relationship between seismic signal amplitude and debris flow rate. ~~Ongoing research focuses on event timing, location, parameter evolution, and detection to improve early warning systems (Schimmel and Hübl, 2016; Lai et al., 2018; Beason et al., 2021; Andrade et al., 2022; Schimmel et al., 2022).~~

However, high-frequency seismic signals from debris flows are challenging to detect due to their rapid attenuation and short propagation distances. These signals are often only recorded by close-range instruments (Zhang, 2021). ~~For instance, the Zhouqu debris flow's high-frequency signals were captured by nearby seismic stations (Huang et al., 2020). Near-field stations can provide detailed information on debris flow events, while far-field stations offer a broader overview (Cook and Dietze, 2021a, b). 2022). Remote monitoring primarily relies on low-frequency seismic signals, which are less attenuated over distance and provide a better signal-to-noise ratio (Huang et al., 2008; Cook et al., 2021).~~ Unlike landslides, debris flows lack significant low-frequency features in seismic signals, making remote monitoring impractical. Understanding debris flow seismic signals and their ~~development~~source processes is still limited, but near-field seismic monitoring offers more detailed insights, enhancing event analysis. Therefore, near-field monitoring is the preferred method. Current research on debris flows focuses on the timing, localization, parameter development, and detection of events with the aim of analyzing the entire debris flow process and providing references for debris flow hazard mitigation and early warning systems (Schimmel and Hübl, 2016; Lai et al., 2018; Beason et al., 2021; Andrade et al., 2022; Schimmel et al., 2022). The generation of debris flow seismic signals is closely related to the forces acting on the riverbed by the debris flow. Existing physical models of debris flow seismic sources are mainly derived from the theory of river transport and the theory of particle impact

on the bed, and are closely related to the base forces acting on the riverbed (Tsai et al., 2012; Burtin et al., 2014; Farin et al., 2019; Zhang et al., 2021). However, since the particle impact on the riverbed during debris flow movement is extremely complex, there is currently no universally applicable debris flow seismic source model. Lai et al. (2018) suggested that high-frequency seismic signals from debris flows are closely related to the area of the head zone, the particle size contained in the debris flow, and the average flow velocity of the head zone. However, this model also assumes vertical particle impacts on the ground, neglecting the influence of channel shape and topographic variations on the particle impact angle. Kean et al. (2015) found that the sediment cover on the debris flow bed strongly suppresses ground vibrations. Belli et al. (2025) proposed that, in addition to particle collisions, turbulence also radiates seismic waves within the debris flow.

~~Debris flows usually occur in mountainous regions (Tang et al., 2011), such as Er Gully (Guo et al., 2016; Cui et al., 2018), where transportation is limited, complicating the installation of monitoring equipment. These areas often lack electricity, making battery-powered instruments necessary, which is challenging in remote locations. Solar energy could help address these electricity shortages, but inadequate sunlight in mountainous areas may hinder the operation of high-power monitoring devices. Thus, there is an urgent need to explore affordable, reliable, and convenient methods for effective debris flow monitoring.~~

~~As for characteristics of debris flow in the western part of China, we designed a near field debris flow monitoring system, which is comprised of seismic equipment, rainfall gauge, and infrared camera, and monitored three debris flows on August 19, 2022, in the Wenchuan Earthquake area of China. Then, we do a comprehensive analysis of recovered seismic data, infrared imagery, post-event field investigation, and rainfall data and gain semi-quantitative data on the debris flow. The study offers a framework for establishing debris flow monitoring and semi-quantitative analysis~~

~~based on seismic signals. It introduces a cost-effective, dependable, and convenient approach for monitoring debris flows in intricate mountainous terrains.~~

Although the debris flow seismic source model is not yet fully understood, experimental results from Allstadt et al. (2020) demonstrated that high-frequency seismic signals from debris flows can reflect overall movement characteristics, such as flow depth, gravity, density, momentum, and kinetic energy. The seismic signals generated during the debris flow process contain rich information about debris flow parameters (e.g., flow depth, particle size, flow velocity). Therefore, using seismic signals to reconstruct the debris flow process is a reliable method.

This study is based on the characteristics of debris flows in the Wenchuan region of China and uses a near-field debris flow observation system consisting of seismic instruments, rain gauges, and infrared cameras. We collected data on three debris flows that occurred in Wenchuan on August 19, 2022. The data collected during these debris flows were then analyzed. First, we investigated the time-frequency characteristics of the seismic signals of the Wenchuan debris flows by short-time Fourier transform (STFT) and power spectral density (PSD). We also used the cross-correlation algorithm to compute the average velocity of debris flow. Subsequently, relevant motion parameters of the debris flow process were extracted from the seismic signals and combined with video and field investigation data to reconstruct the entire debris flow process.

2 Study site and field ~~monitoring~~observation system

2.1 Study area

The study area is located in Wenchuan County, Sichuan Province, China (Figure Fig. 1), characterized by north-northeast trending mountains divided by the Minjiang River and its tributaries. This region, formed by tectonic uplift and river erosion, features undulating terrain, ravines, and steep slopes. River gradients range from 5° to 30°, while hillslope gradients range from 25° to 50°. The climate is humid,

with annual rainfall between 800-1200 mm (Guo et al., 2016). The area experiences frequent seismic activity, and signs of the May 12, 2008 Wenchuan Earthquake are still evident, with loose rocks and soils providing abundant sediment for debris flows (Zhang et al., 2023). This study focuses on the Er and Fotangba Gullies in the Minjiang River Basin, which has experienced numerous debris flow events in recent years, yearly frequency ranges from 0.17 to 2.67, threatening nearby villages, roads, and hydropower stations (Guo et al. (2016)). Notable incidents include 17 documented events by Guo et al. (2016), as well as specific events like the debris flow in Er Gully on July 10, 2013 (Guo et al., 2016), in Fotangba on the same date (Cao et al., 2019), and another in Er Gully on July 5, 2016 (Cui et al., 2018).

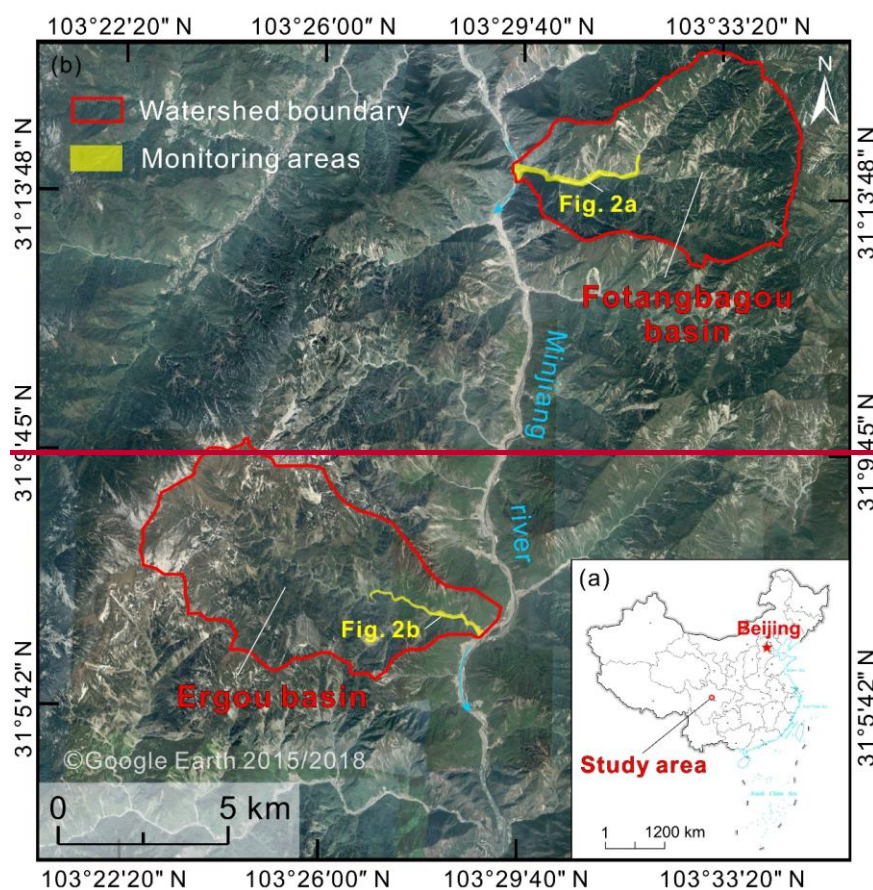


Figure 1 Overview of the study area. (a) Location of the study area within China; (b)

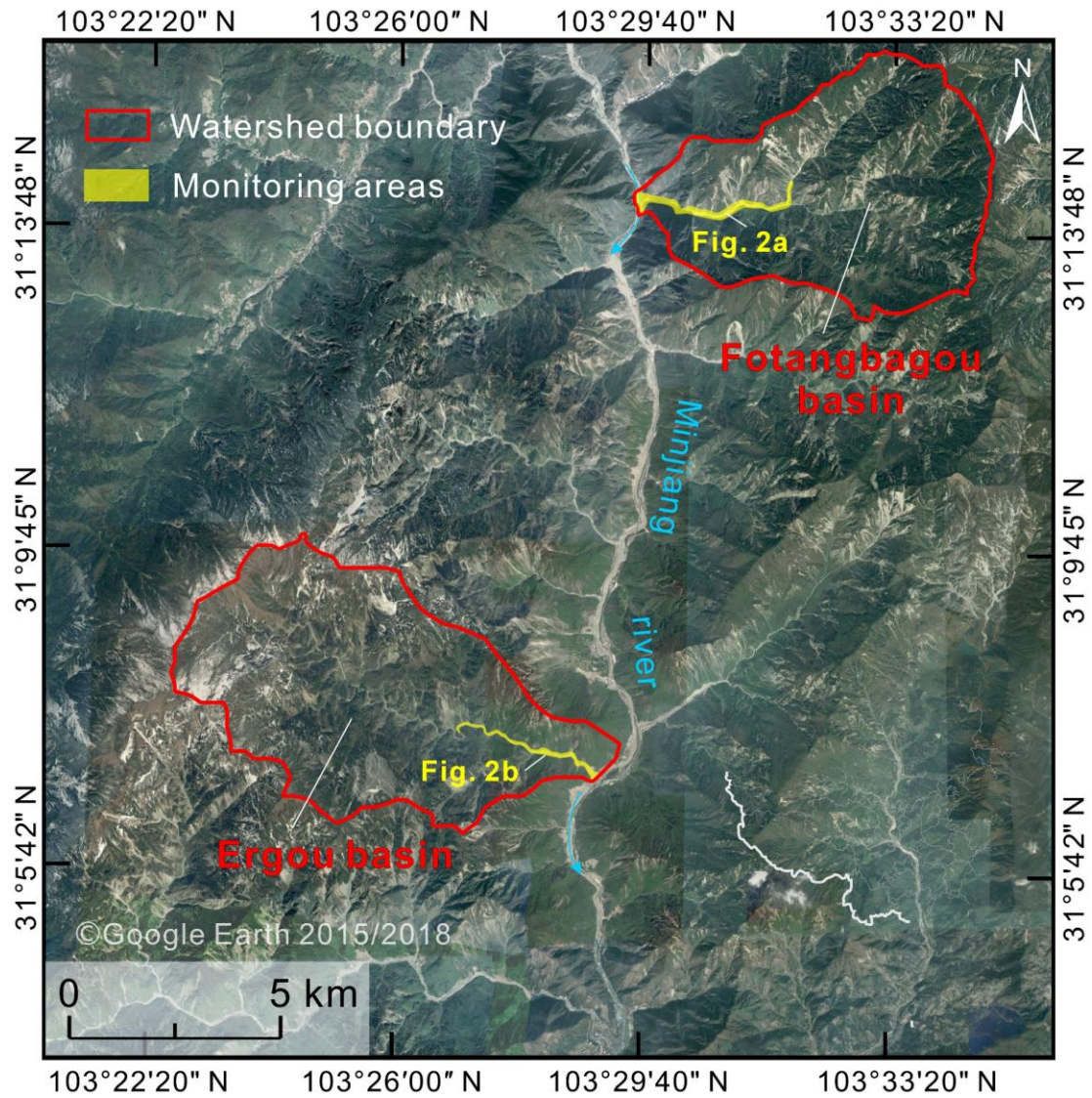


Fig. 1. The two study catchments, Er and Fotangba Gullies, on the Minjiang River, Wenchuan, Sichuan, China.

Er Gully drains an area of 39.4 km² and is about 6 km from the epicenter of the Wenchuan Earthquake; it ranges in altitude from 930 to 4120 m, has a channel length of about 12 km, an average slope of about 12° (Guo et al., 2016). The Fotangba Gully basin has an area of 33.6 km²; it ranges in altitude from 1117 to 3462 m, has a channel length of about 9.78 km, with an average slope of 6.1°, and has bank slopes of 25° to 45° (Cao et al., 2019). , and a debris flow transportation area of between 5 to 12° (Guo et al., 2016). The Gully is located on the right bank of the Minjiang River and drains west to east, with steep walls, a narrow and winding channel, and abundant water

sources. The average slope is 10.5° . Important nearby infrastructure at risk includes a factory at the end of the Gully, a village on the left bank of the Minjiang River facing the Gully mouth, and national highway G213 adjacent to the bank.

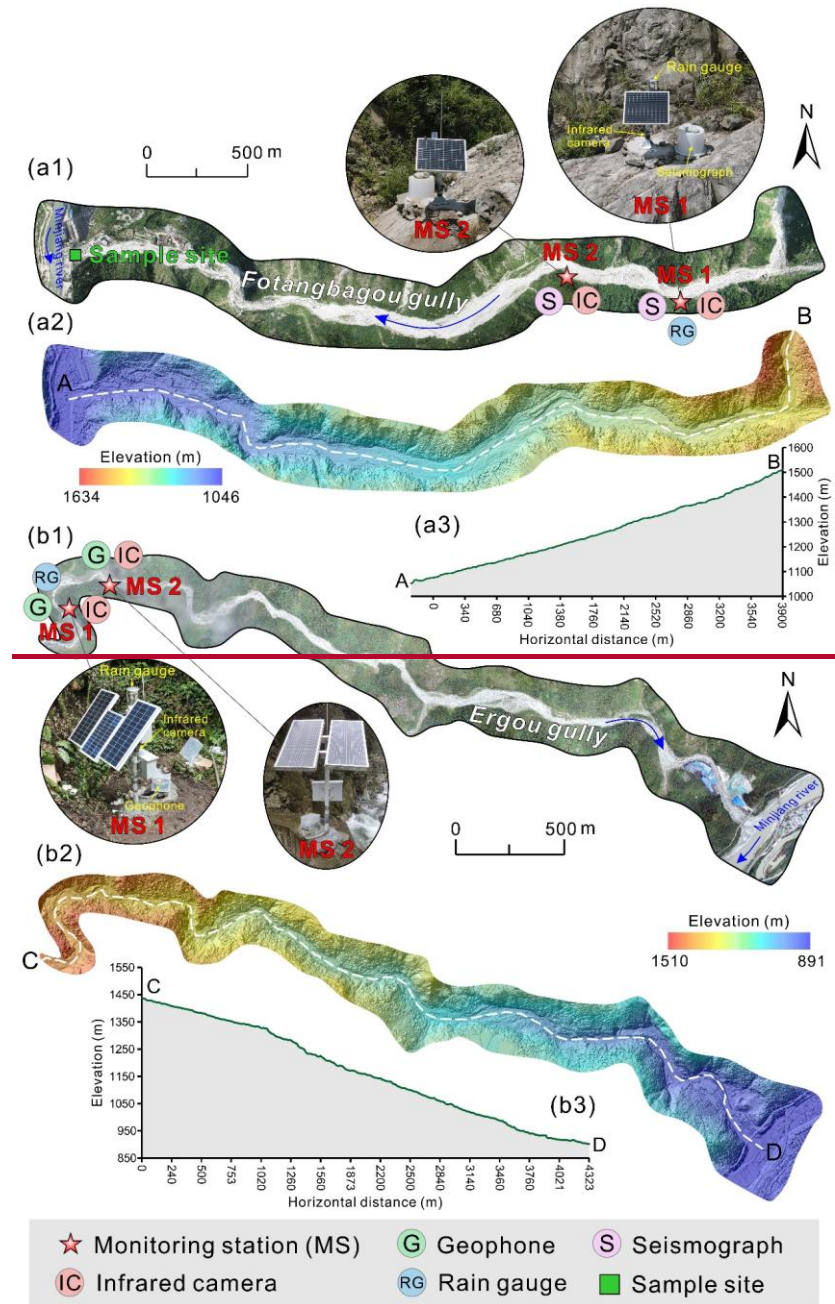
The Fotangba Gully basin has an area of 33.6 km^2 ; it ranges in altitude from 1117–3462 m, has a channel length of about 9.78 km, and has bank slopes of 25° – 45° (Cao et al., 2019). The Gully is on the left bank of the Minjiang River and drains east to west. The Gully has abundant water sources, with steep walls and a wide and gently winding channel. The average slope is 6.1° . There are hydropower stations on the Minjiang River near the Gully and on the north side of the Gully mouth.

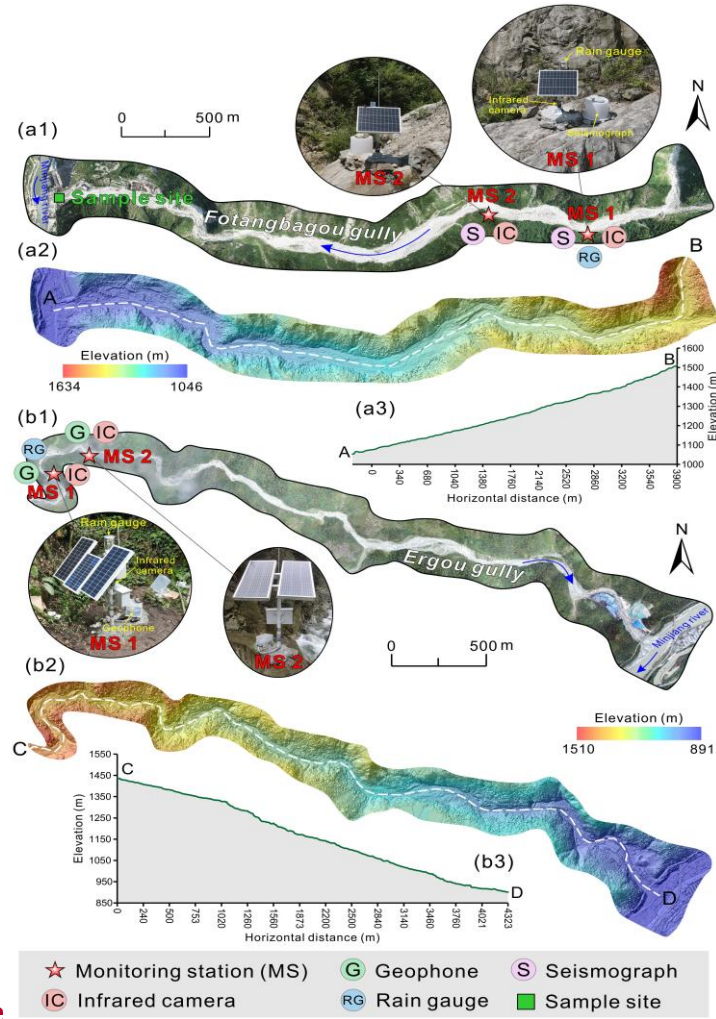
2.2 Monitoring Observation systems

We have developed installed a near-field debris flow monitoring observation system with locations along the debris flow channels with unobstructed views. The system includes seismic monitoring devices, infrared cameras, and precipitation rain gauges. This system provides a cost-effective, reliable, and practical solution for debris flow monitoring. It primarily utilizes seismic signals and infrared camera images. The main function of the system is to comprehensively monitor the debris flow process through seismic signals and infrared camera images, while precipitation the rain gauges provide real-time precipitation data. Infrared cameras with 5-min interval shooting have a lower electric power consumption than infrared videos with better infrared monitoring range and higher resolution, which is available in our study area. Infrared cameras are cheap, plus solar energy about \$ 78, and Hikvision's infrared video camera plus solar energy about \$ 425. Hikvision's infrared video camera (Type: DS-2CD3T46WDV3-L) exhibits high power consumption. The power generated by the solar panel is only sufficient to sustain continuous video monitoring for approximately 74 hours. Infrared cameras, which are equipped with solar cells and eight 1.5-volt dry batteries, can provide continuous monitoring for up to 18 months.

