26 January 2024
Earth Surface Dynamics Manuscript No.: egusphere-2023-2015

Reply to Reviewer Comments

(C and R denotes comment and reply, respectively)

Reviewer 2:

General comments:

C1: In this study, seismic sensors have been used to investigate three debris flow events that occurred in the Fotangbagou and Ergou catchments, in Wenchuan (China). The authors combined seismic observations with rainfall measurements, photos by infrared cameras, and a post-event survey to get additional information on the debris flows. The velocity of the debris flows has been estimated through the seismic signals recorded at different stations and then compared with results from the application of the Manning formula, while the relative magnitude of the events has been inferred after taking into account the decay of the seismic energy during propagation. The topic addressed here is relevant and within the scope of ESurf, as although seismology has been used to monitor debris flows for decades, the link between the seismic signature and the properties of the events still needs to be properly understood. The quality of the seismic data is good, and the study areas seem interesting. However, I find the current state of the manuscript far from being considered for publication. My major concerns are (i) the large gap between the aims raised by the authors and what is actually shown afterwards, (ii) the lack of accuracy in most of the methods and analyses shown herein, and (iii) the quality of the writing.

R1: Thank you for spending the time to review and assess our manuscript. After carefully analyzing the reviewers’ comments, we were deeply convinced that we had not been able to accurately summarize the innovations and research objectives of our current study in the previous manuscripts, and we carefully analyzed the content of our Methodology and research. We therefore determined the research purpose in this manuscript: a theoretical basis and a case study exemplar for the real-time monitoring, analyzing the debris flow by a debris flow monitoring system based on the core of seismic monitoring, the determination of early warning thresholds and hazard assessment and analysis. We have rewritten the abstract to emphasize the technical line of the study and the results obtained, highlighting the strengths of the study and eliminating “the large gap between the aims” as pointed out by the reviewer. We have rewritten the abstract, highlighted the technical line of the study and the results obtained highlights the strengths of the study and eliminates “the large gap between the aims”, as pointed out by the reviewer.

Regarding the reviewer’s suggestion of “the lack of accuracy in most of the methods and analyses shown herein”, we have made a targeted revision in this round of revision, and we have sorted out and refined the contents of section 4.1~4.3, rewritten the manuscript to avoid ambiguity, and corrected some of the errors, e.g., Fig.8a incorrectly labelled point A and C. The modification has improved the accuracy of analyses. We have made an overall introduction to the methodology and necessary modifications to highlight the feasibility of our research methodology.

Besides, we have improved the quality of the writing.

The abstract has been modified, as follows:

Lines 25 to 51

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. An important approach to mitigating debris flows is monitoring and early warning. However, it is difficult to deploy many large instruments in an ideal location for continuous monitoring due to complex topographic condition of areas like Wenchuan, China. In addition, there is usually no electricity, and it is difficult to place more batteries to provide power for the large instruments, which is unavailable in the area with dangerous terrain and poor transportation. Given that environmental seismology has proven to be a powerful method for monitoring debris flows and other geohazards, our study aims to establish a debris flow monitoring system based on the core of seismic monitoring which is proven to be cost-effective, reliable, practical, and monitored three debris flows of different scale in Wenchuan, China. We comprehensively analyzed seismic signals and infrared images gained by the system with other post-event field investigations to obtain basic parameters such as debris flow velocity and grain size. First, we selected the second debris flow in the Fotangbagou gully as a case to show the process to determine the duration of the debris flow that passed the monitoring station by the energy recovered seismic signal, and establish that rainfall triggered the debris flow. Second, we comprehensively analyzed the infrared imagery, the power spectral density (PSD) and the PSD forward, and revealed that the debris flow seismic energy and its frequency spectrum characteristic are highly correlated with the development process of the debris flow; and the three debris flows were analyzed to show the seismic characteristics of rapid excitation and slow decay. Finally, the cross-correlation function is used to calculate the maximum velocity of 7.0 m/s of the second debris flow, which was confirmed by the Manning formula. The study provides a theoretical basis and a case study example for real-time monitoring, analysis of a debris flow monitoring system based on seismic signal, early warning, and hazard assessment.