This near field debris flow monitoring system is well suited for complex

~~mountainous regions with little sunlight and difficult power supply conditions. The~~
~~placement of the instruments requires the selection of unobstructed locations along the~~
~~banks of the canyon to ensure a wide field of view~~The Fotangba Gully observation
stations 1 and 2 are located 3,260 meters and 2,740 meters from the canyon entrance,
respectively, while the ~~seismic monitoring equipment should be installed on stable~~
~~bedrock or on poured concrete piers to ensure sufficient solar power supply, wide video~~
~~recording angles, and accurate seismic data. Wenchuan has an average annual sunshine~~
~~duration of around 1693.9 to 1042.2 hours (Huang et al., 2018). The monitoring~~
~~instruments~~Er Gully Observation stations 1 and 2 are located 4,130 meters and 3,670
meters from the entrance (Table 1, Fig. 2). The distance between the two monitoring
stations in Fotangba Gully and Er Gully is 520 meters and 460 meters, respectively.
Both monitoring stations are installed on rocky platforms on the left bank of the river.
The two observation stations in Fotangba Gully are ~~installed on the left bank of~~located
approximately 20 meters and 15 meters from the centerline of the river. However, due
to the lack of a network signal, real-time transmission of the recorded data via the
~~channel, which is about 90 meters wide and has a left-sided slope of about 40 degrees.~~
~~According to rough estimates on site, Internet/GSM is not possible. The seismic~~
monitoring devices operate at a sampling frequency of 100 Hz, and the ~~daily solar~~
~~radiation in summer is about 6 hours. The earthquake monitoring system was in~~
~~continuous operation at most from July 2023 to March 2024, which corresponds to a~~
~~monitoring period of 9 months. In other, relatively narrow gullies, the daily solar~~
~~radiation in summer is around 4 to 5 hours, and the seismic monitoring system is~~
~~monitored continuously for at least 4 months in each case~~infrared cameras are set to
take images every 5 minutes. The specific parameters are listed in Table 1.





Figure

Fig. 2. Schematic overview of monitoring observation network layout in the two study catchments. (a) Fotangba Gully: (a1) drone aerial photography, (a2) Digital Terrain Model map, (a3) longitudinal profile; (b) Er Gully: (b1) drone aerial photography, (b2) Digital Terrain Model map, (b3) longitudinal profile. See Figure 1 for Gully locations.

The monitoring system has been implemented in multiple Gullies in Wenchuan County, China, including Fotangba Gully, Er Gully, and Mozi Gully, and successfully recorded debris flow events. Two monitoring stations were established in both Fotangba and Er gullies. In Fotangba, Station 1 is 3,260 meters from the valley entrance, while Station 1 in Er Gully is 4,130 meters from the entrance (Table 1, Figure 2). The distance between the two monitoring stations in Fotangba Gorge is about 520 meters, with both

stations installed on platforms on the left bank of the channel, about 20 meters from the middle of the channel, where they are located on exposed rock. In the Er Gully Gorge, which is about 460 meters long, the measuring stations are installed on platforms on the right bank slope, about 15 meters from the middle of the channel. All data is recorded in real time; however, due to the lack of a network signal, data transmission via the Internet/GSM is not possible. The seismic monitoring equipment operates at a sampling frequency of 100 Hz, while the infrared cameras are set to record at 5-minute intervals, with specific parameters listed in Table 1. This monitoring system captures seismic signals, images, and real-time precipitation data throughout the debris flow process and provides reliable data to support the reconstruction and dynamic analysis of debris flows.

Table 1 Instrument parameters for ~~monitoring~~ observation stations in the two study catchments.

Equipment	Instrument parameters	
	Fotangba Gully	Er Gully
Seismograph (NOISESCOPE)	Sampling rate 100 Hz Corner frequency not offered Power consumption: <3 Channel: Three components Sensor type: Capacitive force balance pendulum Dynamic range: Greater than 140 dB Bandwidth: 10 s - 50 Hz Sensitivity: 2000 V/(m/s)	—
Geophone (DATA-CUBE ³)	—	Sampling rate 100 Hz Corner frequency of 4.5–150 Hz Power consumption: 128mW Type: Delta-Sigma 24 Bit Channels: Three components Dynamic range: 125db @ 100sps (128db @ 50sps) Noise level: 10nV/sqrt (Hz) Input impedance:

		100kOhm
	Voltage sensitivity: 2000V • S/m	
	Normalized coefficient: 98696	
	Zero point: $z1=0.0+0.0i$	Logger: "Cube3ext",
Instrument	$z2=0.0+0.0i$	Gain: 16
response	Main Pole: $p1=-0.444221-0.6565i$	(DATA-CUBE³ User
	$p2=-0.444221+0.6565i$	Manual)
	$p3=-222.110595-222.17759i$	
	$p4=-222.110595+222.17759i$	
Rain gauge	Record once per hour with a resolution of 0.2 mm	
Infrared camera	1 shot every 5 minutes at 2592×1944, 1920×1080 dpi resolution	
	during the day and at night	
	Continuous shooting: ≥18 months	

3 Methodology

~~Process and interpret debris flow seismic signals according to the steps in Figure 3 to extract information on the evolution of debris flow. Firstly, perform absorption attenuation compensation on the extracted debris flow seismic signals to restore energy loss caused by propagation differences and obtain debris flow seismic signals unaffected by sensor placement. Next, generate seismic spectrograms using the short-time Fourier transform to conduct characteristic analysis of debris flow evolution, and estimate the maximum velocity of debris flow through cross-correlation functions. Analyze the results using infrared imagery and on-site investigations. Finally, analyze the particle and flow velocity characteristics of debris flow by calculating the power spectral density of keyframes. The amplitude method is used to obtain the absolute value of time-domain amplitude, and the processed signal is referred to as a simplified signal (Arattano and Moia, 1999).~~

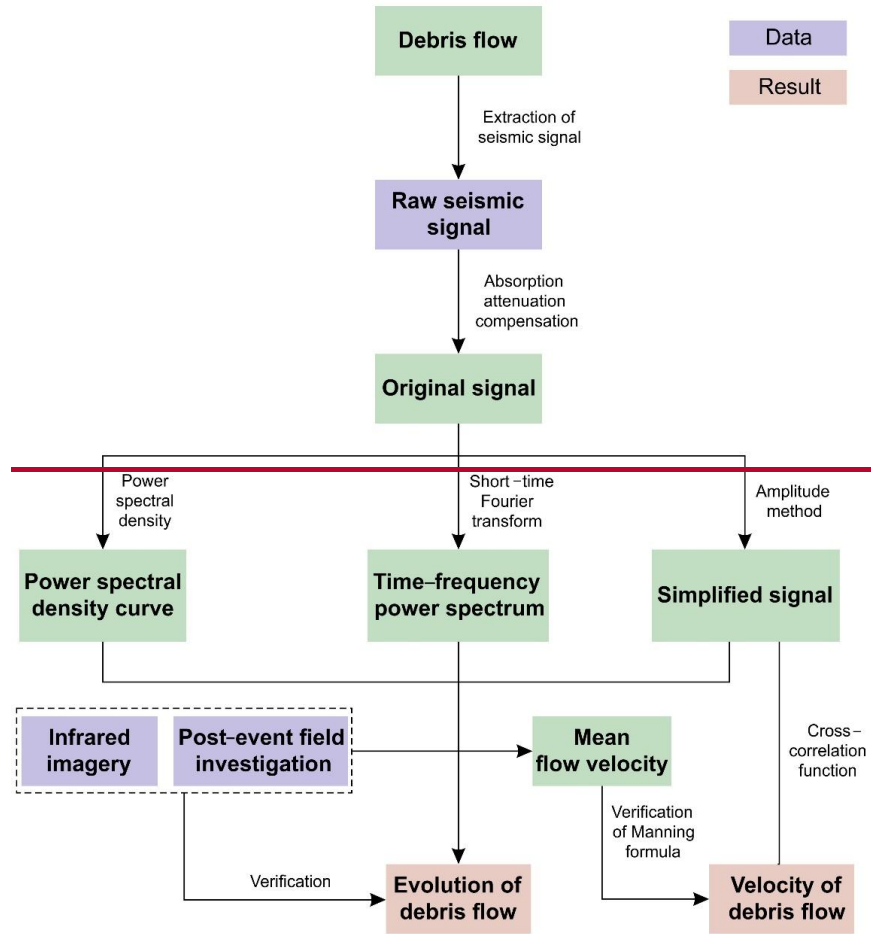


Figure With the aim to investigate to get the evolution of debris flow, we have designed the seismic signal processing and interpretation flow, as shown in Fig. 2. The power spectral density, time-frequency spectrum and simplified signal of the debris flow seismic signals by the compensated seismic data record by in-situ monitoring network in Fig. 2. The infrared imagery, Manning formula velocity, and other post-event on-site investigations will be used to validate the debris flow evolution reconstructed from the seismic signals. To achieve this, we designed a research methodology, as shown in Fig. 3.

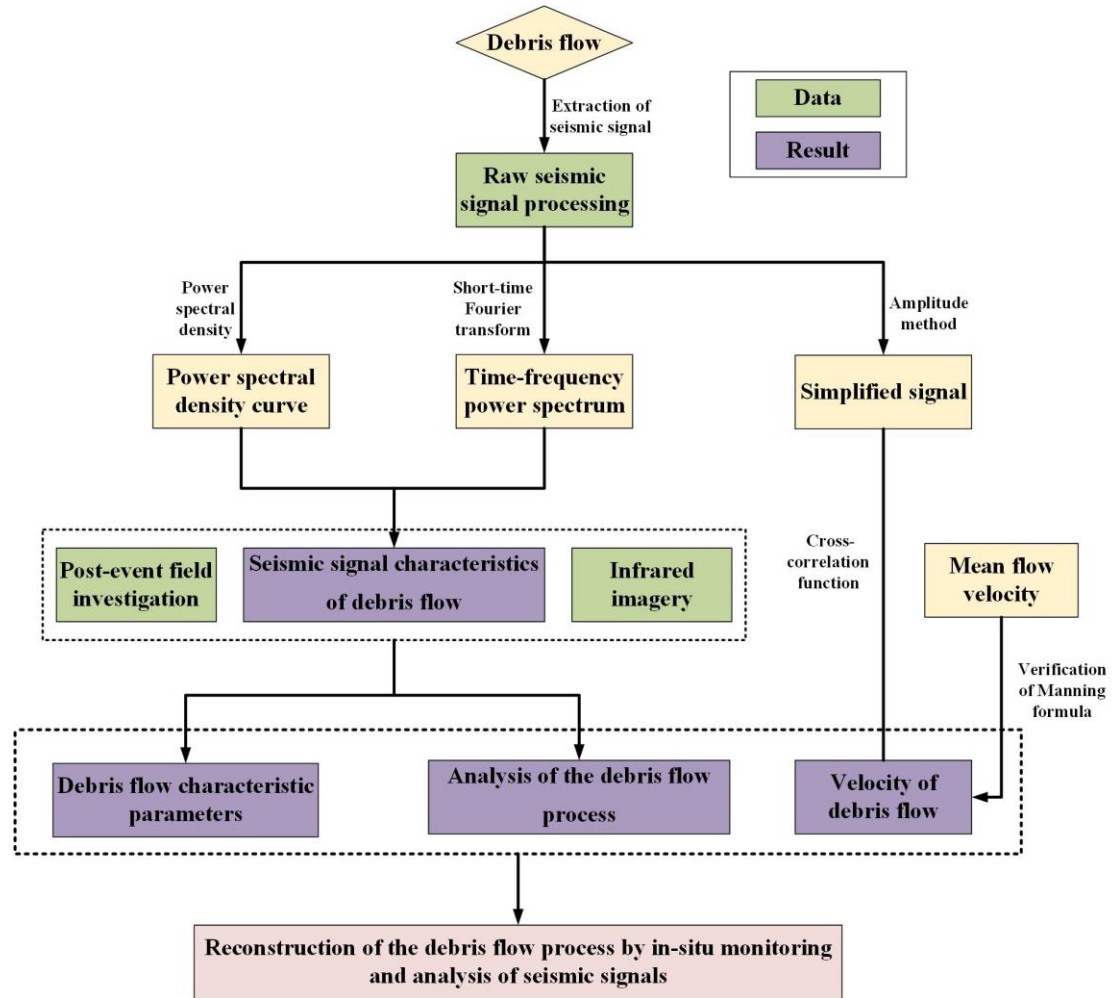


Fig. 3. Research methodology for processing and analysis of debris flow seismic signal.

3.1 Short-time fourier transform

The short-time Fourier transform (STFT, Eq. (1)) is used to analyze the time-frequency domain characteristics of the debris flow seismic signal (Yan et al., 2021, 2022, 2023). The method allows the time domain and frequency domain characteristics of the signal to be analyzed simultaneously:

Absorption attenuation compensation is first applied to the seismic signals of the debris flow to restore the different energy losses across frequencies. This helps to restore the original seismic excitation signals as far as possible so that the seismic signals more accurately reflect the changes in debris flow properties. The power spectral density (PSD) calculated from the compensated seismic signals is used to analyze the variations in the characteristic parameters of the debris flow based on the

PSD model for debris flows proposed by Lai et al. (2018). The time-frequency spectrum is used to roughly analyze the overall changes in debris flow characteristics and to establish a preliminary framework for PSD analysis of these changes.

In addition, infrared images and on-site investigations are used to perform quality control of the debris flow development process reconstructed from the PSD analysis and to validate the accuracy of the analysis. Finally, a simplified signal, the absolute value of the time domain amplitude (Arattano and Moia, 1999), is used to calculate the average flow velocity of the debris flow by cross-correlation, and the reliability of this result is verified using the Manning formula. Next, we will present some of our most important research methods in detail.

3.1 Power spectral density analysis

Tsai et al. (2012) developed a PSD model for sediment transport that links seismic signals with water turbulence, precipitation, and sediment transport in rivers. In their model, they considered the relationship between seismic signals and the transport of bedload in rivers. Tsai et al. (2012) adapted this model for debris flows by including absorption damping during the propagation process and established the PSD model for debris flows near the source shown in Eq. (1). This model links debris flow parameters such as length, particle size, width, velocity, and attenuation factors (due to absorption) as well as viscoelastic parameters during propagation with the seismic PSD of the debris flow.

$$X(t, \omega) = \sum_{m=-\infty}^{\infty} x(m)W(t-m)e^{-j\omega m}, \quad (1)$$

$$PSD \approx 1.9 \cdot LWD^3 u^3 \cdot \frac{f^{3+5\xi}}{v_c^5 r_0} e^{-\frac{8.8 f^{1+\xi} \eta}{v_c Q}},$$

where W is width of the channel, D represents the 94th centile of the grain size distribution, u represents debris flow velocity, f is frequency, v_c is Rayleigh wave phase velocity at 1 Hz, r_0 is distance between the monitoring station and channel, L is effective length of $L=r_0$, $\xi=0.4$ is a parameter related to how strongly seismic velocities increase

with depth at the site, and Q is an attenuation factor (Tsai et al., 2012; Lai et al., 2018). where debris flow seismic Power spectral density calculated by Eq. (2), which means the power per frequency for different frequencies in a specific period (Yan et al., 2020, 2022, 2023), and allows debris flow evolution to be analyzed from the seismic signal. The power of full band seismic is calculated by the short-time Fourier transform (STFT, Eq. 3), allowing getting the frequency domain characteristics of the signal versus time, which can help us to get the PSD changes versus the time.

$$PSD_{f_{\min} \sim f_{\max}}(t) = \frac{1}{(f_{\max} - f_{\min})} \times \sum_{f=f_{\min}}^{f_{\max}} X(t, f), \quad (2)$$

$$X(t, f) = \sum_{-\infty}^{\infty} x(m)W(t - m)e^{-j2\pi fm} \quad (3)$$

where f is the angular frequency, f_{\min} and f_{\max} represent minimum frequency and maximum frequency, respectively, t is time for the seismic signal, $X(t, f)$ represents the spectrogram based on STFT (Yan et al., 2017). x are time domain signals of time-frequency and time domain, W is the window function, m is the start time of the window function, ω is the angular frequency, e is a natural constant, t is time, and j is the imaginary number (Yan et al., 2021). A Hanning window length of 2056 and a time length of 20.56 s correspondingly is used. A built-in function “spectrogram” of MATLAB is used to achieve STFT directly from the software manual. The sampling rate is 100 Hz, so we choose 1 Hz and 50 Hz (i.e., a half of 100 Hz) as f_{\min} and f_{\max} .

3.2 Absorption attenuation compensation

During the actual propagation of seismic waves through geological layers, scattering and absorption attenuation effects occur, which means that the phase velocity and group velocity are different and the amplitude of the seismic waves is subject to varying degrees of attenuation. This phenomenon has been well documented and studied in many related works (Futterman, 1962; Strick, 1967). In this study, we use the constant Q model (Kjartansson, 1979) to describe the absorption attenuation in the actual geological layers, and we have established a 1D plane wave amplitude

attenuation equation for linear viscoelastic media (Eq. 4) to approximate the energy loss of seismic signals from debris flows during propagation. From this equation, it can be deduced that the amplitude of seismic waves is exponentially negatively correlated with both the propagation time and the frequency. In other words, as the propagation distance increases and the frequency rises, the amplitude of the seismic waves decreases significantly. This also explains why seismic signals from debris flows generally have lower frequencies when measured from greater distances.

$$h(t, f) = e^{-\frac{\pi f t}{Q} \left| \frac{\omega_0}{\omega} \right|^{\frac{2}{\pi} \arctan\left(\frac{1}{2Q}\right)}}, \quad (4)$$

where f is the frequency of the seismic signal, t is the spreading time (i.e., 0.02 s and 0.05 s) which is equal to distance r_0 between the monitoring station and channel divided by Rayleigh wave velocity v_c in Eq. (1), Q represents attenuation factor quantitatively depicting the absorption attenuation, and ω_0 and ω are reference angular velocity at 1 Hz ($\omega_0=2\pi$) and angular velocities, respectively.

Direct use of Eq. (4) to compensate for absorption attenuation results in significant attenuation in the high-frequency range, leading to a lower signal-to-noise ratio (SNR) and an excessively large amplitude compensation factor. This can cause the compensated amplitude to become too large and the SNR to be extremely low (Wang, 2002). In this study, we will use the gain control method proposed by Wang (2002) (Eq. 5) to maintain the stability of the high-frequency range. This method aims to improve the energy of the high-frequency range while keeping the overall SNR of the entire frequency band relatively controlled.

$$\Gamma(t, f) = \frac{h(t, f) + \sigma^2}{h^2(t, f) + \sigma^2}, \quad (5)$$

where σ is a constant named stability control factor, whose value comes from a numerical experiment., with a σ^2 value of 0.02 used here.

After applying absorption damping compensation according to Eq. (5), not all absorption damping terms in Eq. (1) are completely compensated. However, the partial

compensation of absorption damping allows the PSD and the time-frequency characteristics of the seismic signal to reflect the changes in the characteristic parameters of the debris flow more accurately. This allows the PSD of the seismic signal of the debris flow obtained using Eq. (2) to be analyzed more effectively using Eq. (1).

3.3 Cross-correlation function and Manning formula

The cross-correlation function is used to compute the time delay of τ that corresponds to the travel duration of the source between the stations. The time delay of the signals comes from sampling signals, such as M signal samples $[x_K], [y_K]$ in Eq. (2) and (3) at different locations when the maximum calculation result $\phi_{yx}(\tau)$ is obtained based on Eq. (4) (Arattano and Marchi, (2005). Arattano and Marchi (2005) proposed) found that the value of the velocity computation is values calculated using cross-correlation were close to the value of the measured velocity measurement values. In the context of debris flows, the average flow velocity between monitoring observation stations can be obtained by dividing the distance between the stations by the signal time delay. This method has been used to objectively calculate the mean velocity of debris flows (Coviello et al., 2015):

$$[x_K] = [x_0, x_1, x_2, \dots, x_{M-1}] \quad [x_K] = \quad (26)$$

$$[x_0, x_1, x_2, \dots, x_{M-1}]$$

$$[y_K] = [y_0, y_1, y_2, \dots, y_{M-1}] \quad [y_K] = \quad (37)$$

$$[y_0, y_1, y_2, \dots, y_{M-1}]$$

$$\phi_{yx}(\tau) = \frac{\sum_{t=0}^{M-1} x_t y_{t+\tau}}{\quad}, \quad (48)$$

$$\phi_{yx}(\tau) = \sum_{t=0}^{M-1} x_t y_{t+\tau},$$

where y from station 2 is another signal of time domain for the same event as x from station 1, t and K which are absolute sampling time series from 0 to $M-1$, ϕ represent cross-correlation function. When t exceeds $M-\tau-1$ and is less than 0, x_t and $y_{t+\tau}$ is equal

to 0.

3.3 Power spectral density

Power spectral density (PSD, Eq. (5)) can be used to estimate power per frequency for different frequencies in a specific period (Yan et al., 2020), and allows debris flow evolution to be analyzed from the seismic signal.