C2: The core of the abstract and the introduction is the aim of inverting the seismic signals into dynamic parameters of debris flows to provide a "theoretical basis for reconstruction and inversion of the debris flow process", and offer "a framework for upscaling debris flow monitoring networks and the determination of early warning thresholds (e.g. lines 31-33 and 52-56 in the abstract, and lines 124-128 and 134-137 in the introduction). However, among the many debris flow parameters (e.g. flow height, flow volume or mass, velocity, solid concentration) only the velocity of one debris flow out of the three is estimated. I believe that this gap between scientific questions and results is mainly due to a lack of independent information on the debris flow events. The rainfall measurements have been used to propose rainfall as the triggering factor of the debris flows, but they cannot help deciphering the flow characteristics. The grain size distribution's estimation of one debris flow through the post-event survey can been exploited only partially, and the authors use different diameters for the modelling section (please see my specific comments on this topic below). Images from infrared cameras usually give useful insights for monitoring debris flows, but they are available here only for the debris flow occurred in the daytime, and the camera frame rate of 5 minutes seems too low to me to catch the highly variable nature of debris flows and the associated seismic signals. Moreover, at this stage there is no mention along the text about how this work can be used for early monitoring systems, and as underlined by the other reviewer I don't see applications to the "real-time monitoring" mentioned in the title.

R2: We are thankful to our reviewer's encouraging comments on the scientific contents of the present study. We have modified the abstract and the introduction. These monitoring data like rainfall, images, grain size distribution help semi-quantitative analysis for debris flows.

It does not usually have electric power and the instruments need battery to offer electric power which is lacking in the uninhabited area. Solar energy can be usually considered to solve the problem of lack of electric power in mountainous areas, but there is lack of enough sunlight to offer enough solar energy to support monitoring debris flow with instruments of high electric power consumption. Thus, we use infrared cameras with 5-min interval shoots characterized by less power consumption instead of video equipment. Hikvision's infrared video camera (Type: DS-2CD3T46WDV3-L) consumes a lot of power, and the power of the solar panel can only support the continuous monitoring of the device by video for 74h, and in more than three consecutive days of cloudy and rainy weather, the solar energy and its lack of solar energy makes it difficult to support the continuous monitoring of the video device. Whereas infrared cameras with 5-min interval shoots have been continuously monitoring the debris flow channel from June to October in both years 2021,2022. The solar cell and eight 1.5-volt dry cell batteries of this infrared camera can support monitoring for 18 months.

Therefore, our research purpose has been focused on a low-cost, reliable, convenient method to monitor debris flow based on seismic signal in complex mountainous areas. We have applied it to early monitoring systems. Based on this, we can achieve semi-quantitative analysis. The title of the manuscript has not mentioned content about "real-time monitoring" after we changed structure of the manuscript.

The abstract has been modified, it contains we proposed a cost-effective, reliable, and practical method, which is shown in R1 for general comments of reviewer 2.

We have modified the introduction, as follows:

Lines 162 to 182

To enable the widespread adoption of debris-flow early warning systems using seismic monitoring, the approach needs to be standardized, quantified, and systematized (Bessason et al., 2007; Arattano et al., 2015; Allstadt et al., 2019). However, this is constrained at present by a lack of detail in understanding the characteristics of the debris flow seismic signal and the debris flow evolution process. Compared to landslides, debris flows typically involve a smaller volume and the seismic signals they generate propagate over a finite distance. As a result, unlike landslides, debris flows cannot be effectively monitored by earthquake networks due to their limited scale and the shorter reach of their seismic emissions.

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, where insufficient sunlight impedes the normal functioning of solar-powered monitoring equipment.