The Manning formula (Eq. 9) is used to calculate the peak flow velocity of a debris flow passing through a section, based on characteristic terrain parameters of the section (Yu and Lim, 2003; Cui et al., 2013; Guo et al., 2016). Here, the velocity calculated using the Manning formula is compared with that from the cross-correlation method, to verify the relative accuracy of the cross-correlation algorithm:

$$PSD_{f_{\min} \sim f_{\max}}(t) = \frac{1}{(f_{\max} - f_{\min})} \times \sum_{f=f_{\min}}^{f_{\max}} X(t, f), \quad (59)$$
$$v = \frac{1}{n} J^{\frac{1}{2}} R^{\frac{2}{3}}$$

where f_{\min} and f_{\max} represent minimum frequency and maximum frequency, respectively, t is time for the seismic signal, and $X(t, f)$ represents the spectrogram based on STFT (Yan et al., 2017). where v represents debris flow velocity, n represents the roughness coefficient of the channel, J is the slope ratio of the section, and R is the hydraulic radius of the section.

In Eq. (9), n is calculated using Eq. (10) (Smart, 1999):

The sampling rate is 100 Hz, so we choose 1 Hz and 50 Hz (i.e., a half of 100 Hz) as f_{\min} and f_{\max} .

PSD can be calculated by Eq. (6) based on seismic signals (Lai et al., 2018). PSD has a link with transporting bed load in rivers, Roth et al. (2016) provide insight into that the component signals come from water turbulence, rainfall, and sediment transport. It gives us a research direction about applying PSD to studying debris flows.

$$PSD \approx 1.9 \cdot LWD^3 u^3 \frac{f^{3+5\xi}}{v_c^5 r_0} e^{-\frac{8.8 f^{1+\xi} r_0}{v_c Q}}, \quad (610)$$

$$n = \frac{d_{50}^{\frac{1}{6}}}{6.7\sqrt{g}}$$

where d_{50} represents median particle size, and g represents the acceleration due to gravity.

~~where W is width of the channel, D represents the 94th centile of the grain size distribution, u represents debris flow velocity, f is frequency, v_e is Rayleigh wave phase velocity at 1 Hz, r_0 is distance between the monitoring station and channel, L is effective length of $L=r_0$, $\xi=0.4$ is a parameter related to how strongly seismic velocities increase with depth at the site, and Q is an attenuation factor (Tsai et al., 2012; Lai et al., 2018).~~

3.4 Absorption attenuation compensation

~~Elastic wave travel makes energy and velocity smaller. The two effects are a function of frequency and are mathematically expressed by Eq. (7) with some parameters (Kjartansson, 1979; Futterman, 1962; Strick, 1967). It can be used to restore a part of energy loss as:~~

$$h(t, f) = e^{\frac{\pi f t \left| \omega_0 \right|^{\frac{2}{\pi} \arctan\left(\frac{1}{2Q}\right)}}{Q \left| \omega \right|}} \quad (7)$$

~~where f is the frequency of the seismic signal, t is the spreading time (i.e., 0.02 s and 0.05 s) which is equal to distance r_0 between the monitoring station and channel divided by Rayleigh wave velocity v_e in Eq. (6), Q represents attenuation factor quantitatively depicting the absorption attenuation, and ω_0 and ω are reference angular velocity at 1 Hz ($\omega_0=2\pi$) and angular velocities, respectively.~~

$$\Gamma(t, f) = \frac{h(t, f) + \sigma^2}{h^2(t, f) + \sigma^2} \quad (8)$$

~~where σ is a constant named stability control factor, whose value comes from a numerical experiment, with a σ^2 value of 0.02 used here.~~

~~The high frequency signal can be restored by Eq. (8) better with a comparison of Eq. (7). Because the seismic signal of debris flow belongs to a high frequency signal, we always use Eq. (8) at all the frequencies of 1 Hz to 50 Hz.~~

4 Results and analysis

4.1 ~~Debris~~ Characteristics of the debris flow seismic ~~energy recovery and process reconstruction~~signal

4.1.1 Debris flow seismic and rainfall data

~~This study effectively captured seismic signals from three debris flows that occurred on August 19, 2022, in the Fotangba and Er gullies using a near field monitoring system. After preprocessing the raw data, we analyzed the vertical component (Figure 4). The seismic signals recorded by the monitoring system exhibited significant amplitude increases and fluctuations during the debris flow events. The analysis revealed two debris flows in the Fotangba Gully and one in the Er Gully. The spectrograms and amplitude trends at both monitoring stations displayed similar characteristics of rapid increase followed by gradual decrease. Notably, the second debris flow in Fotangba exhibited greater amplitude and duration compared to the first, with more pronounced signal variations observed at monitoring station 1 than at station 2. In Er Gully, monitoring station 2 recorded higher amplitudes and fluctuations in seismic signals compared to station 1, which can be attributed to the instrument layout and site conditions. We calculated the signal-to-noise ratios (SNR) for the debris flows at different monitoring stations. The SNRs for the first debris flow in Fotangba were 20.66 dB and 7.96 dB at the two stations, while the second debris flow had SNRs of 19.60 dB and 15.80 dB. In Er Gully, the SNRs were 20.47 dB and 17.62 dB at the two stations. All three debris flows showed relatively high SNRs. The analysis indicated better seismic signal quality at Fotangba monitoring station 1 and Er Gully monitoring station 2. Given the larger magnitude, longer duration, and smaller channel bends of the second debris flow in Fotangba. The following research will focus on a more detailed analysis and reconstruction of this event.~~

Based on the instrument response data in Table 1, the original seismic data was corrected for the instrument response and converted to velocity (m/s). Through a joint

analysis of the seismic signals recorded by the observation system on August 19, 2022, and precipitation data, we were able to determine that two debris flows occurred in Fotangba and one in Er Gully. All three debris flows were likely triggered by precipitation. As shown in Fig. 4, significant amplitude increases and fluctuations in the seismic signals were observed during the debris flows. By analyzing the wavefield characteristics of the debris flows, we were able to determine the approximate times of all three events. The rainfall record for Fotangba Gully shows hourly rainfall of 6.4 mm and 14.2 mm before the first and second debris flows, respectively (Figure Fig. 4e). In Er Gully, the hourly rainfall before the debris flow was 3.8 mm (Figure Fig. 4f). Analysis indicates precipitation occurred before the three debris flows. Additionally, the rainfall data can be linked to the initiation time of the flows and significant changes in seismic signals. The two debris flows in Fotangba Gully coincided with the maximum hourly rainfall on the day of the events (second highest and highest) within a 24-hour period, while the Er Gully debris flow did not coincide with a maximum. However, the cumulative rainfall before the Er Gully debris flow reached 15 mm, greater than the cumulative rainfall for the first debris flow in Fotangba Gully. Therefore, rainfall is considered the triggering factor for debris flow initiation in both gullies.

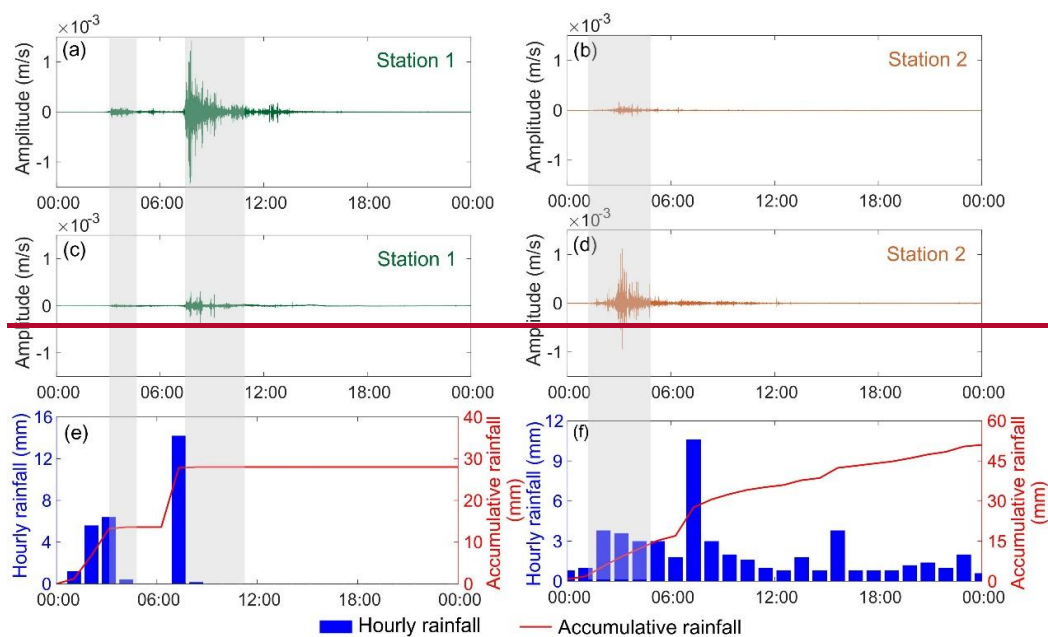


Figure 4 ~~The seismic signals and rainfall of the debris flow in their raw form.~~ The

seismic amplitude of the three debris flow events showed a characteristic rapid increase followed by a gradual decline. However, the amplitude values and variation characteristics differed significantly. The seismic amplitude and duration of the second debris flow event in Fotangba Gully were both greater than those of the first event. The signal at measuring station 1 showed more pronounced changes during both debris flows than during periods when no debris flows occurred. We selected the seismic signals from the same time period on the day prior to the debris flow event as the background noise, and calculated the ratio of the debris flow signal power to the noise power as the signal-to-noise ratio (SNR) (Fu et al., 2020). In terms of signal-to-noise ratio (SNR), the SNR for the first debris flow in Fotangba Gully was 20.66 dB and 7.96 dB, while for the second debris flow it was 19.60 dB and 15.80 dB. Similarly, at measuring station 2 in Er Gully, the amplitude and fluctuations of the seismic signals were higher than at station 1, with SNR values of 20.47 dB and 17.62 dB, respectively. For the same debris flow, the signals recorded by the two measuring stations showed considerable differences, which could be due to different sensor placement conditions and the degree of signal attenuation during propagation. In addition, differences in the flow dynamics of the debris flows at different stations probably also contributed to these deviations. When analyzing the seismic signal waveform, I found clear differences in the signal peak characteristics between different measurement points within the same channel. For example, at measurement point 1 in Fotangba Gully, the largest signal peak occurred during the second debris flow in the initial phase, with the subsequent peaks gradually decreasing. In contrast, the signal peaks recorded at measurement point 2 were similar in magnitude, and the number of peaks also differed between the two measurement points. A similar pattern was observed at measurement point 2 in Er Gully, where the largest peak occurred at the beginning of the event and the subsequent peaks gradually decreased. Several peaks of similar magnitude were observed at measurement

point 1. These striking differences in signal characteristics at different measurement points within the same channel indicate that the dynamic parameters of the debris flow changed during its development.

Based on the above analysis, it was determined that the flow dynamics of debris flows recorded at different measuring stations can vary. In addition, the geological characteristics near the different stations differ, which prevents a direct comparison of the amplitude values between the two measurement points within the same channel. Therefore, our subsequent comparisons focus primarily on analyzing the development of debris flows over different time periods at a single station, while comparisons between different stations are mainly used to analyze the occurrence times of the debris flows. Given the larger extent, longer duration, and lower curvature of the second debris flow in Fotangba Gully, as well as the better quality of the infrared images, we will use the second debris flow in Fotangba Gully as a case study in our future research to illustrate our analysis process.

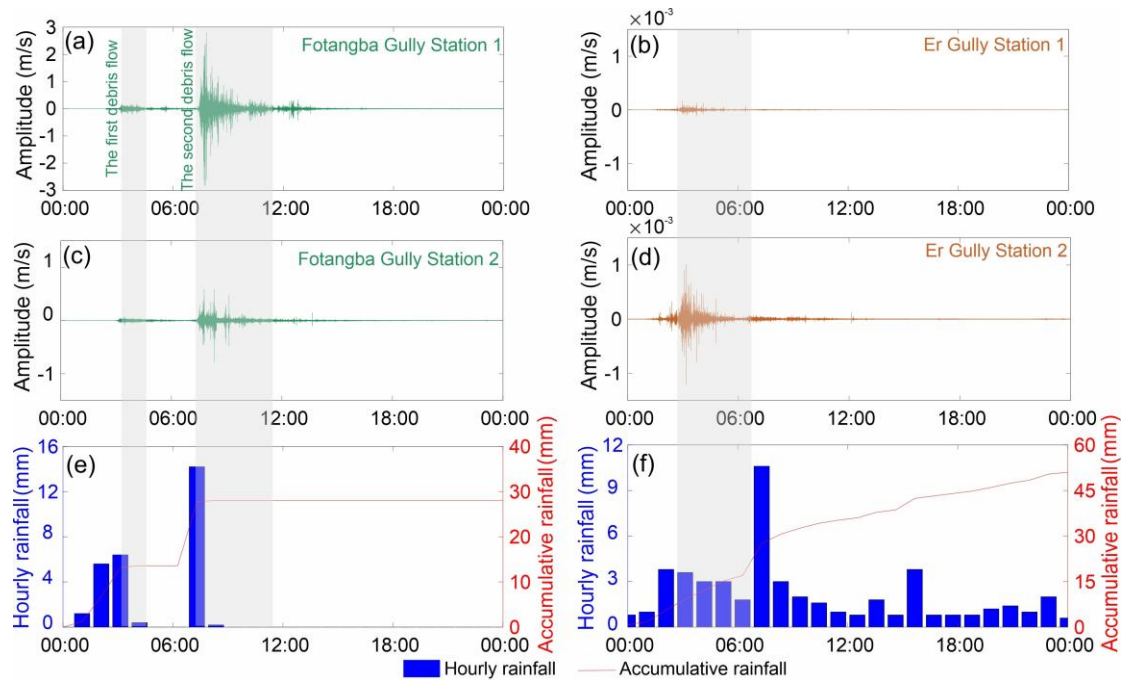


Fig. 4. Raw seismic signals and rainfall data. (a) and (c) represent monitoring station 1 and station 2 in the Fotangba Gully; (b) and (d) represent monitoring station 1 and station 2 in the Er Gully; (e) Rainfall at Fotangba Gully; (f) Rainfall at Er Gully.

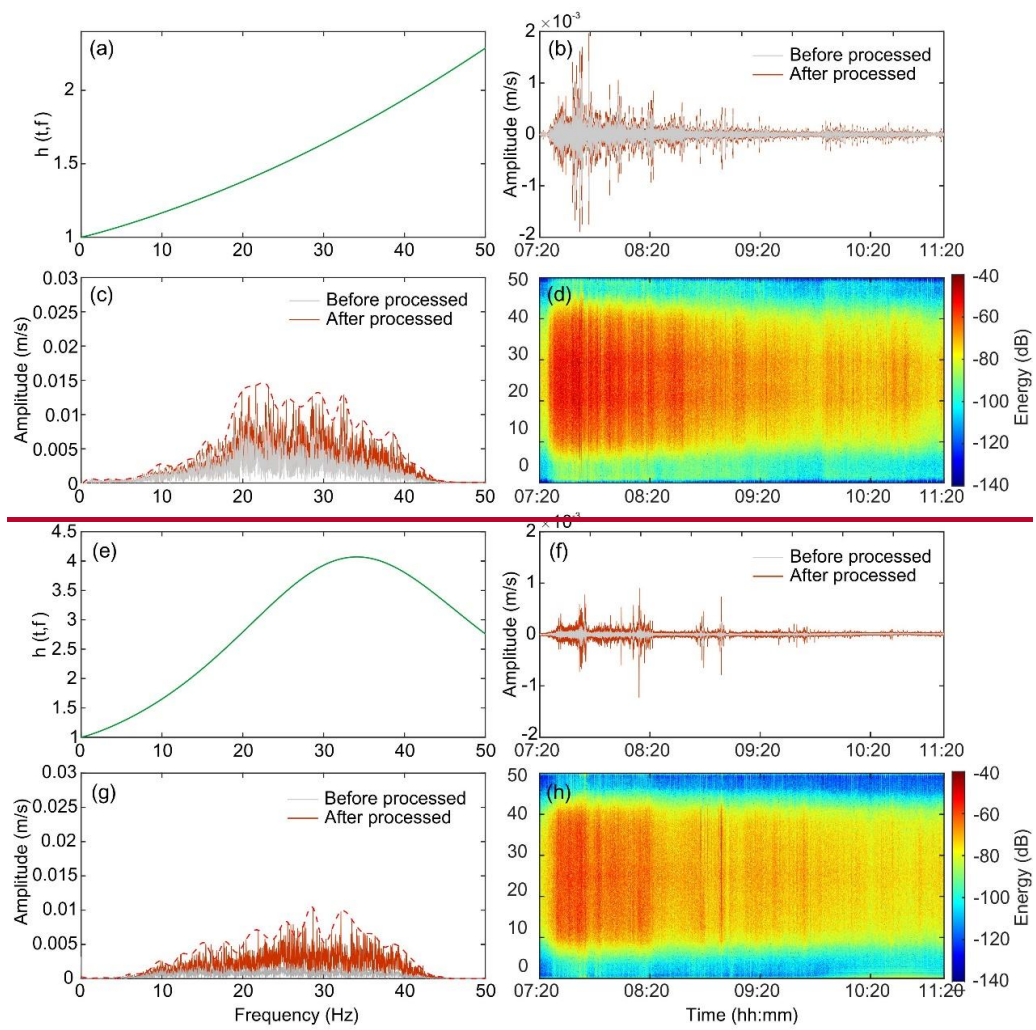
4.1.2 Debris flow seismic energy recovery and time-frequency

We applied Eq. (74) and (85) to compensate for the maximum possible energy loss during the propagation of debris flow seismic signals. These signals were recorded along the river channel. As the debris flow travels through the channel, it generates vibration signals that propagate to the monitoring observation stations and are recorded by sensors. This seismic signal is a superposition of the vibration signals generated by the entire debris flow, characterized as a "line source." To accurately reproduce the energy of this "line source" seismic signal, it is essential to precisely determine the propagation paths of individual "sources." However, due to factors such as river channel morphology and surface velocity variations, this information is challenging to ascertain accurately. To simplify the compensation process, we considered the area within 50 meters upstream and downstream of the monitoring station as the primary sources of the seismic signals recorded at the station. We calculated the geometric mean of seismic wave propagation times from the center of this 50-meter river channel to the monitoring station at 0.5-meter intervals, using this geometric mean as the seismic wave propagation time for energy compensation. Another important parameter is the velocity and amplification factor (σ^2) of the 1 Hz Rayleigh surface wave, which is influenced by the geological conditions near the monitoring station. Since we performed near-field observations, we neglected velocity variations near the station and assumed that the velocity of the 1 Hz Rayleigh surface wave remains constant. This assumption simplifies the geometric mean of the transit times to the geometric mean distance of this flux section relative to the observation point. The amplification factor (σ^2), ensuring numerical stability, was determined through numerical experiments. The principle of these experiments was to expand the compensation frequency range as much as possible while maintaining a high signal-to-noise ratio for the debris flow signal.

~~Based on~~ Under the ~~second debris flow event in Fotangba Gully, we analyzed the surface conditions near the site and conducted practical investigations help~~ of near-

surface velocities investigations in ~~the bank areas~~ using petroleum seismic techniques (Liu et al., 2013). This), we analysis ~~allowed us to the surface conditions near the second debris flow event in Fotangba Gully and~~ determine the Q values and reference velocities for two specific locations in Fotangba Gully. The Q values were found to be 4 and 2.4, with corresponding Rayleigh wave velocities of 800 m/s and 500 m/s at a frequency of 1 Hz. We calculated the geometric mean travel times for these two locations to be 0.02 seconds and 0.04 seconds, respectively. After numerous numerical experiments, we set the gain control factors for both locations to 0.02. ~~There is only limited reference material available for the standard velocity of surface waves. To estimate this velocity, we refer to the results of surface surveys during seismic exploration of petroleum deposits. These estimates may vary, but the principle we apply in our practical compensation "maximizing energy in all frequency bands while maintaining numerical stability" allows us to correct any discrepancies during the actual compensation process (Yang et al., 2019).~~

From the compensation spectrum curve, the high-frequency components have been significantly restored, and both sites show similar improvements in their spectrum curves (Figure Fig. 5). The time domain curve indicates that the characteristic changes at site 2 after compensation further enhances enhance its similarity to site 1, with these changes being more pronounced. In terms of effectiveness, the compensation has proven to be quite effective, as it mitigates the absorption attenuation of the debris flow seismic signals to some extent. Therefore, in the following sections, we will use the compensated seismic signals for further analysis of the second debris flow event at Fotangba Gully.