We have modified the section “limitations and future works”, as follows:

Lines 843 to 869

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 are able to 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, on the basis of 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 emplace 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.

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.

We have modified the section “conclusion”, as follows:

Lines 872 to 902

In this study, the characteristics of the seismic signal from three debris flows on August 19, 2022, in the Wenchuan earthquake area of China are investigated. The three debris flow events studied here were generated under conditions of heavy rainfall. Three debris flows were analyzed that they exhibit the seismic characteristics of fast excitation and slow recession. Even to a large extent eliminating the propagation effect, the seismic amplitude and frequency characteristics of different monitoring stations of the same debris flow have a large difference, which indicates that the dynamic parameters of the debris flow are changing in the evolution process. The change in the flow state of the debris flow results in a different range of frequencies in the energy spectrum at the beginning and end of the debris flow, which is confirmed by our continuous photo analysis, PSD of the current records, and PSD of the forward modeling. At the start of the three debris flows, the energy is strong when debris flow goes through the monitoring point, mainly in the 10–42 Hz frequency range, while later in the event, the main frequency spectrum reduce to 20–23 Hz which roughly reflects the dynamic parameters evolution of debris flow. According to the seismic amplitude and frequency characteristic changes at different monitoring points of debris flows, the relative changes in the debris flow evolution process can be roughly analyzed.

The cross-correlation function can be a good choice to calculate maximum debris flow velocity in relative debris flow with riverbed changing simply. Compared with the result based on the Manning formula, it is reasonable for calculation result of the mean velocity of 7.0 m/s for the second debris flow in Fotangbagou gully. However, in Ergou Gully with relatively complex topography, the cross-correlation function was less successful, probably due to its more complex topographic setting causing strong variations in the kinematic parameters of the debris flow. Hence, the cross-correlation function may be an appropriate approach for peak flow calculation in simple debris flow, but not appropriate in much more complex debris flow.

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

The part about velocity, discharge, sediment concentration has been modified in the section “Infrared imagery analysis”, as follows:

Lines 494 to 575

The analysis of a series of infrared images of debris flows serves as a reliable method for validating the accuracy of the process reconstruction performed through debris flow seismic studies. Infrared imaging, particularly during nighttime conditions, often presents challenges due to its limited visible range and lower resolution. Consequently, the first Fotangbagou debris flow and the Ergou debris flow, both of which occurred at night, suffered from suboptimal image quality, making them less suitable for analysis. To address these limitations, we opted to focus our verification analysis on the second debris flow in Fotangbagou Gully, which occurred during daytime conditions. This choice allowed us to benefit from improved image quality and clarity, making it a more suitable example for our analysis.

Infrared images were captured at 5-minute intervals between 7:39 and 8:04 (Fig. 7b-7g) during the debris flow event. However, the image quality suffered due to water droplets on the camera lens caused by the passage of the debris flow, resulting in blurry images at station 2. Consequently, we chose to rely solely on the infrared camera at station 1 for our analysis. The early infrared images (Fig. 7b-7g) illustrate a gradual increase in both discharge and particle content of the debris flow, with a peak occurring around 7:54. However, the changes in velocity appeared to exhibit complexity during this phase. In contrast, the later images (Fig. 7e-7g) depict a reduction in particle content, a decrease in flow rate, and lower velocities, with distinct flow characteristics evident towards the end (Fig. 7g). The overall trend in debris flow evolution, as observed through infrared imagery, aligns with the trend observed through seismic analysis. In a macroscopic perspective, seismic signals effectively capture the general development trend of the debris flow. However, it's noteworthy that the peak state time of the debris flow, as indicated by the infrared imagery, does not coincide with the seismic data. To comprehensively analyze this discrepancy, we will delve into a detailed examination of the dynamic features of the debris flow, including discharge, flow velocity, and particle content, as reflected in the imagery. Additionally, in the next section, we will combine this analysis with the PSD forward modeling to gain further insights.

At 7:39 (Fig. 7b), the discharge of the debris flow remained relatively low. At this point, point A, located at a higher position within the old channel, remained unaffected by inundation. Most of the flow was concentrated along its right channel, with only a small portion following the left channel. There was no evidence of flooding or erosion along the left bank at point B. By 7:44, the debris flow initiated the flooding of point A and began eroding the left bank at point B. The water depth and left bank erosion reached their maximum extent in the image captured at 7:59. Subsequently, the water depth began to decrease. In summary, the infrared imagery reveals a gradual increase in flow rate between 7:39 and 7:54, followed by a gradual decrease after 7:54.

Regarding particle content, it follows a similar trend to the discharge. Specifically, there is a gradual increase in particle content from 7:39 to 7:49. This elevated particle content is sustained between 7:49 and 7:54, after which there is a notable decrease in particle concentrations observed at 7:59 and 8:04.

Regarding flow velocity, it exhibited an interesting pattern, with its highest point observed at 7:39, followed by a gradual decrease as observed at point C, where it remained relatively stable across the six consecutive infrared images. At this location, marked as point C, the flow exhibited maximum turbulence in Fig. 7b, indicating peak velocity, which then gradually declined. In Fig. 7d and 7e, eddies are visible near point A, situated at a higher position, suggesting the possibility of higher flow velocities at both moments. Conversely, the flow pattern at point C, upstream, indicated relatively slower velocities at both instances. Eddies near point C could be attributed to excessive discharge originating from lower elevations.

Analyzing the evolution of the debris flow, we observed a gradual increase in debris flow discharge from 7:39 to 7:59. This increase can be attributed to the relatively high flow velocity during this period, leading to intensified erosion along the course of the rock and soil body adjacent to the accumulation area. As a result, the fluid-solid phase material content increased, leading to a tendency for the flow rate to rise. At 7:59, the flow velocity decreased to some extent, resulting in weaker erosion. The debris flow gradually transitioned into a state resembling a "flood". In Fig. 7f, point A exhibits a stationary stone block that cannot be moved, and in Fig. 7g, the rock bed becomes clearly visible. These observations indicate that the erosion capability and carrying capacity of the debris flow were weak at this moment. This complex behavior in the trend of flow velocity, discharge, and particle composition changes during the debris flow's evolution underscores the inconsistency in their characteristics. In the next section, we will integrate these variables with the seismic PSD forward modeling of debris flow generation to analyze their respective impacts on the signal. This analysis will provide insights into the contradictory peak time observations between infrared imagery and seismic interpretation.