Figure

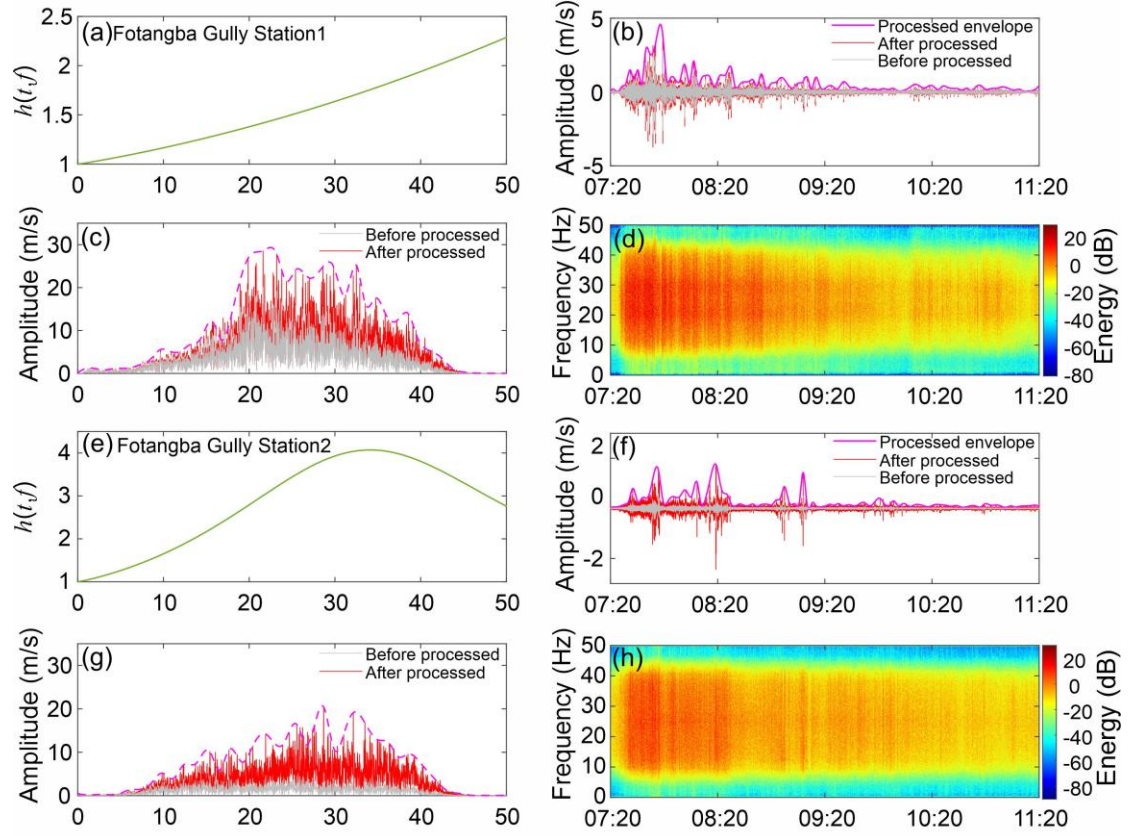


Fig. 5. Restored seismic signal for the second debris flow in Fotangba Gully. (a) Compensation function curve for monitoring station 1; (b) Time domain signal at monitoring station 1; (c) Frequency domain signal at monitoring station 1; (d) Restored spectrogram for monitoring station 1; (e) Compensation function curve for monitoring station 2; (f) Time domain signal at monitoring station 2; (g) Frequency domain signal at monitoring station 2; (h) Restored spectrogram for monitoring station 2. The red dashed lines in (c) and (g) are envelopes that represent peak amplitudes after processing.

4.1.3 Process reconstruction by seismic

Through the analysis of section 4.1.1, we selected data from Fotangba station 1 and Er Gully station 2, which had high-quality signal records, for further time domain and time-frequency spectral analysis (Figure 6). Notably, at Fotangba Gully, the second debris flow event shows more significant amplitude changes and energy release compared to the first. The time-frequency spectral analysis further indicates that the scale and duration of the second debris flow event exceeded those of the first.

By monitoring the abrupt changes in amplitude and frequency spectra of seismic signals, we can estimate the start and end times of debris flow events. As shown in Figure 6, the seismic signals in Fotangba Gully experienced a sharp increase in amplitude and energy around 3:07 a.m., stabilizing around 5:26 a.m., lasting approximately 2.5 hours. Then, around 7:25 a.m., the signals changed again, returning to stability around 11:24 a.m., lasting about 4 hours. In Er Gully, the seismic signals began to change around 2:44 a.m. and stabilized around 4:49 a.m., lasting approximately 2 hours. By combining information from local villagers about debris flows, we determined the specific start and end times of the three events (Table 2). Additionally, images from time-lapse cameras provided strong support for determining the start and end times of these events.

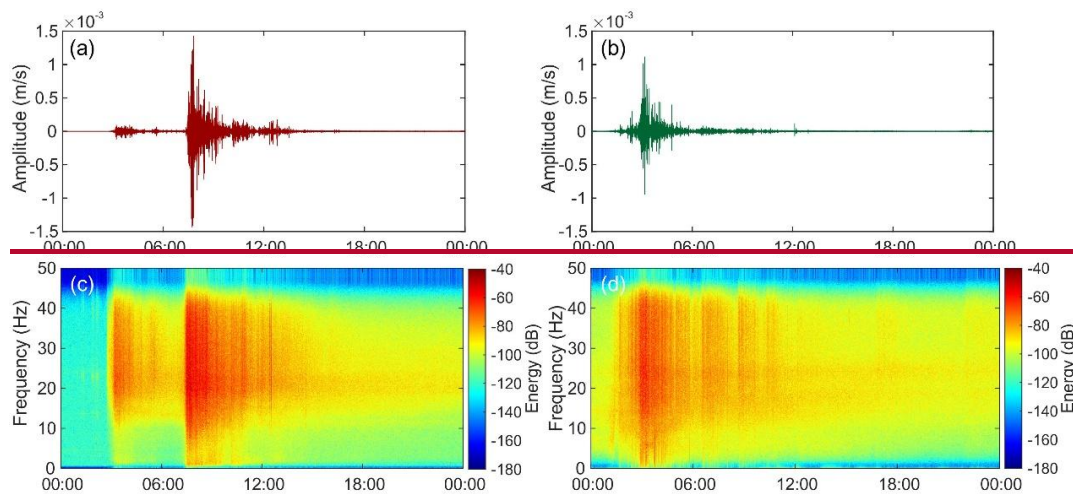


Figure 6 Time domain and time-frequency spectrum of debris flow ground motion signal. (a) and (c) Fotangba monitoring station 1; (b) and (d) Er Gully monitoring station 2.

Table 2 Starting and ending time of three debris flow events at Wenchuan, China (August 19, 2022), picked from the seismic signals.

	Fotangba Gully		Er Gully
	1 st	2 nd	
Starting	03:07 am	7:25 am	2:44 am
Ending	05:26 am	11:24 am	4:49 am

To investigate the seismic manifestation of the second debris flow evolution in Fotangba Gully, we processed seismic signals according to the workflow depicted in Figure 2, resulting in compensated time-domain and time-frequency spectra (Figure 7). By analyzing characteristics such as amplitude profiles, average amplitudes, and vertical spectra, we attempted to reconstruct the debris flow's evolution.

At Monitoring Point 1, the debris flow onset was recorded at 7:25, with subsequent rapid increases in point 1, the signal amplitude and frequency range. Amplitudes peaked around 7:42 and then gradually declined; the rapidly increased when the debris flow occurred. The frequency range associated with high power increased rapidly from 8 to 43 Hz post debris flow initiation, maintaining high power at 22 Hz until 8:45. Monitoring Point 2 data broadly aligned with Point 1, noting a debris flow onset at 7:26, with peak amplitudes occurring around 7:45, followed by a gradual decline. However, slight differences in frequency bandwidth were observed, primarily concentrated between 10-40 Hz from 7:30 to 7:50. Combining seismic signal characteristics from both points, the debris flow commenced around 7:25, progressively escalating in scale, reaching peak magnitudes at approximately 7:42 and 7:45 at Points 1 and 2, respectively, and subsequently stabilizing, with the entire event lasting about 4 hours. Throughout the debris flow event, peak frequencies observed at both 8 Hz and 43 Hz. During the debris flow event, the energy initially concentrated and then gradually decreased, with a range between -120 dB and -60 dB. The data from monitoring point 2 was essentially consistent with that from monitoring point 1, recording the debris flow starting at 7:26 AM, with a peak amplitude observed around 7:45 AM, followed by a gradual decline. However, there were minor differences in the frequency bandwidth at monitoring point 2, which concentrated between 10 Hz and 40 Hz. The energy variation trend and range were almost the same as those at monitoring point 1. Throughout the entire debris flow event, the observed peak frequencies at the two monitoring points were 21.6 Hz and 28.6 Hz, with respectively. The frequency evolution between the two points

indicating indicates an increase in the peak frequency, potentially due which may be related to varying changes in particle impacts and scale. Factors such as rockfall rock falls and channel erosion may might also influence the peak frequencies. The frequency. To reflect the surge reflects the wave nature characteristics, we used the upper envelope of the signal waveform (Fig. 5b and 5f). The surge waves corresponded with the wave characteristics of the debris flow, and the number of surges is consistent with matched the number of waves. The flow depth between the surges is surge waves was significantly discontinuous, with a sudden increase in flow depth from one surge to the next, similar to the flow characteristics of the surge flow. Monitoring Point point 1 and 2 observed about 8 and 7 significant surges, respectively, with different numbers. surge waves, while monitoring point 2 recorded 7. Additionally, we found noticed that Monitoring Point monitoring point 2 recorded two significant surge surge waves around 9:00 AM, while Monitoring Point monitoring point 1 did not observe notable any significant surges at that the same time. This indicates changes in that the flow dynamics of the debris flow movement characteristics between the two monitoring points along the channels of Monitoring Points 1 and 2, potentially river channel have changed, possibly due to variations in channel topography and the solid-phase material content of the debris flow.

Overall, the trends in the time-domain and time-frequency spectra at the two monitoring points are similar, exhibiting rapid increases followed by gradual declines, consistent with the overall movement of the debris flow. However, Monitoring Point 1 recorded higher average amplitudes, wider frequency bands, and stronger energy. This may be attributed to the shorter distance between Monitoring Point 1 and the Gully, resulting in less energy loss during the propagation of seismic signals from the debris flow. Additionally, varying geological conditions may also contribute to the differences in seismic signal attenuation between the two monitoring points.

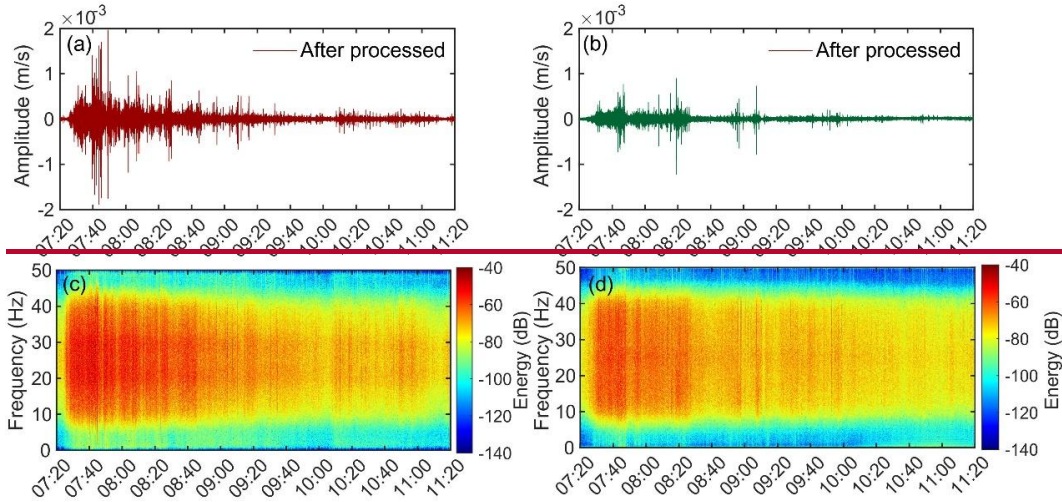


Figure 7 Restored seismic signal for the second debris flow in Fotangba Gully. (a) Time domain signal at monitoring station 1; (b) Time domain signal at monitoring station 2; (c) Time frequency domain energy spectrum for monitoring station 1; (d) Time frequency domain energy spectrum for monitoring station 2.

4.2 Debris flow velocity analysis

Cross-correlation functions can calculate the time delay between two measuring stations for debris flows, as shown in Eq. (4). The average flow velocity can be derived from the distance between neighboring monitoring stations and this time lag.

4.2 Post-event field investigation

Field investigations and UAV surveys at Fotangba Gully began three days after the debris flow events, and local villagers confirmed that the accumulation fans had not been disturbed. UAV aerial images of the accumulation fan at the Gully mouth, along with close-ups of surface conditions, are shown in Fig. 6a to 6c. Field measurements indicate that the fan thickness at location ① is about 1.2 m, with a thin layer (1 – 2 mm) of clay covering the surface in some areas (Fig. 6c). Some rocks larger than 1 m in diameter (Fig. 6b and 6c) suggest that the debris flow had a relatively high carrying capacity. Larger rocks are found at the bottom of the alluvial fan (Fig. 6b), while smaller rocks are located at the front (Fig. 6c), indicating that the carrying capacity of the debris flow decreases sharply after being released from the channel constraints as the cross-

sectional area increases.

A sediment sample weighing about 4.7 kg was collected from the accumulation fans in Fotangba Gully to estimate the particle size distribution of the debris flow, taken from location ① in Fig. 6a. Grain size analysis was performed using sieving and a Malvern particle sizer. Due to the lack of several sample analyses in this study, more analyses should be conducted for better variability estimation. We also neglected to record the portion of materials above the maximum particle size shown in the granulometric curve, which should be addressed in future research. The results indicate that clay particles (size < 0.005 mm) made up only 0.041% of the total sample weight (Fig. 6d), consistent with field observations. The low cohesive sediment content in the accumulation fan sample may result from removal by post-event processes, such as the flushing action of the Minjiang River or human clearance. The particle size distribution shows that 94% of the sample particles are 0.018 m, denoted as D in Eq. (1). In the next section, we will use D as a basis for analyzing the PSD curve features of the debris flow. Field investigations confirmed the occurrence of debris flows and provided data on the maximum size of the boulders and the grain size distribution. These findings provide valuable information for the subsequent reconstruction of the debris flow process and the analysis of its parameters.

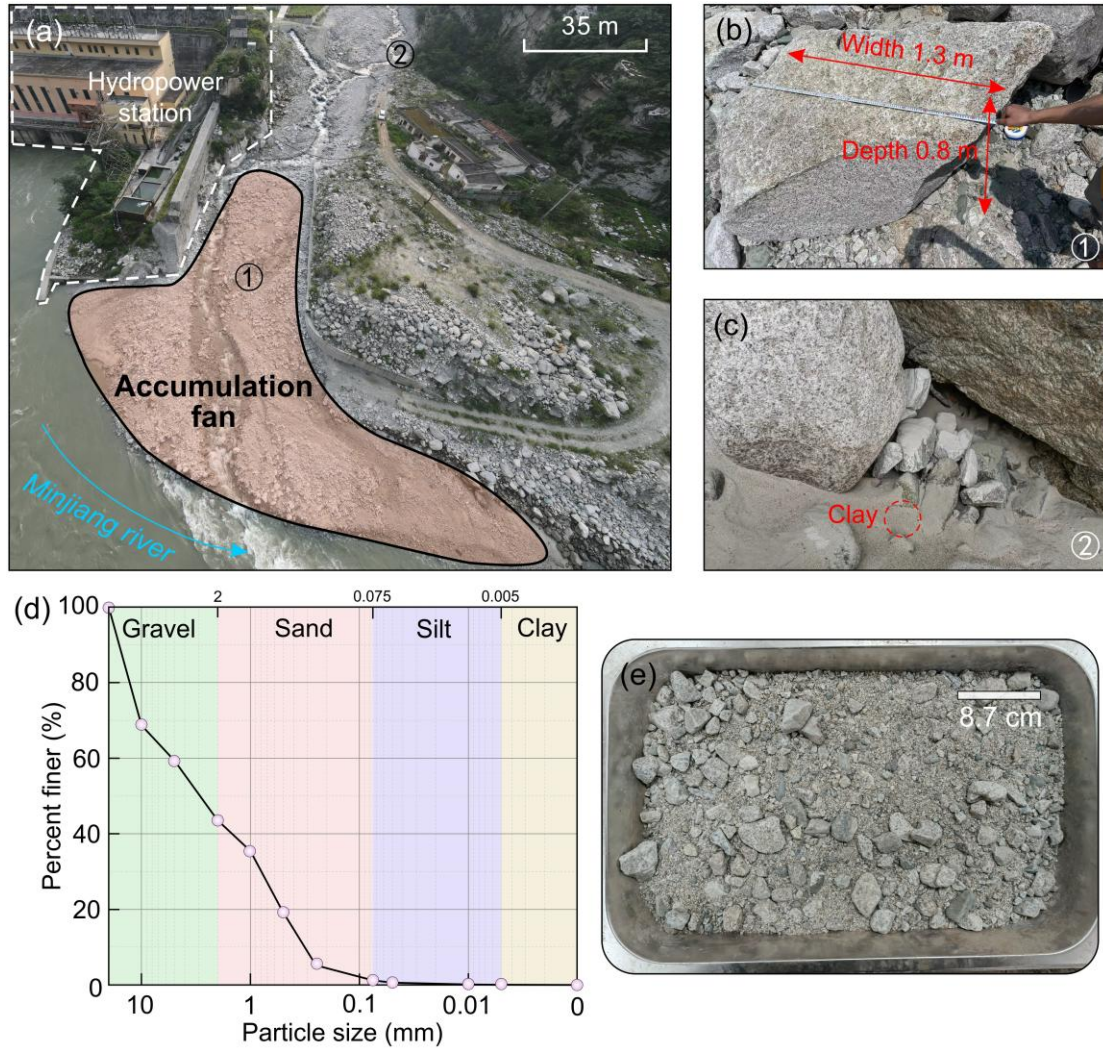


Fig. 6. Post-event field survey of accumulation fans in Fotangba Gully. (a) Aerial view of the Fotangba Gully fan; (b) Largest particle on the Fotangba Gully fan, marked ① in image (a); (c) Thin layer of clay covering the accumulation surface in Fotangba Gully, marked as ② in image (a); (d) Particle size distribution for Fotangba Gully sediment samples; (e) Fotangba Gully sediment sample. Clay has not been marked in the subplot (d) because the particles with grain size less than 0.005 mm account for 0.041% of the total weight of the sample.

4.3 Reconstruction of the debris flow process and analysis of characteristic parameters

4.3.1 Debris flow breaking time picked by seismic signals

By analyzing the seismic signal characteristics of debris flows in Section 4.1, we selected seismic data from observation point 1 at the Fotangba Gully and observation point 2 at the Er Gully to reconstruct the event times of the debris flows. We estimated the start, duration, and end of the debris flow events by observing sudden changes in the amplitude and frequency spectrum of the seismic signals. As shown in Fig. 4 and Fig. 5, the seismic signal in the Fotangba Gully initially showed a sharp increase in amplitude and energy at 3:07 a.m. The signal then continued to rise, reaching its peak at 3:13 a.m. and gradually declining until it stabilized at 5:26 a.m. At approximately 7:25 a.m., the signal changed again, and at 7:42 a.m., the amplitude reached its second peak, stabilizing around 11:24 a.m. In Er Gully, the seismic signal began to change at around 2:44 a.m. and stabilized at around 4:49 a.m. Based on this, we have made a preliminary reconstruction of the timing of the debris flows. The results show that the first debris flow in Fotangba Gully began at 3:07 a.m., gradually intensified, and ended at 5:26 a.m., lasting about 2.5 hours. The second debris flow in Fotangba Gully began at 7:25 a.m., intensified, and began to slow down at 7:42 a.m., finally ending at around 11:24 a.m. and lasting approximately 4 hours. The debris flow in Er Gully began at 2:44 a.m., slowed down at 2:58 a.m., and ended around 4:49 a.m., lasting approximately 2 hours (Table 2).

Table 2 Starting and ending time of three debris flow events at Wenchuan, China (August 19, 2022), picked from the seismic signals.

	Fotangba Gully		Er Gully
	1 st	2 nd	
Starting	03:07 am	7:25 am	2:44 am
Ending	05:26 am	11:24 am	4:49 am

Building on a clear understanding of the temporal sequence of the debris flow, we further analyzed the development of the debris flow process by combining seismic signal data and image material.

4.3.2 debris flow processes analysis based on infrared imagery

Continuous analysis of infrared imagery of debris flow characteristics can validate the evolution processes indicated by seismic signals. However, the analysis is hindered by the low quality of the initial debris flow images captured at night with a limited visible range and low resolution from Fotangba Gully and Er Gully. Therefore, this study utilizes the infrared imagery collected of the second debris flow in Fotangba Gully during daytime.

During the debris flow event, we captured infrared images at 5-minute intervals from 7:39 to 8:04 (Fig. 7b to 7g). Due to blurriness from water droplets on the camera lens at Monitoring Point 2, we relied solely on the infrared camera at Monitoring Point 1. The images showed that at 7:39, the debris flow volume was low, and the channel had not yet been submerged. Most of the flow is concentrated in the right channel, with less flow in the left channel. By 7:44, the debris flow began to submerge Point A and erode the left bank at Point B. Water depth and left bank erosion peaked at 7:59, after which water depth started to decrease. Overall, the infrared images indicated a gradual increase in flow from 7:39 to 7:54, followed by a decrease.

Flow velocity peaked at 7:39 and then gradually decreased, remaining relatively stable in subsequent images. The maximum turbulence at Point C indicated the highest flow velocity, which then gradually declined. The vortices near Point A suggested higher flow velocities, while the fluid patterns upstream at Point C indicated slower speeds. The vortices near Point C may have been caused by excessive discharge from lower elevations. Notable surges were observed in Fig. 7b to 7e, particularly at 7:49 and 7:54, with significant debris flow surges. From 7:39 to 7:59, the debris flow volume gradually increased due to higher flow velocities, which eroded the sediments along the channel, enhancing solid-phase material content and flow volume. After 7:59, the reduced flow velocity led to weaker erosion and a gradual decrease in particle content, evolving into a "flood" state. The debris flow surges matched the small peaks observed

in the seismic signals. The trends in particle content mirrored those of flow volume, gradually increasing from 7:39 to 7:49, remaining high from 7:49 to 7:54, and significantly decreasing at 7:59 and 8:04.

Through the analysis of debris flow evolution, we found that flow volume gradually increased from 7:39 to 7:59, with flow velocity peaking at 7:39 before gradually decreasing and experiencing multiple surges. The image analysis largely matched the debris flow evolution reconstructed through seismic signals, and the corresponding image timestamps further confirmed the consistency between the characteristics of the Fotangba Gully seismic signals and the observations from the images, supporting the accuracy of reconstructing the second Fotangba Gully debris flow event through seismic signals. However, the peak times were not entirely consistent with the seismic data, possibly due to the 5-minute recording interval.

By combining seismic signal data with image analysis, we achieved an accurate reconstruction of the second debris flow event at Fotangba Gully based on its temporal progression and evolutionary characteristics. In the following sections, we will integrate these variables with the forward modeling results of the seismic power spectral density (PSD) generated by the debris flow. This will allow us to explore the effects of flow velocity and particle size distribution, thereby analyzing the changes in characteristic parameters during the debris flow motion process.

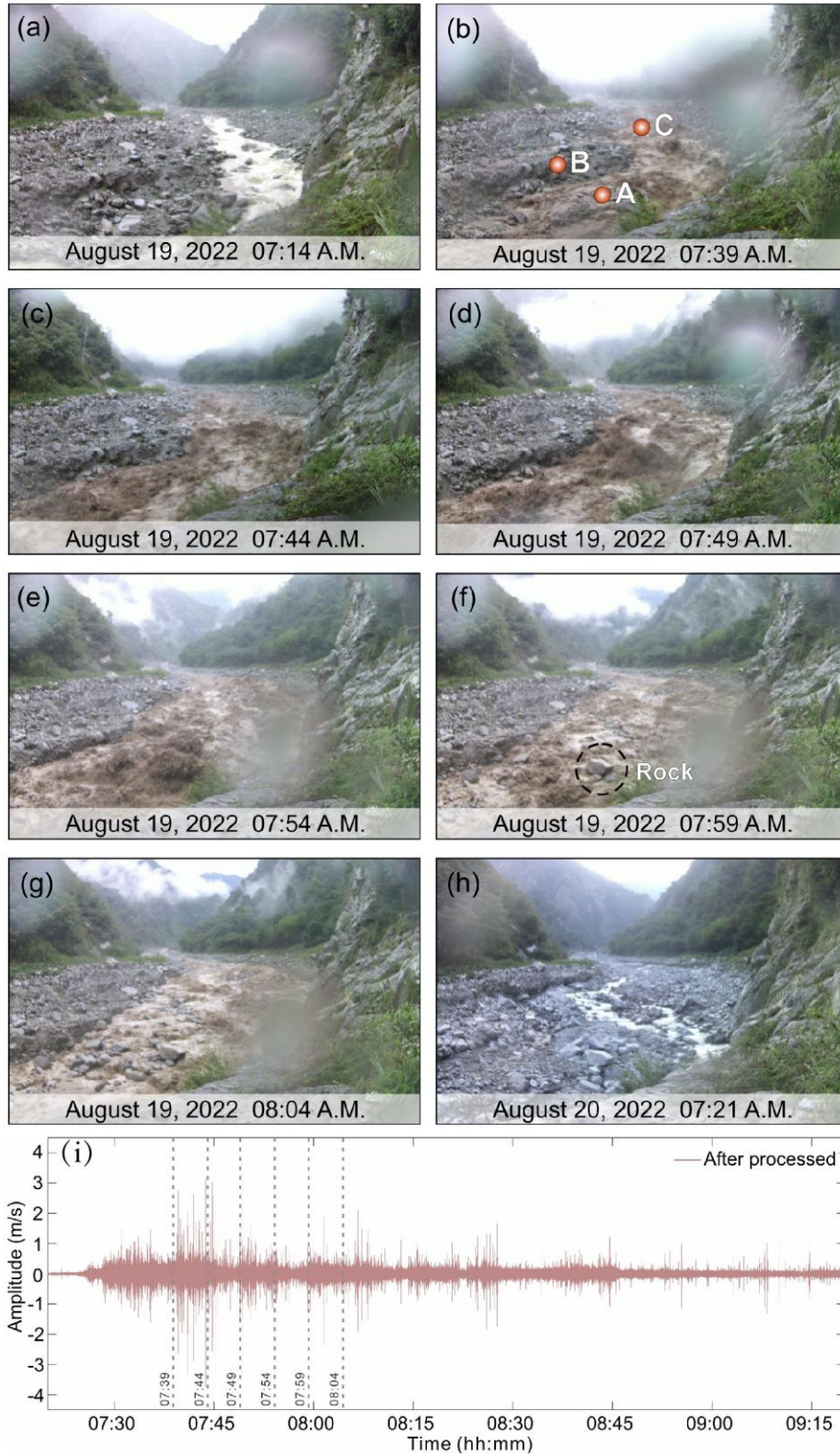


Fig. 7. Infrared camera images taken and the seismic signal recorded at monitoring station 1 in Fotangba Gully during the second debris flow on the morning of August 19, 2022. Images were recorded every 5 minutes: (a) 7:14 frame (b) 7:39 frame; (c) 7:44

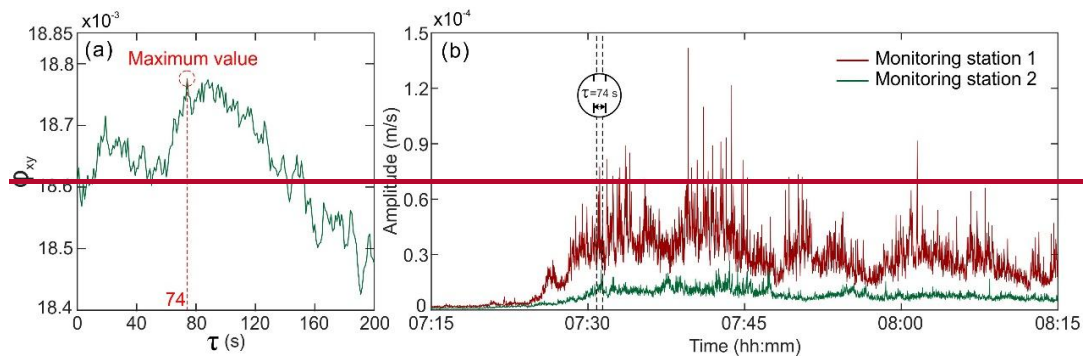
frame; (d) 7:49 frame; (e) 7:54 frame; (f) 7:59 frame; (g) 8:04 frame; (h) August 20, 2022, 8:04 Frame; (i) seismic signal recorded at the point.

4.3.3 Debris flow velocity analysis

In Section 4.3.1, we established the accuracy of the entire debris flow reconstruction process. However, some characteristic parameters of the debris flow process have not been quantitatively analyzed. This subsection will use seismic signal data to calculate the average flow velocity of the debris flow process. Cross-correlation functions can calculate the time delay between two measuring stations for debris flows, as shown in Eq. (48). The average flow velocity can be derived from the distance between neighboring ~~monitoring~~ observation stations and this time lag. Arattano et al. (2012), Comiti et al. (2014), and Schimmel et al. (2022) installed seismic instruments in different regions and found that the cross-correlation function can effectively calculate the debris flow velocity. In their studies, the measurement points were arranged along almost straight river channels, with the distance between the measurement points and the center of the channel being less than the straight-line distance between the measurement points. At the Fotangba Gully, the channel between points 1 and 2 is relatively flat and linear with a gradient of about 9° . The straight-line distance between these two points is 520 meters, which is greater than the 25 meters distance between the measuring points and the center of the channel. This arrangement of the instruments is similar to that in the studies mentioned above. In contrast, the river channel between the two measuring points in the Er Gully is convex (~~Figure 2b~~ Fig. 2b) and has a gradient of around 16° . The distance between the two measuring points is approximately 460 meters, which is greater than the 200 meters straight-line distance between the two points. This instrument arrangement differs significantly from those used in previous studies. Therefore, our research mainly focuses on using the cross-correlation function to calculate the debris flow velocity at the Fotangba Gully.

The sampling rate for seismic signal monitoring is 100 Hz. The average amplitude

for each second of seismic data is calculated using the amplitude method (Arattano, 1999), whereby 100 seismic signals are recorded within each second and their amplitudes are averaged. This method helps to smooth out high-frequency noise and provides a more stable representation of the amplitude of the seismic signal. Using simplified time domain signals processed with the seismic amplitude method, the ϕ_{yx} of the time domain signal for the second debris flow event in the Fotangba channel was calculated (Figure 8a), with a time delay τ of 74 s corresponding to the maximum value of ϕ_{yx} for this event. The amplitude range for calculating flow velocity based on the cross-correlation function for the second debris flow event is shown in Figure 9b. The distance between monitoring sections in the Fotangba channel is 520 m, resulting in an average velocity of 7.0 m/s for the second debris flow. To further validate the cross-correlation algorithm's applicability, we calculated average flow velocities of 3.0 m/s for the first debris flow event and 38.3 m/s for the Er Gully event using the same method (Table 3). The velocity for Er Gully was significantly higher than those for the two debris flow events in Fotangba and exceeded the flow velocities of 1–6 m/s observed by Cui et al. (2018) in the S1 section, indicating it may be inaccurate.



Figure

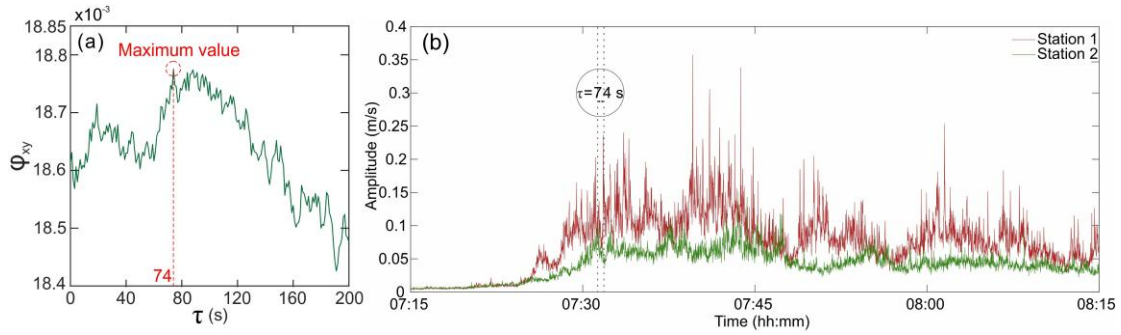
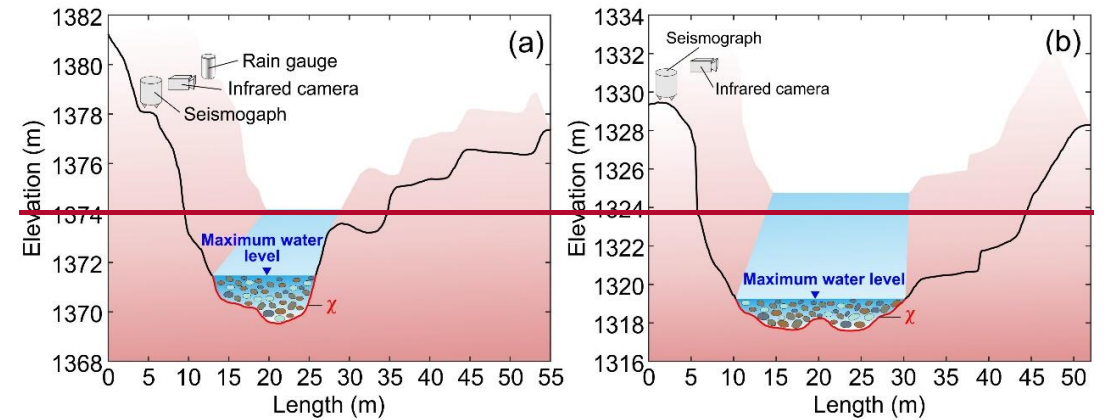


Fig. 8. The cross-correlation algorithm calculates the second debris flow in Fotangba Gully. (a) signal lag time τ between two monitoring observation stations; (b) Amplitude range of debris flow (vertical direction).

To verify the reliability of the velocity calculations derived from the cross-correlation function, the average velocity was also computed using the Manning formula (Yu and Lim, 2003; Cui et al., 2013; Guo et al., 2016). Channel parameters were obtained from the cross-sections at the monitoring observation stations (Figure Fig. 9). The channel roughness coefficient- n - was set at 0.05 (Xu and Feng, 1979). The gradient ratio- J - for the monitoring section was determined from the output of the UAV aerial survey's digital surface model (DSM). For monitoring station 1, the area and wet perimeters were 17.7 m² and 14.2 m, respectively. For the other cross-section, these values were 27.5 m² and 21.6 m. Consequently, the hydraulic radii RR for the two monitoring stations were 1.25 m and 1.27 m, respectively. observation stations were 1.25 m and 1.27 m, respectively. The Manning formula calculation yielded a flow velocity of 7.921 m/s for the second debris flow event at Fotangba, which is in close agreement with the velocity of 7.027 m/s obtained through cross-correlation calculations. Additionally, the field investigation results in Section 4.2 revealed that the largest boulder displaced by the debris flow had a diameter of approximately 1.3 meters. Preliminary analysis through imagery suggests that the debris flow is of a dilute type. Reference to relevant literature on river transport indicates that a flow velocity of 7.027 m/s is capable of transporting boulders with a diameter of around 1.3 meters. Therefore,

this suggests that the flow velocity obtained through the cross-correlation algorithm in this study is reliable.



Figure

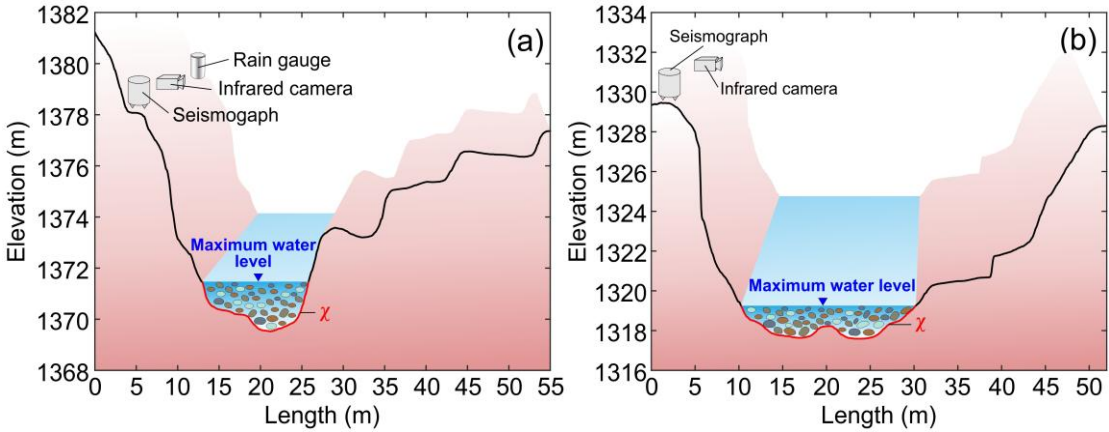


Fig. 9. Cross-sections of Fotangba Gully showing maximum water level used in calculation of mean velocity by the Manning formula. (a) Monitoring station 1; (b) Monitoring station 2.

Table 3 Results of maximum velocity calculations for Fotangba Gully and Er Gully debris flows.

Debris flow	Maximum velocity calculated using each method (m/s)	
	Cross-correlation algorithm	Manning formula
First debris flow in Fotangba Gully	3.006	—
Second debris flow in Fotangba Gully	7.027	7.921

Debris flow in Er Gully	38.333	—
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4.3.4 Analysis of ~~changes in debris flow reconstruction effectiveness based on seismic signals~~ characteristic parameters by PSD

~~Taking the second Fotangba Gully debris flow as an example, we will use infrared imagery and field survey data to analyze the effectiveness of the debris flow evolution process and analyze the impact of flow velocity and particle size on seismic motion signals through PSD.~~

4.3.1 Infrared imagery analysis

~~To verify the accuracy of reconstructing debris flow processes through seismic signals, we analyzed infrared images of the debris flows. Nighttime infrared imaging often faces limitations due to low visibility and resolution, resulting in poor image quality for the first and second Fotangba Gully debris flows during the night, making them unsuitable for analysis. To overcome these issues, we focused on the second daytime debris flow, which benefited from significantly improved image quality.~~

~~During the debris flow event, we captured infrared images at 5-minute intervals from 7:39 to 8:04 (Figure 10 b to g). Due to blurriness from water droplets on the camera lens at Monitoring Point 2, we relied solely on the infrared camera at Monitoring Point 1. The images showed that at 7:39, the debris flow volume was low, and the channel had not yet been submerged. Most of the flow is concentrated in the right channel, with less flow in the left channel. By 7:44, the debris flow began to submerge Point A and erode the left bank at Point B. Water depth and left bank erosion peaked at 7:59, after which water depth started to decrease. Overall, the infrared images indicated a gradual increase in flow from 7:39 to 7:54, followed by a decrease.~~

~~Flow velocity peaked at 7:39 and then gradually decreased, remaining relatively stable in subsequent images. The maximum turbulence at Point C indicated the highest flow velocity, which then gradually declined. The vortices near Point A suggested higher flow velocities, while the fluid patterns upstream at Point C indicated slower~~

speeds. The vortices near Point C may have been caused by excessive discharge from lower elevations. Notable surges were observed in Figure 10 b to e, particularly at 7:49 and 7:54, with significant debris flow surges. From 7:39 to 7:59, the debris flow volume gradually increased due to higher flow velocities, which eroded the sediments along the channel, enhancing solid phase material content and flow volume. After 7:59, the reduced flow velocity led to weaker erosion and a gradual decrease in particle content, evolving into a "flood" state. The debris flow surges matched the small peaks observed in the seismic signals. The trends in particle content mirrored those of flow volume, gradually increasing from 7:39 to 7:49, remaining high from 7:49 to 7:54, and significantly decreasing at 7:59 and 8:04.

Through the analysis of debris flow evolution, we found that flow volume gradually increased from 7:39 to 7:59, with flow velocity peaking at 7:39 before gradually decreasing and experiencing multiple surges. The image analysis largely matched the debris flow evolution reconstructed through seismic signals, and the corresponding image timestamps further confirmed the consistency between the characteristics of the Fotangba seismic signals and the observations from the images, supporting the accuracy of reconstructing the second Fotangba debris flow event through seismic signals. However, the peak times were not entirely consistent with the seismic data, possibly due to the 5-minute recording interval. In the next section, we will integrate these variables with forward modeling of the In Sections 4.2 and 4.3.3, the particle size distribution and average flow velocity of this debris flow were obtained, respectively. Based on this, the seismic power spectral density (PSD) generated by the debris flow to analyze their impacts on the signals, providing deeper insights into the discrepancies in peak times observed between infrared images and seismic interpretations.

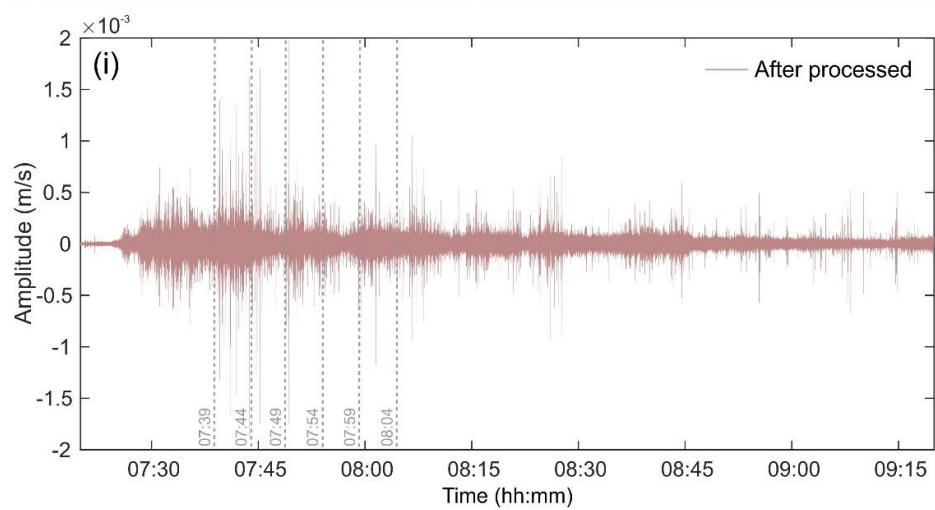


Figure 10 Infrared camera images taken and the seismic signal recorded at monitoring station 1 in Fotangba Gully during the second debris flow on the morning of August 19, 2022. Images were recorded every 5 minutes from 7:39 to 8:04: (a) 7:39 frame; (b) 7:44 frame; (c) 7:49 frame; (d) 7:54 frame; (e) 7:59 frame; (f) 8:04 frame. (g) seismic signal recorded at the point.

4.3.2 Post-event field investigation

Field investigations and UAV surveys at Fotangba Gully began three days after the debris flow events, and local villagers confirmed that the accumulation fans had not been disturbed. UAV aerial images of the accumulation fan at the Gully mouth, along with close-ups of surface conditions, are shown in Figure 11a to c. Field measurements indicate that the fan thickness at location ① is about 1.2 m, with a thin layer (1–2 mm) of clay covering the surface in some areas (Figure 11c). Some rocks larger than 1 m in diameter (Figure 11b and 11c) suggest that the debris flow had a relatively high carrying capacity. Larger rocks are found at the bottom of the alluvial fan (Figure 11b), while smaller rocks are located at the front (Figure 11c), indicating that the carrying capacity of the debris flow decreases sharply after being released from the channel constraints as the cross-sectional area increases.

A sediment sample weighing about 4.7 kg was collected from the accumulation fans in Fotangba Gully to estimate the particle size distribution of the debris flow, taken from location ① in Figure 11a. Grain size analysis was performed using sieving and a Malvern particle sizer. Due to the lack of several sample analyses in this study, more analyses should be conducted for better variability estimation. We also neglected to record the portion of materials above the maximum particle size shown in the granulometric curve, which should be addressed in future research. The results indicate that clay particles (size < 0.005 mm) made up only 0.041% of the total sample weight (Figure 11d), consistent with field observations. The low cohesive sediment content in the accumulation fan sample may result from removal by post-event processes, such as

the flushing action of the Minjiang River or human clearance. The particle size distribution shows that 94% of the sample particles are 0.018 m, denoted as D in Eq. (6). In the next section, we will use D as a basis for analyzing the PSD curve features of the debris flow.

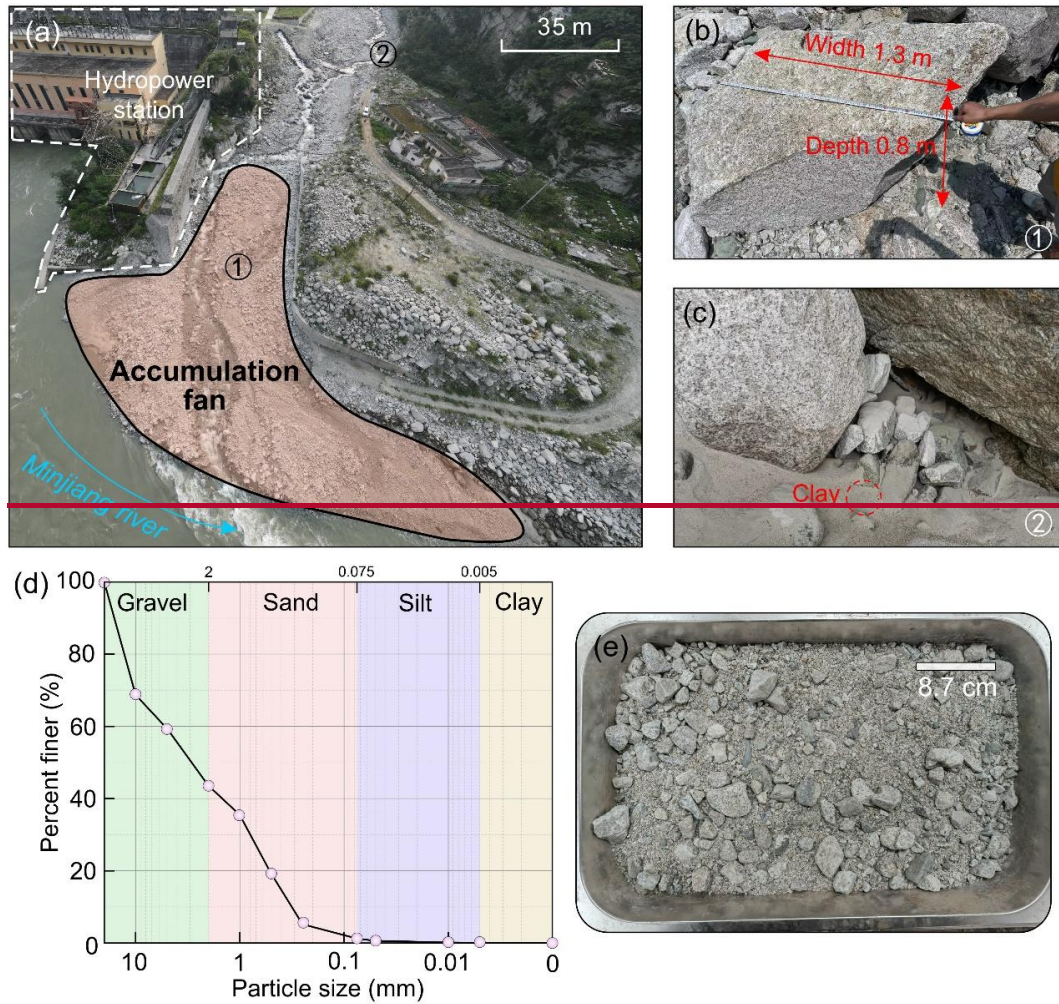


Figure 11 Post-event field survey of accumulation fans in Fotangba Gully. (a) Aerial view of the Fotangba Gully fan; (b) Largest particle on the Fotangba Gully fan, marked ① in image (a); (c) Thin layer of clay covering the accumulation surface in Fotangba Gully, marked as ② in image (a); (d) Particle size distribution for Fotangba Gully sediment samples; (e) Fotangba Gully sediment sample. Clay has not been marked in the subplot (d) because the particles with grain size less than 0.005 mm account for 0.041% of the total weight of the sample.

4.3.3 PSD analysis of the key points

The seismic power spectral density (PSD) is utilized to analyze the variations in the characteristic parameters of the debris flow. PSD curves for six time points, corresponding to their infrared images (Fig. 7b to 7h), were calculated using Eq. (5) (Figure 12a1) (Fig. 10a). These curves show a clear decrease in maximum power energy from 7:39 to 8:04, with power energy initially increasing with frequency before decreasing. The peak frequency band across all intervals. The, which is the frequency bands are categorized as corresponding to the maximum energy marked by black dots in Fig. 10a, increased slightly first and then a significant large increase and decrease, which flowed by slight decreases over time. Spectral width shows a feature of first broadening, which get the widest at 7:44, and then gradually narrows, but changes at different times are still relatively complex. We partitioned the frequency range into three parts for the analysis of PSD variation characteristics: low frequency (<15 Hz), main medium frequency (15-30 Hz), and high frequency (>30 Hz). The PSD of high-frequency power energy decreases gradually from 7:39 to 8:04, dropping decreased rapidly from 7:39 to 7:49 and more slowly from 7:54 to 8:04. In contrast, the low-frequency power energy increases significantly from 7:39 to 7:44, sharply decreases around 7:54, and then stabilizes. These variations highlight the need for further understanding. We will use a seismic PSD forward modeling approach to interpret these results comprehensively.

We conducted debris flow seismic PSD forward modeling (Figure 12b) using Eq. (6) with parameters from observations of the second debris flow in Fotangba Gully. Particle size, D , was based on 94% of the particle size distribution, resulting in values of 0.01 m, 0.015 m, 0.02 m, and 0.025 m. Velocity, u , was set at 2 m/s, 4 m/s, and 6 m/s, consistent with the mean velocity in Section 4.2. The seismic propagation distance, r_0 , was measured from Point 1 to the central channel of the second debris flow. Other parameters in Eq. (6) were consistent with those used for seismic signal recovery in

Section 4.1.2.

As shown in Figure 12b, debris flow velocity significantly affects the PSD energy level, while particle size has a weaker impact. For the same particle radius, energy increases sharply across the 47, while a spike in low frequency band with higher flow velocities. In contrast, energy increases within specific occurred from 7:39 to 7:44, followed by a quick drop from 7:44 to 7:54. The frequency bands are modest when varying particle size at a constant flow velocity. The effect of flow velocity is more pronounced at the high-frequency end, suggesting that high-frequency energy can effectively indicate variations in flow velocity changes during the rest of the time were not significant.

Examining the PSD curves for the six time points shows a gradual decrease at the high-frequency end, indicating a reduction in debris flow velocity. The decline is rapid from 7:39 to 7:59 and then slows down, aligning with flow rate analyses based on infrared imagery. In the low-frequency range, velocity also affects energy, but the changes are smaller than in the high-frequency range. Notably, low-frequency energy increases at 7:44 compared to 7:39, contrasting with high-frequency behavior. Figure 10c shows an infrared image indicating a higher concentration of particles in the debris flow at 7:44, suggesting that this low-frequency energy may result from these particles.

The peak frequency is influenced by both particle size and flow velocity (Figure 12b). Smaller particle sizes and higher flow velocities result in higher peak frequencies, and vice versa. This phenomenon arises from the combined effects of particle size and flow velocity. Additionally, particle content, including flux and concentration, significantly affects seismic signal energy. Therefore, when considering the model in Eq. (6), accounting for particle concentration is essential. Analyzing the peak frequency of seismic signals from 7:39 to 8:04 reveals an interesting pattern: the peak frequency increases, decreases, and then rises again. This reflects the response of particle size and flow velocity to the PSD. Specifically, as flow velocity decreases, particle size increases.

Significant changes in flow velocity should correspond with changes in sediment concentration.

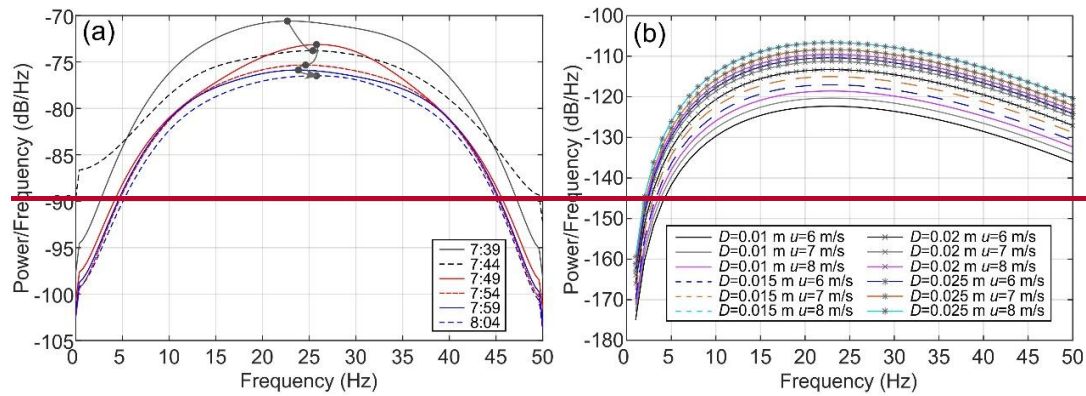


Figure 12 The amplitude of PSD shows a gradually decreasing trend, reflecting that the flow velocity of debris flows as a whole shows a decreasing trend. D94 grain size, flow velocity, width and length of the channel only influence the PSD amplitude (Eq. 1), while r_0 , v_c , and Q affect the shape of the PSD. The parameters, width and length of debris flow, which are positively correlated with flow velocity given the short duration of the event, mainly characterize the flow volume, which determines the volume of particle hitting the riverbed, and has a linear relationship with the PSD amplitude. We assumed that D94 grain size is proportional to flow velocity, given that starting velocity is proportional to the square of the particle size and the force maintaining the movement of particles is much smaller. So, the amplitude is reckoned to be scaled to the sixth power of the flow velocity (Eq. 1). Based on the above analysis, we can consider that the PSD energy is mainly controlled by the flow velocity of the debris flow. The amplitude of PSD showing a gradually decreasing trend, reflect that the flow velocity of the debris flow is gradually decreasing, and the extent of the debris flow speed reduction is gradually decreasing.

Propagation distance (r_0), Rayleigh wave phase velocity at 1HZ (v_c), and attenuation factor (Q) determine the spectrum shape characteristics of PSD (Eq. 1). We investigated the effect of these three parameters and linked the frequency features variation and dynamic parameters of debris flow via a simple forward algorithm based

on Eq. 1. The key parameters were derived from the second debris flow at Fotangba Gully: the D94 value is determined by the 94th centile of the grain size distribution; the flow velocity of 7 m/s is obtained through cross-correlation calculation; the r_0 , v_c , and Q are set near the values during the seismic signal restoration. The results are shown in Fig. 10b. The peak frequency of PSD shifts towards a higher frequency and a broader band as r_0 decreases or a contrary alteration of v_c and Q .

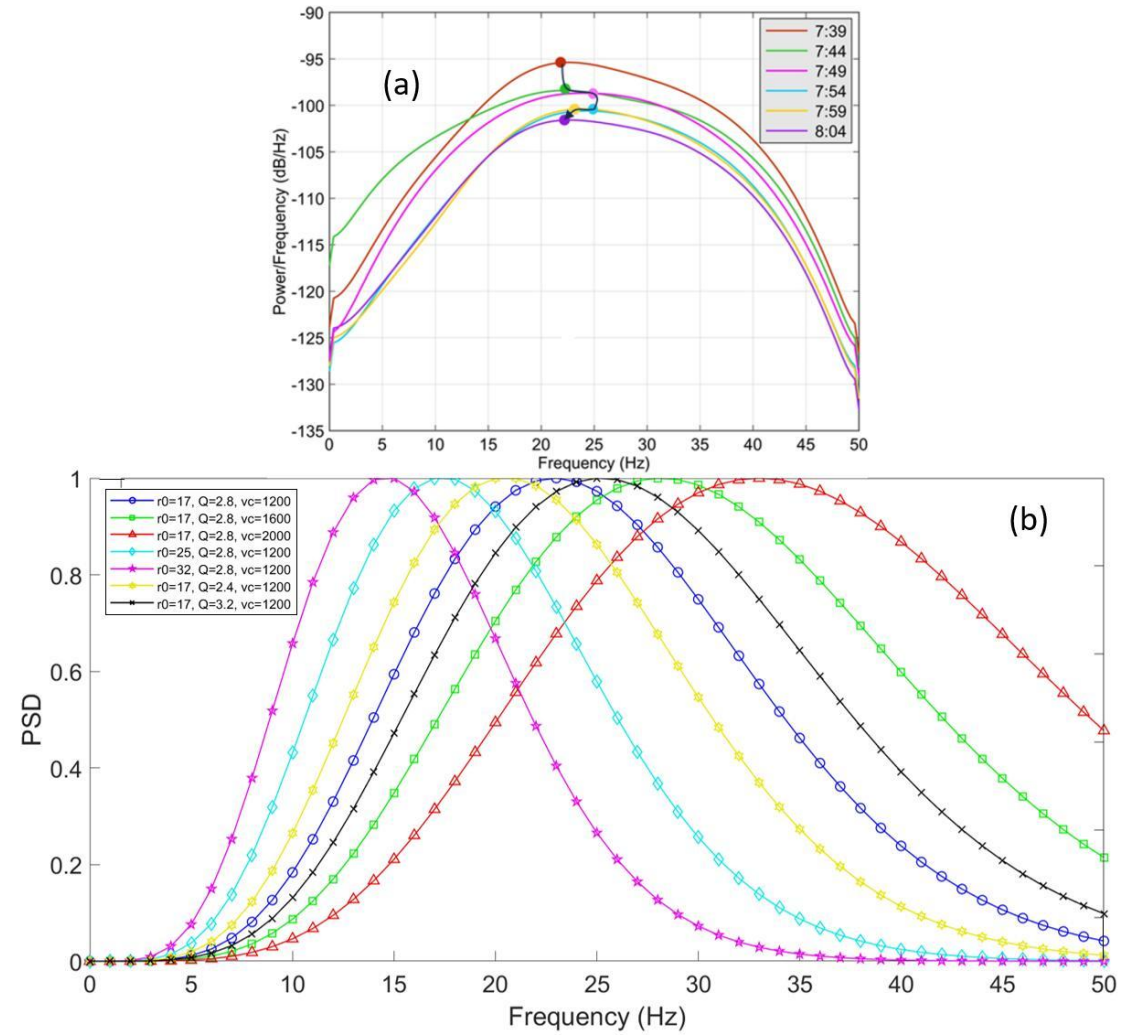


Fig. 10. Characteristic change of power spectral density (PSD). (a) Evolution of PSD during the second debris flow in Fotangba Gully on the morning of August 19, 2022, from 7:39 to 8:04; (b) Comparison of PSD for different grain sizes (D) and velocities (u). Each curve represents PSD frequency over 60 s. r_0 , Q , and v_c . The six dots in subplot (a) correspond to the PSD maximum at the six-time points from 7:39 to 8:04, and the

black arrows indicate the time course of these six-time points. ~~The PSD values of $D=0.015$ m and $u=8$ m/s, $D=0.02$ m, and $u=6$ m/s are equal, so the curves coincide in subplot (b).~~

~~From our analysis, we conclude that in the six moments from 7:39 to 8:04, the flow velocity gradually decreases, and the particle size, particle concentration, and flow velocity first increase and then decrease. This pattern is consistent with the results of the infrared image analysis in Section 4.4.1 and confirms that the trend of the debris flow can be determined from the time-frequency characteristics of the seismic signals.~~

In our study, the seismic signals generated by the vibrations of debris flow particles with the riverbed within a certain range around the sensors are superimposed and received. We assumed that the variation of v_c and Q near the channel mainly composed of debris flow deposition changes slightly. The seismic signals, generated by debris flow channel farther away from the sensor, travel much longer leading the seismic mainly dominated by low-frequency signals and with relatively low peak frequencies; whereas the seismic signal from the nearby channel is opposite, dominated by high-frequency signals and with relatively high peak frequencies. Flow velocity, flow volume, and particle content vary throughout the entire river channel. The seismic signals received from the debris flow with a high velocity, massive volume, and rich particle content primarily consist of low frequencies with lower peak frequencies. Conversely, the signals are mainly high frequencies under the opposite conditions. The low- and high-frequency energy shows a substantial enhancement from 7:44 to 7:49, along with an alteration in the peak frequency toward a higher frequency, indicating an increasing signal strength at different propagation distances. In contrast, low-frequency energy decreases and high-frequency energy stays stable at 7:54, suggesting that the seismic energy from distant sources weakens and from nearby sources remains steady. The variation of grain concentration (flow volume and particle content) near the channel affects the shape of PSD. An anomaly observed at 7:44 in low-frequency

energy is due to the upstream flow volume rising. As debris flow with high grain concentration moves toward the sensors and flows downstream, the low-frequency energy decreases and eventually recovers to a normal level.

We believed that the flow velocity decreases and grain concentration follows a trend of increasing first and then dropping during the six key moments with a 5-minute sampling interval from 7:39 to 8:04. The results are consistent with the findings from infrared image analysis in Section 4.3.2, demonstrating that analyzing the evolution of the debris flow using the time-frequency characteristics of seismic signals is feasible.

5 Discussion

5.1 Characteristics and evolution of debris flow events

This study successfully monitored three debris flows in Wenchuan, China, using a seismic signal-based observation system. Given the quality and completeness of the data collected, particular attention was paid to the second debris flow in Fotangba Gully. By analyzing the seismic signal characteristics in combination with time-delayed camera recordings and post-event investigations, the debris flow process and changes in characteristic parameters were examined, leading to the reconstruction of the second debris flow process in Fotangba Gully. The seismic signals ~~from~~of the three ~~debris flow~~mudflow events ~~show~~showed similar amplitude and time-frequency ~~patterns, but~~ variations in characteristics. However, differences in the monitoring locations ~~lead~~led to ~~differences~~deviations in signal propagation and attenuation. ~~By combining seismic signal analysis with imagery and using~~By applying compensation functions to ~~closely~~partially restore the original seismic signals, signal attenuation was minimized, allowing the movement of the debris flow to be mapped more accurately. The seismic signal characteristics captured the entire course of the debris flow process, and in combination with image analysis from time-lapse cameras, the development of the debris flow could be derived more accurately. After determining the entire movement sequence of the debris flow, characteristic parameters of the debris flow were extracted

from the seismic signals. These parameters were then verified by field investigations, ensuring the accuracy of the reconstruction of the debris flow process.

The average velocity of the second debris flow event at Fotangba Gully, calculated using the cross-correlation function, was validated as reliable by the Manning formula. However, using the same method, the flow velocity of the Er Gully debris flow was calculated to be 38.3 m/s. Due to the damage observed in the Er Gully debris flow images and at the site, we ~~can effectively reconstruct the debris flows' motion and dynamics.~~ were unable to verify this result using the Manning formula. Since this velocity exceeds the 1-6 m/s range found by Cui et al. (2018) for the Er Gully debris flow, we infer that the flow velocity derived from the cross-correlation calculation for this event is likely incorrect. Upon reviewing previous studies that used the cross-correlation algorithm to calculate debris flow velocities, we found that the channels between the two measurement stations in these studies were relatively straight (with small curvature) (Arattano et al., 2012; Comiti et al., 2014; Schimmel et al., 2022). By comparing the locations of the Er Gully and Fotangba Gully observation points, we hypothesized that the significant curvature of the channel between the two observation points in Er Gully may be a key factor. Therefore, directly using the cross-correlation algorithm to calculate the flow velocity for debris flows in highly curved channels between monitoring stations may not be reliable.

When selecting the analysis ~~timeperiod~~ for the ~~Power Spectral Density~~power spectral density (PSD) curve, it is important to consider the ~~seismic signal~~ characteristics of the seismic signals and ~~chooses~~select representative time points. ~~Estimating flow velocity and particle size~~It is also recommended to estimate both the flow velocity and the particle size, as these factors can significantly ~~affect~~influence the PSD curve. ~~Integrating~~By integrating detailed data from post-disaster ~~investigation data~~investigations, dynamic parameters, and ~~forward modeling~~results ~~can greatly improve~~from forward simulations, the reliability of ~~analyzing debris flow evolution~~

using seismic signals seismic signal-based analysis of the development process of debris flows can be significantly improved.

~~By comparing the mean velocity calculations from the cross-correlation function and Manning's formula, we observed discrepancies in the cross-correlation results for the Fotangba Gully debris flows (Table 3). Comiti et al. (2014) noted that the cross-correlation function tends to underestimate debris flow velocities, a finding corroborated by this study. One potential factor influencing the velocity calculations is the distance between seismic sensors. In this study, the sensors were approximately 500 meters apart, while Arattano and Marchi (2005) suggested that sensor spacing exceeding 100 meters may reduce the accuracy of velocity calculations based on the cross-correlation function. Our velocity result of 7.0 m/s falls within the range of 3.0–9.1 m/s reported by Arattano and Marchi (2005), thereby enhancing the credibility of our findings. Additionally, the empirical nature of the Manning formula may contribute to the differences observed between the two methods (Kang, 1987). For the Er Gully debris flow, the velocity obtained through cross-correlation was an order of magnitude larger, indicating that excessively curved channels may not be suitable for velocity calculations using the cross-correlation function.~~

5.2 Limitations and future works

~~This study addresses the situation of debris flow that is difficult to reach and inconvenient to install instruments and proposes a monitoring system that is easy to monitor, reliable, and low-cost. Through this system, we can explain and analyze the debris flow process well by using seismic signal monitoring and analysis, combined with time-lapse camera image analysis, and post-event investigation. Of course, due to the unsystematic nature of the monitoring instruments (only seismic monitoring instruments and time-lapse cameras), many of the analyses in this study are mostly preliminary and lack a certain degree of accuracy. However, based on this study, we expect to improve the monitoring and analysis based on seismic signals for subsequent~~

debris flow detection, early warning, and inversion.

There were some issues with the application of infrared cameras in the study. The cameras were not able to record images of nighttime debris flows. Even for daytime debris flows, factors such as rainfall or debris flow splashes caused water droplets to adhere to the infrared camera lens, partially blurring the recorded images. Also, the 5-minute interval between recorded images is fine for determining debris flow movement, but the time resolution is too coarse to determine changes in flow characteristics during debris flow evolution. In follow-up studies, the interval between images should be decreased. It would also be useful to have a wider array of instruments at each monitoring station, including flow level gauges, to aid seismic signal analysis and velocity estimation and place more stations over a larger area to generate a larger dataset. This would allow future research to focus on the identification of early warning thresholds for debris flow disasters.

Although this study successfully reconstructed the debris flow process, the reconstruction was based mainly on time and monitoring location cross-sections due to the limited and unsystematic monitoring instruments (which only included seismic monitoring devices and time-lapse cameras). It was unable to provide a detailed analysis of the debris flow process at all locations, as is possible with numerical simulations. However, by combining the seismic signal characteristics with the image analysis of the time-lapse cameras, we were able to gain a better understanding of the timing and duration of the debris flow and extract parameters such as flow velocity and particle size. These findings are valuable for understanding debris flow dynamics.

In this study, the seismic signals alone were not sufficient to fully reconstruct the debris flow process, which is why the image analysis from the cameras was also included. However, some problems arose with the use of infrared cameras. The cameras were unable to capture images of the debris flow at night, and even during the day, rain or splashing debris caused water droplets to stick to the camera lens, making some of

the images blurry. In addition, the image recording interval was 5 minutes, which was useful for tracking the debris flow but lacking the time resolution to capture changes in the flow field during the development of the debris flow. Future research should shorten the image interval and equip each monitoring station with a wider range of instruments, including flow meters, to support seismic signal analysis and velocity estimation. More observation stations should be set up over a larger area to generate a more comprehensive dataset. Ultimately, we hope that this study will contribute to a better understanding of the entire debris flow process and, through improvements in seismic signal-based monitoring and analysis, enable a more accurate quantitative reconstruction of the debris flow process, thereby improving the effectiveness of subsequent debris flow detection, early warning, and inversion efforts.

We have used the assumptions of point sources and plane waves to simplify the calculation of the compensation. Theoretically, the compensation should be calculated by integrating over the channel. However, due to variations in the response functions of the point sources at different locations in the channel and factors such as loose surface, meandering flow and varying river width, integration becomes difficult. Therefore, we chose a simplified approach. We assumed a constant propagation velocity and a constant quality factor in the propagation area, ignoring changes in river width, and calculated the weighted travel time from a river section near the monitoring point to the monitoring point itself. The compensation of the propagation effect was then based on the assumption of a plane wave. Since this method is inherently subject to some errors, we adjusted the gain factor to maximize compensation and ensure numerical stability. ~~Accurate measurement of seismic wave propagation velocity, quality factor and flow morphology near the monitoring point would improve the accuracy of the compensation. However, these parameters are labor-intensive to measure, unstable, and significantly affected by precipitation and human subjective consciousness influences, making their repeated use difficult. Therefore, in practical~~

~~applications, we integrated the line source characteristics and considered the planar features of seismic wave propagation velocity, quality factor, and river morphology near the monitoring point, adopting a numerically stable approach. This method requires careful consideration of the effects of location on the results to ensure effective and accurate compensation. In addition, there are considerable lateral fluctuations due to the weak compaction of the river channel sediments and the relative instability of these sediments. These factors increase the difficulty of compensation, which complicates the accurate measurement of the compensation parameters and reduces their reliability. In practice, we therefore adhere to the principle of numerical stability. This means that we prevent the noise energy from exceeding the signal energy and at the same time try to maximize the energy in all frequency bands.~~

~~The small dataset of the current study does not allow a broader analysis of debris flow dynamics; however, it does demonstrate the effectiveness of using an in-situ seismic network for real time monitoring of debris flows, provides theoretical support for the inversion of debris flow dynamics, and highlights the potential for application in early warning systems.~~

6 Conclusions

~~This~~In this study ~~successfully monitored the~~, a seismic signal characteristics of three debris flows that occurred in the Wenchuan earthquake area of China on August 19, 2022, using a near-field ~~based~~-based debris flow monitoring system. ~~The research investigated the seismic characteristics of these three debris flows, which exhibited fast excitation and slow decay. Even after largely eliminating the propagation effect, significant differences were observed in the seismic amplitude and frequency characteristics at different monitoring stations of the same debris flow, indicating changes in the dynamic parameters of the debris flow during its evolution. By utilizing the seismic signal characteristics, the study determined the occurrence time and duration of the three debris flows and reconstructed the entire process of~~ successfully

recorded three debris flow events in Wenchuan, China, on August 19, 2022. Analysis revealed that all three events showed rapid excitation followed by slow attenuation of their seismic signals. Attenuation compensation applied to the second debris flow in Fotangba. ~~Using the cross-correlation function, the average flow velocity of Gully~~ showed that the kinematic characteristics of the debris flow changed during its progression. By combining seismic signals, video and field investigation analyses, the second debris flow event in Fotangba Gully was ~~determined~~reconstructed. The average flow velocity was found to be 7.0 m/s, ~~and this result~~ using cross-correlation, which was validated ~~for reliability using with~~ the Manning formula.

~~In the case of Er Gully with relatively complex topography, the effectiveness of the cross-correlation function was limited, likely due to the more complex terrain leading to significant variations in the kinematic parameters of the debris flow. Therefore, while the cross-correlation function may be~~ Furthermore, a suitable method for calculating peak flow in simple debris flows, it may not be as appropriate for more complex debris flows.

~~These three debris flow events occurred~~synchronous relationship between PSD and debris flow characteristics was clear under heavy rainfall conditions. ~~Changes in the flow state of the debris flow, identified through image~~a short period of debris flow events. The decline of PSD amplitude reflected the decrease of debris flow velocity. Our results are helpful to the reconstruction analysis and ~~field investigations, resulted in different frequency ranges in the energy spectrum at the beginning and end of the debris flow, as confirmed by continuous photo analysis, PSD of current records, and forward modeling. By analyzing the seismic amplitude and frequency characteristic changes at different monitoring stations of the debris flows, rough insights into the relative changes during the evolution process of the debris flow can be obtained.~~

Through the case application of this study, we propose a simple, inexpensive, and remote monitoring system for the situation of debris flow monitoring stations with

~~inconvenient installation of instruments and low budget. This study is expected to~~
~~provide a theoretical basis for future debris flow monitoring and warning methods~~
~~based on seismic signal and inversion methods.~~ of the evolution process of debris flow.

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Code/Data availability

All raw data can be provided by the corresponding authors upon request.

Author contributions

The authors of this manuscript entitled “Monitoring, analysis and application of debris flow based on seismic signal” are Yan Yan, Renhe Wang, Cheng Zeng, Renhe Wang, Yifei Cui, Sheng Hu, Xinglu Wang, and Hui Tang. Yan Yan is the first author and is responsible for Conceptualization, Methodology, Writing-Original draft preparation in this research. Cheng Zeng Renhe Wang is the second author, is responsible for data organization, validation, and revising the original draft. Renhe Wang Cheng Zeng is the third author, responsible for data collection, field investigation, and manuscript revision. Yifei Cui is the fourth author and the corresponding author, is responsible for the Review & Editing, Supervision. Sheng Hu is the fifth author and is responsible for Visualization. Xinglu Wang is responsible for the Investigation, Validation. Hui Tang is the seventh author and is responsible for Writing- Reviewing and Editing.

1371 **Competing interests**

1372 The authors declare that they have no conflict of interest.

References

- Aaron, J., Spielmann, R., McArdell, B. W., Graf, C., 2023. High-Frequency 3D LiDAR Measurements of a Debris Flow: A Novel Method to Investigate the Dynamics of Full-Scale Events in the Field. *Geophys. Res. Lett.* 50(5), e2022GL102373; <https://doi.org/10.1029/2022GL102373>, 2023.
- Allstadt, K. E., Farin, M., Iverson, R. M., Obryk, M. K., Kean, J. W., Tsai, V. C., Logan, M., 2020. Measuring basal force fluctuations of debris flows using seismic recordings and empirical green's functions. *Journal of Geophysical Research: Earth Surface*, 125(9), e2020JF005590.
- Andrade, S.D., Almeida, S., Saltos, E., Pacheco, D., Hernandez, S., Acero, W., 2022. A simple and general methodology to calibrate seismic instruments for debris flow quantification: application to Cotopaxi and Tungurahua volcanoes (Ecuador). *Landslides* 19(3), 747-759; <https://doi.org/10.1007/s10346-021-01784-5>, 2022.
- Arattano, M., 1999. On the use of seismic detectors as monitoring and warning systems for debris flows. *Nat. Hazards* 20(2-3), 197-213; <https://doi.org/10.1023/A:1008061916445>, 1999.
- ~~Arattano, M., Moia, F.: Monitoring the propagation of a debris flow along a torrent. *Hydrol. Sci. J.* 44(5), 811-823, <https://doi.org/10.1080/02626669909492275>, 1999.~~
- Arattano, M., Marchi, L., 2005. Measurements of debris flow velocity through cross-correlation of instrumentation data. *Nat. Hazards Earth Syst. Sci.* 5(1), 137-142; <https://doi.org/10.5194/nhess-5-137-2005>, 2005.
- Arattano, M., Marchi, L., 2008. Systems and sensors for debris-flow monitoring and warning. *Sensors* 8(4), 2436-2452; <https://doi.org/10.3390/s8042436>, 2008.
- ~~Arattano, M., Marchi, L., Cavalli, M.: Analysis of debris flow recordings in an instrumented basin: confirmations and new findings. *Natural Hazards and Earth System Sciences*, 12(3), 679-686. <https://doi.org/10.5194/nhess-12-679-2012>, 2012.~~
- ~~Barrière, J., Oth, A., Hostache, R., Krein, A.: Bed load transport monitoring using seismic observations in a low gradient rural gravel bed stream. *Geophys. Res. Lett.* 42(7), 2294-2301, <https://doi.org/10.1002/2015GL063630>, 2015.~~
- Beason, S.R., Legg, N.T., Kenyon, T.R., Jost, R.P., 2021. Forecasting and seismic detection of proglacial debris flows at Mount Rainier National Park, Washington, USA. *Environ. Eng. Geosci.* 27(1), 57-72; <https://doi.org/10.2113/EEG-D-20-00014>, 2021.
- Belli, G., Marchetti, E., Walter, F., Gheri, D., 2025. Infrasound unmasks flow turbulence as an additional seismic source in debris flows. *Geophysical Research Letters*, 52(8), e2025GL116107.
- Belli, G., Walter, F., McArdell, B., Gheri, D., Marchetti, E., 2022. Infrasonic and seismic analysis of debris - flow events at Illgraben (Switzerland): Relating signal features to flow parameters and to the seismo - acoustic source mechanism. *J. Geophys. Res.-Earth Surf.* 127(6), e2021JF006576; <https://doi.org/10.1029/2021JF006576>, 2022.
- ~~Berti, M., Genevois, R., LaHusen, R., Simoni, A., Tecce, P.R.: Debris flow monitoring in the Aequabona watershed on the Dolomites (Italian Alps). *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* 25(9), 707-715, <https://doi.org/10.1016/S1464->~~

1413 ~~1909(00)00090-3, 2000.~~

1414 Burtin, A., Bollinger, L., Cattin, R., Vergne, J., Nábělek, J.L., 2009. Spatiotemporal sequence of
 1415 Himalayan debris flow from analysis of high-frequency seismic noise. *J. Geophys. Res.* 114,
 1416 F04009, <https://doi.org/10.1029/2008JF001198>, 2009.

1417 Burtin, A., Hovius, N., Mcardell, B. W., Turowski, J. M., Vergne, J., (2014). Seismic constraints
 1418 on dynamic links between geomorphic processes and routing of sediment in a steep mountain
 1419 catchment. *Earth Surface Dynamics*, 2(1), 21-33.

1420 Cao, C., Yu, B., Ma, E.L., Liu, S., 2019. Study on debris flow in Fongtuba Gully after the
 1421 earthquake at Wenchuan County of Sichuan Province. *Journal of Sediment Research* 44(1), 38-
 1422 43, 2019. (in Chinese).

1423 ~~Chen, C.Y., Lin, L.Y., Yu, F.C., Lee, C.S., Tseng, C.C., Wang, A.H., Cheung, K.W.: Improving debris~~
 1424 ~~flow monitoring in Taiwan by using high-resolution rainfall products from QPESUMS. *Nat.*~~
 1425 ~~*Hazards* 40, 447-461, <https://doi.org/10.1007/s11069-006-9004-2>, 2007.~~

1426 ~~Chien-Yuan, C., Tien-Chien, C., Fan-Chieh, Y., Wen-Hui, Y., Chun-Chieh, T.: Rainfall duration and~~
 1427 ~~debris flow initiated studies for real time monitoring. *Environ. Geol.* 47, 715-724,~~
 1428 ~~<https://doi.org/10.1007/s00254-004-1203-0>, 2005.~~

1429 Chang, M., Liu, Y., Zhou, C., Che, H., 2020. Hazard assessment of a catastrophic mine waste debris
 1430 flow of Hou Gully, Shimian, China. *Engineering Geology*, 275, 105733.

1431 Chen, X., Cui, P., You, Y., Chen, J., Li, D., 2015. Engineering measures for debris flow hazard
 1432 mitigation in the Wenchuan earthquake area. *Engineering Geology*, 194, 73-85.

1433 Comiti, F., Marchi, L., Macconi, P., Arattano, M., Bertoldi, G., Borga, M., Brardinoni, F., Cavalli,
 1434 M., D'Agostino, V., Penna, D., Theule, J., 2014. A new monitoring station for debris flows
 1435 in the European Alps: first observations in the Gadia basin. *Nat. Hazards*, 73, 1175-1198;
 1436 <https://doi.org/10.1007/s11069-014-1088-5>, 2014.

1437 ~~Cook, K.L., Rekapalli, R., Dietze, M., Pilz, M., Cesca, S., Rao, N.P., Srinagesh, D., Paul, H., Metz,~~
 1438 ~~M., Mandal, P. and Suresh, G.: Detection and potential early warning of catastrophic flow~~
 1439 ~~events with regional seismic networks. *Science*, 374(6563), pp.87-92,~~
 1440 ~~<https://doi.org/10.1126/science.abj1227>, 2021.~~

1441 ~~Cook, K. L., Dietze, M.: Seismic advances in process geomorphology. *Annu. Rev. Earth Planet. Sci.*~~
 1442 ~~50, 183-204, <https://doi.org/10.1146/annurev-earth-032320-085133>, 2022.~~

1443 Coviello, V., Arattano, M., Turconi, L., 2015. Detecting torrential processes from a distance with
 1444 a seismic monitoring network. *Nat. Hazards* 78, 2055-2080, [https://doi.org/10.1007/s11069-](https://doi.org/10.1007/s11069-015-1819-2)
 1445 [015-1819-2](https://doi.org/10.1007/s11069-015-1819-2), 2015.

1446 Crowley, J. K., Hubbard, B. E., Mars, J. C., 2003. Analysis of potential debris flow source areas on
 1447 Mount Shasta, California, by using airborne and satellite remote sensing data. *Remote Sensing*
 1448 *of Environment*, 87(2-3), 345-358.

1449 Cui, P., Guo, X., Yan, Y., Li, Y., Ge, Y., 2018. Real-time observation of an active debris flow
 1450 watershed in the Wenchuan Earthquake area. *Geomorphology* 321, 153-166,
 1451 <https://doi.org/10.1016/j.geomorph.2018.08.024>, 2018.

1452 Cui, P., Zhou, G.G., Zhu, X.H., Zhang, J.Q., 2013. Scale amplification of natural debris flows
 1453 caused by cascading landslide dam failures. *Geomorphology*, 182, 173-189,

<https://doi.org/10.1016/j.geomorph.2012.11.009>, 2013 182, 173-189.

~~Dammeier, F., Moore, J.R., Hammer, C., Haslinger, F., Loew, S.: Automatic detection of alpine rockslides in continuous seismic data using hidden Markov models. J. Geophys. Res. 121(2), 351-371, <https://doi.org/10.1002/2015JF003647>, 2016.~~

Deparis, J., Jongmans, D., Cotton, F., Baillet, L., Thouvenot, F., Hantz, D., 2008. Analysis of rock-fall and rock-fall avalanche seismograms in the French Alps. Bull. Seismol. Soc. Amer. 98(4), 1781-1796, <https://doi.org/10.1785/0120070082>, 2008.

~~Ekström, G., Stark, C.P.: Simple scaling of catastrophic landslide dynamics. Science 339(6126), 1416-1419, <https://doi.org/10.1126/science.1232887>, 2013.~~

Farin, M., Tsai, V. C., Lamb, M. P., Allstadt, K. E., 2019. A physical model of the high-frequency seismic signal generated by debris flows. Earth Surf. Process. Landf. Surface Processes and Landforms, 44(13), 2529-2543, <https://doi.org/10.1002/esp.4677>, 2019.

Fu, J., Wang, X., Li, Z., Meng, H., Wang, J., Wang, W., Tang, C., 2020. Automatic phase-picking method for detecting earthquakes based on the signal-to-noise-ratio concept. Seismological Research Letters, 91(1), 334-342.

Fuchs, F., Lenhardt, W., Bokelmann, G., AlpArray Working Group, 2018. Seismic detection of rockslides at regional scale: examples from the Eastern Alps and feasibility of kurtosis-based event location. Earth Surf. Dyn. 6(4), 955-970, <https://doi.org/10.5194/esurf-6-955-2018>, 2018(4), 955-970.

Futterman, W. I., 1962. Dispersive body waves. J. Geophys. Res. 67(13), 5279-5291, <https://doi.org/10.1029/JZ067i013p05279>, 1962.

Guo, N., Zhou, X., Xu, K., Wang, Y., Lyu, J., Duan, M., 2023. Near-surface Q -value survey method based on uphole with hammer excitation and receiving using multi-stage geophones on wells. Oil Geophysical Prospecting 58(2), 295-304, 2023. (in Chinese).

Guo, X., Cui, P., Li, Y., Zou, Q., Kong, Y., 2016. The formation and development of debris flows in large watersheds after the 2008 Wenchuan Earthquake. Landslides 13, 25-37, <https://doi.org/10.1007/s10346-014-0541-6>, 2016.

~~Hibert, C., Mangeney, A., Grandjean, G., Shapiro, N.M.: Slope instabilities in Dolomieu crater, Réunion Island: From seismic signals to rockfall characteristics. J. Geophys. Res. 116, F04032, <https://doi.org/10.1029/2011JF002038>, 2011.~~

~~Huang, C.J., Yeh, C.H., Chen, C.Y. and Chang, S.T.: Ground vibrations and airborne sounds generated by motion of rock in a river bed. Natural Hazards and Earth System Sciences, 8(5), pp.1139-1147, <https://doi.org/10.5194/nhess-8-1139-2008>, 2008.~~

He, K., Liu, B., Hu, X., Zhou, R., Xi, C., Ma, G., Luo, G., 2022. Rapid characterization of landslide-debris flow chains of geologic hazards using multi-method investigation: Case study of the Tiejianwan LDC. Rock Mechanics and Rock Engineering, 55(8), 5183-5208.

Huang, C. J., Chu, C. R., Tien, T. M., Yin, H. Y., Chen, P. S., 2012. Calibration and deployment of a fiber-optic sensing system for monitoring debris flows. Sensors 12(5), 5835-5849, <https://doi.org/10.3390/s120505835>, 2012.

~~Huang, Z., Xu, M., Chen, W., Lin, X., Cao, C., Singh, R. P.: Postseismic restoration of the ecological environment in the Wenchuan region using satellite data. Sustainability, 10(11), 3990.~~

<https://doi.org/10.3390/su10113990>, 2018.

Huang, X., Li, Z., Fan, J., Yu, D., Xu, Q.: Frequency characteristics and numerical computation of seismic records generated by a giant debris flow in Zhouqu, Western China. *Pure Appl. Geophys.* 177, 347–358, <https://doi.org/10.1007/s00024-019-02177-5>, 2020.

Hübl, J., Schimmel, A., Kogelnig, A., Suriñach, E., Vilajosana, I., McArdell, B.W., 2013. A review on acoustic monitoring of debris flow. *International Journal of Safety and Security Engineering* 3(2), 105-115, <https://doi.org/10.2495/SAFE-V3-N2-105-115>, 2013.

Hürlimann, M., Abancó, C., Moya, J., Vilajosana, I.: Results and experiences gathered at the Rebaixader debris flow monitoring station, Central Pyrenees, Spain. *Landslides*, 11, 939–953, <https://doi.org/10.1007/s10346-013-0452-y>, 2014.

Hürlimann, M., Coviello, V., Bel, C., Guo, X., Berti, M., Graf, C., Hürl, J., Miyata, S., Smith, J.B., Yin, H.-Y., 2019. Debris-flow monitoring and warning: Review and examples. *Earth-Sci. Rev.* 199, 102981, <https://doi.org/10.1016/j.earseirev.2019.102981>, 2019, 102981.

Iverson, R. M., Hürlimann, M., Rickenmann, D., Graf, C.: Field and monitoring data of debris flow events in the Swiss Alps. *Can. Geotech. J.* 40(1), 161–175, <https://doi.org/10.1139/t02-087>, 2003.

2015. Scaling and design of landslide and debris-flow experiments. *Geomorphology*, 244, 9-20.

Iverson, R.M., 1997. The physics of debris flows. *Rev. Geophys.* 35(3), 245-296, <https://doi.org/10.1029/97RG00426>, 1997.

Kang, Z.C.: Kean, J. W., Coe, J. A., Coviello, V., Smith, J. B., McCoy, S. W., –velocity research Arattano, M., 2015. Estimating rates of debris flow and its calculating method in China. *Mountain entrainment from ground vibrations. Geophysical Research Letters*, 42(15), 6365-6372.

Kean, J. W., Staley, D. M., Leeper, R. J., Schmidt, K. M., Gartner, J. E., 2012. A low - cost method to measure the timing of postfire flash floods and debris flows relative to rainfall. *Water Resour. Res.* 48(5), 247–259, 1987), W05516.

Kean, J.W., Staley, D.M., Lancaster, J.T., Rengers, F.K., Swanson, B.J., Coe, J.A., Hernandez, J.L., Sigman, A.J., Allstadt, K.E., Lindsay, D.N., 2019. Inundation, flow dynamics, and damage in the 9 January 2018 Montecito debris-flow event, California, USA: Opportunities and challenges for post-wildfire risk assessment. *Geosphere* 15(4), 1140-1163, <https://doi.org/10.1130/GES02048.1>, 2019.

Kean, J. W., Staley, D. M., Leeper, R. J., Schmidt, K. M., Gartner, J. E.: A low - cost method to measure the timing of postfire flash floods and debris flows relative to rainfall. *Water Resour. Res.* 48(5), W05516, <https://doi.org/10.1029/2011WR011460>, 2012.

Kjartansson, E., 1979. Constant Q - wave propagation and attenuation. *J. Geophys. Res.-Solid Earth* 84(B9), 4737-4748, <https://doi.org/10.1029/JB084iB09p04737>, 1979.

Kogelnig, A., Hübl, J., Suriñach, E., Vilajosana, I., McArdell, B.W., 2014. Infrasound produced by debris flow: propagation and frequency content evolution. *Nat. Hazards* 70, 1713-1733, <https://doi.org/10.1007/s11069-011-9741-8>, 2014.

Lai, V.H., Tsai, V.C., Lamb, M.P., Ulizio, T.P., Beer, A.R., 2018. The seismic signature of debris flows: Flow mechanics and early warning at Montecito, California. *Geophys. Res. Lett.* 45(11),

5528-5535, <https://doi.org/10.1029/2018GL077683>, 2018.

Li, Z., Huang, X., Xu, Q., Yu, D., Fan, J., Qiao, X., 2017. Dynamics of the Wulong landslide revealed by broadband seismic records. *Earth, Planets and Space* 69, 1-10; <https://doi.org/10.1186/s40623-017-0610-x>, 2017.

Liang, X., Segoni, S., Yin, K., Du, J., Chai, B., Tofani, V., Casagli, N., 2022. Characteristics of landslides and debris flows triggered by extreme rainfall in Daoshi Town during the 2019 Typhoon Lekima, Zhejiang Province, China. *Landslides*, 19(7), 1735-1749.

Liu C., Feng X., Zhang J., 2013. A stable inverse Q filtering using the iterative filtering method. *Oil Geophysical Prospecting* 48(6), 890-895, 2013. (in Chinese).

~~Liu, S., Hu, K., Zhang, Q., Zhang, S., Hu, X., Tang, D.: Quantitative analysis of the effects of an earthquake on rainfall thresholds for triggering debris-flow events. *Front. Earth Sci.* 9, 676470; <https://doi.org/10.3389/feart.2021.676470>, 2021.~~

Marchetti, E., Walter, F., Barfucci, G., Genco, R., Wenner, M., Ripepe, M., McArdell, B., Price, C., 2019. Infrasound array analysis of debris flow activity and implication for early warning. *J. Geophys. Res.* 124(2), 567-587; <https://doi.org/10.1029/2018JF004785>, 2019.

Marchi, L., Arattano, M., Deganutti, A. M., 2002. Ten years of debris-flow monitoring in the Moscardo Torrent (Italian Alps). *Geomorphology*, 46(1-2), 1-17; [https://doi.org/10.1016/S0169-555X\(01\)00162-3](https://doi.org/10.1016/S0169-555X(01)00162-3), 2002.

McArdell, B. W., Bartelt, P., Kowalski, J., 2007. Field observations of basal forces and fluid pore pressure in a debris flow. *Geophys. Res. Lett.* 34(7), L07406; <https://doi.org/10.1029/2006GL029183>, 2007.

McCoy, S. W., Kean, J. W., Coe, J. A., Staley, D. M., Waskiewicz, T. A., Tucker, G. E., 2010. Evolution of a natural debris flow: In situ measurements of flow dynamics, video imagery, and terrestrial laser scanning. *Geology* 38(8), 735-738; <https://doi.org/10.1130/G30928.1>, 2010.

~~Moretti, L., Mangeney, A., Capdeville, Y., Stutzmann, E., Huggel, C., Schneider, D., Bouchut, F.: Numerical modeling of the Mount Steller landslide flow history and of the generated long period seismic waves. *Geophys. Res. Lett.* 39(16), L16402; <https://doi.org/10.1029/2012GL052511>, 2012.~~

Nagl, Georg, and Johannes G., Hübl, J. 2017. A check-dam to measure debris flow-structure interactions in the Gadria torrent. In: M., Mikoš, Ž., Arbanas, Y., Yin, K., Sassa (eds.), *Advancing Culture of Living with Landslides*. Volume 5: Landslides in Different Environments. Springer International Publishing, pp. 465-471. https://doi.org/10.1007/978-3-319-53483-1_55, 2017.

Rickenmann, D., 1999. Empirical relationships for debris flows. *Nat. Hazards* 19, 47-77; <https://doi.org/10.1023/A:1008064220727>, 1999.

~~Roth, D. L., Brodsky, E. E., Finnegan, N. J., Rickenmann, D., Turowski, J. M., Badoux, A.: Bed load sediment transport inferred from seismic signals near a river. *J. Geophys. Res. Earth Surf.* 121(4), 725-747; <https://doi.org/10.1002/2015JF003782>, 2016.~~

Schenato, L., Pasuto, A., 2021. On the Use of Optical Fiber Sensors for Debris Flow Monitoring: A Review of Recent Achievements. *Belt and Road Webinar Series on Geotechnics, Energy and Environment* pp. 60-70; https://doi.org/10.1007/978-981-16-9963-4_5, 2021 60-70.

- Schimmel, A., Coviello, V., Comiti, F., 2022. Debris flow velocity and volume estimations based on seismic data. *Nat. Hazards Earth Syst. Sci.* 22(6), 1955-1968, <https://doi.org/10.5194/nhess-22-1955-2022>, 2022.
- Schimmel, A., Hübl, J., 2016. Automatic detection of debris flows and debris floods based on a combination of infrasound and seismic signals. *Landslides* 13, 1181-1196, <https://doi.org/10.1007/s10346-015-0640-z>, 2016.
- Schneider, D., Bartelt, P., Caplan - Auerbach, J., Christen, M., Huggel, C., McArdell, B.W., 2010. Insights into rock-ice avalanche dynamics by combined analysis of seismic recordings and a numerical avalanche model. *J. Geophys. Res.* 115, F04026, <https://doi.org/10.1029/2010JF001734>, 2010, F04026.
- Strick, E., 1967. The determination of Q, dynamic viscosity and transient creep curves from wave propagation measurements. *Geophys. J. Int.* 13(1-3), 197-218, <https://doi.org/10.1111/j.1365-246X.1967.tb02154.x>, 1967.
- Suwa, H., Okano, K., Kanno, T., 2009. Behavior of debris flows monitored on test slopes of Kamikamihorizawa Creek, Mount Yakedake, Japan. *International Journal of Erosion Control Engineering* 2(2), 33-45, <https://doi.org/10.13101/ijece.2.33>, 2009.
- Tang, C., Rengers, N.V., Van Asch, T.W., Yang, Y.H., Wang, G.F., 2011. Triggering conditions and depositional characteristics of a disastrous debris flow event in Zhouqu city, Gansu Province, northwestern China. *Nat. Hazards Earth Syst. Sci.* 11(11), 2903-2912, <https://doi.org/10.5194/nhess-11-2903-2011>, 2011.
- Tecca, P.R., Galgaro, A., Genevois, R., Deganutti, A.M., 2003. Development of a remotely controlled debris flow monitoring observation system in the Dolomites (Acquabona, Italy). *Hydrol. Process.* 17(9), 1771-1784, <https://doi.org/10.1002/hyp.1212>, 2003.
- Tsai, V. C., Minchew, B., Lamb, M. P., & Ampuero, J.-P., 2012. A physical model for seismic noise generation from sediment transport in rivers. *Geophys. Res. Lett.* 39(2), L02404, <https://doi.org/10.1029/2011GL050255>, 2012.
- Turbessi, L., Taboni, B., Umili, G., Fubelli, G., Ferrero, A. M., 2025. Modeling Debris Flow Events in the Rio Inferno Watershed (Italy) Through UAV-Based Geomorphological Survey and Rainfall Data Analysis. *Sensors*, 25(7), 1980.
- Van Herwijnen, A., Schweizer, J., 2011. Monitoring avalanche activity using a seismic sensor. *Cold Reg. Sci. Tech.* 69(2-3), 165-176, <https://doi.org/10.1016/j.coldregions.2011.06.008>, 2011.
- Vilajosana, I., Suriñach, E., Abellán, A., Khazaradze, G., Garcia, D., Llosa, J., 2008. Rockfall induced seismic signals: case study in Montserrat, Catalonia. *Nat. Hazards Earth Syst. Sci.* 8(4), 805-812, <https://doi.org/10.5194/nhess-8-805-2008>, 2008.
- Walter, F., Burtin, A., McArdell, B.W., Hovius, N., Weder, B., Turowski, J.M., 2017. Testing seismic amplitude source location for fast debris-flow detection at Illgraben, Switzerland. *Nat. Hazards Earth Syst. Sci.* 17(6), 939-955, <https://doi.org/10.5194/nhess-17-939-2017>, 2017, 939-955.
- Wang, Y., 2002. A stable and efficient approach of inverse Q filtering. *Geophysics*, 67(2), 657-663.
- Xu, M.D., Feng, Q.H., 1979. Roughness of debris flows. *Proceeding of the First Conference of Chinese Research of Debris Flows*, pp. 51-52, 1979. (in Chinese).

-
- Yan, Y., Cui, P., Chen, S., Chen, X., Chen, H., Chien, Y., 2017. Characteristics and interpretation of the seismic signal of a field-scale landslide dam failure experiment. *J. Mt. Sci.* **14**, 219-236; <https://doi.org/10.1007/s11629-016-4103-3>, 2017 **14**, 219-236.
- ~~Yang, W., Wang, X., Yi, H., et al.: Research and Application of Near Surface Structure Investigation Techniques in the Loess Plateau Region of the Ordos Basin. In: Proceedings of the 2019 Petroleum Exploration Technology Symposium. China Petroleum Society, Petroleum Geophysical Exploration Committee, Chinese Geophysical Society, Exploration Geophysics Committee. Changqing Geophysical Prospecting Division, BGP Inc., China National Petroleum Corporation, pp. 4, 2019. (in Chinese).~~
- Yan, Y., Cui, Y., Huang, X., Zhou, J., Zhang, W., Yin, S., Guo, J., Hu, S., 2022. Combining seismic signal dynamic inversion and numerical modeling improves landslide process reconstruction. *Earth Surf. Dynam.* **10**, 1233–1252; <https://doi.org/10.5194/esurf-10-1233-2022>, 2022.
- Yan, Y., Cui, Y., Liu, D., Tang, H., Li, Y., Tian, X., Zhang, L., Hu, S., 2021. Seismic signal characteristics and interpretation of the 2020 “6.17” Danba landslide dam failure hazard chain process. *Landslides* **18**, 2175-2192; <https://doi.org/10.1007/s10346-021-01657-x>, 2021.
- ~~Yan, Y., Tang, H., Hu, K., Turowski, J. M., Wei, F.: Deriving debris-flow dynamics from real-time impact force measurements. J. Geophys. Res. **128**, e2022JF006715; <https://doi.org/10.1029/2022JF006715>, 2023.~~
- Yan, Y., Cui, Y., Tian, X., Hu, S., Guo, J., Wang, Z., Yin S., Liao, L., 2020. Seismic signal recognition and interpretation of the 2019 “7.23” Shuicheng landslide by seismogram stations. *Landslides* **17**, 1191-1206; <https://doi.org/10.1007/s10346-020-01358-x>, 2020.
- Yan, Y., Tang, H., Hu, K., Turowski, J. M., Wei, F., 2023. Deriving debris-flow dynamics from real-time impact-force measurements. *J. Geophys. Res.* **128**, e2022JF006715.
- Yan, Y., Tang, H., Zhou, K., Turowski, J. M., Cui, Y., & Xiang, B. (2025). Statistical characteristics of basal forces generated by experimental debris flows. *J. Geophys. Res.-Solid Earth* **130**, e2024JB030027. <https://doi.org/10.1029/2024JB030027>.
- Yang, H., Haque, E., & Song, K., 2021. Experimental study on the effects of physical conditions on the interaction between debris flow and baffles. *Physics of Fluids*, **33**(5).
- Yu, G., Lim, S. Y., 2003. Modified Manning formula for flow in alluvial channels with sand-beds. *J. Hydraul. Res.* **41**(6), 597-608; <https://doi.org/10.1080/00221680309506892>, 2003.
- Zhang, W., Chen, J., Ma, J., Cao, C., Yin, H., Wang, J., & Han, B., 2023. Evolution of sediment after a decade of the Wenchuan earthquake: a case study in a protected debris flow catchment in Wenchuan County, China. *Acta Geotechnica*, **18**(7), 3905-3926.
- Zhang, X., Tang, C., Li, N., Xiong, J., Chen, M., Li, M., Tang, C., 2022. Investigation of the 2019 Wenchuan County debris flow disaster suggests nonuniform spatial and temporal post-seismic debris flow evolution patterns. *Landslides*, **19**(8), 1935-1956.
- Zhang, Z., 2021. Study on the inversion of dynamic parameters of landslides and debris flows based on seismic signals. University of Chinese Academy of Sciences (in Chinese).
- Zhang, Z., Walter, F., McArdell, B. W., Haas, T., Wenner, M., Chmiel, M., He, S., 2021a. Analyzing bulk flow characteristics of debris flows using their high frequency seismic signature. *J. Geophys. Res.-Solid Earth* **126**(12), e2021JB022755; <https://doi.org/10.1029/2021JB022755>;

1659 2021.
1660 ~~Zhang, Z.:~~Zhang, Z., Walter, F., McArdell, B. W., Wenner, M., Chmiel, M., de Haas, T., He, S.,
1661 2021b. Insights from the particle impact model into the high-frequency seismic signature of
1662 debris flows. Geophysical Research Letters, 48(1), e2020GL088994. ~~Study on the inversion of~~
1663 ~~dynamic parameters of landslides and debris flows based on seismic signals. University of~~
1664 ~~Chinese Academy of Sciences, 2021. (in Chinese).~~