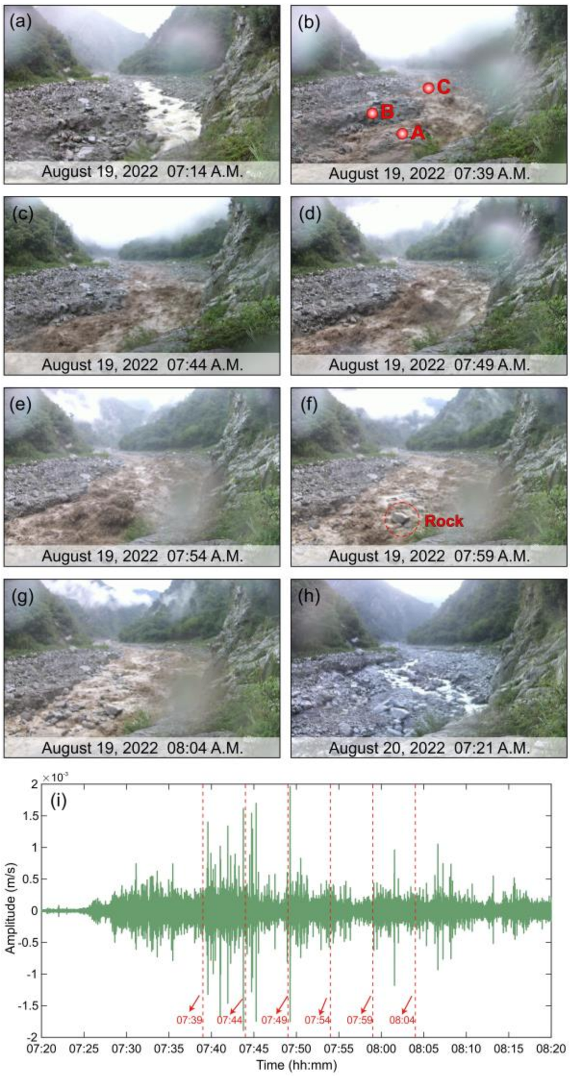


Fig. 7. Infrared camera images and seismic signals were recorded at monitoring point 1 in Fotangbagou Gully during the second debris flow on the morning of August 19, 2022. Images (b)-(g) were recorded every 5 minutes from 7:39 to 8:04: (a) before debris flow; (b) 7:39 frame; (c) 7:44 frame; (d) 7:49 frame; (e) 7:54 frame; (f) 7:59 frame; (g) 8:04 frame; (h) after debris flow. (i) The seismic signal was recorded at the point.

The infrared images show a gradual increase in the particle content of the debris flow from 7:39 to 7:49, with high particle content maintained between 7:49 and 7:54 but far lower concentrations at 7:59 and 8:04. The debris flow evolution analysis showed flow velocity increased gradually from 7:39 to 7:59, and was relatively high; in this condition, there is intense erosion of accumulations next to the channel and entrainment along the flow path, which increases the proportion of solid phase in the fluid. As flow velocity decreases, erosion weakens and the particle content gradually decreases, turning the debris flow into a water flood. The presence of a rock at point A in Fig. 7f and 7g illustrates the lack of transport capacity at this stage of the debris flow.

The section “Post-event field investigation” is modified to estimate the debris flow characteristics, as follows:

Lines 577 to 610

The field investigation and UAV survey at Fotangbagou Gully started on the third day after the debris flow events, and nearby villagers confirmed the accumulation fans had not been disturbed. UAV aerial imagery of the accumulation fan at the gully mouth and close-ups of surface conditions are shown in Fig. 8a–8c. Field measurements indicate the fan is about 1.2 m thick, with a thin layer (1–2 mm) of clay covering the surface in several areas (Fig. 8c). Some rocks with diameter larger than 1 m in Fig. 8b and 8c show that the debris flow has a relatively high carrying capacity, and the rocks at the bottom of the alluvial fan are relatively large (Fig. 8b), while the rocks in the front part of the alluvial fan (Fig. 8c) are relatively small, indicating that the carrying capacity of the debris flow sharply decreases after it is released from the channel constraints (or in other words, the cross-sectional area increases).

A sediment sample was collected from the accumulation fans in the Fotangbagou gully to estimate the particle size distribution of the debris flow. The sample (Fig. 8e) of about 4.7 kg was taken around the location marked ① in Fig. 8a. Grain size analysis was undertaken by sieving and a Malvern particle sizer. Due to lack of several sample analysis in this study, we should consider finishing several sample analyses to estimate the variability in other researches. We forgot to record the fraction of materials that was above the maximum particle size displayed in the granulometric curve. Thus, we should finish it in other similar researches. The results show that clay, i.e., particles with grain size less than 0.005 mm, accounted for only 0.041% of the total weight of the sample from the channel (Fig. 8d), which is consistent with field observations. The low cohesive sediment content of the accumulation fan sample could be due to removal by post-event processes, either by the flushing action of the Minjiang River or by human clearance of the impoundment fan. The particle size distribution shows that 94% of the particle size of the sample is 0.018 m, i.e., *D* in Eq. (7). In the next section, we will use *D* as a guide for forward analysis of the PSD curve features of the debris flow.

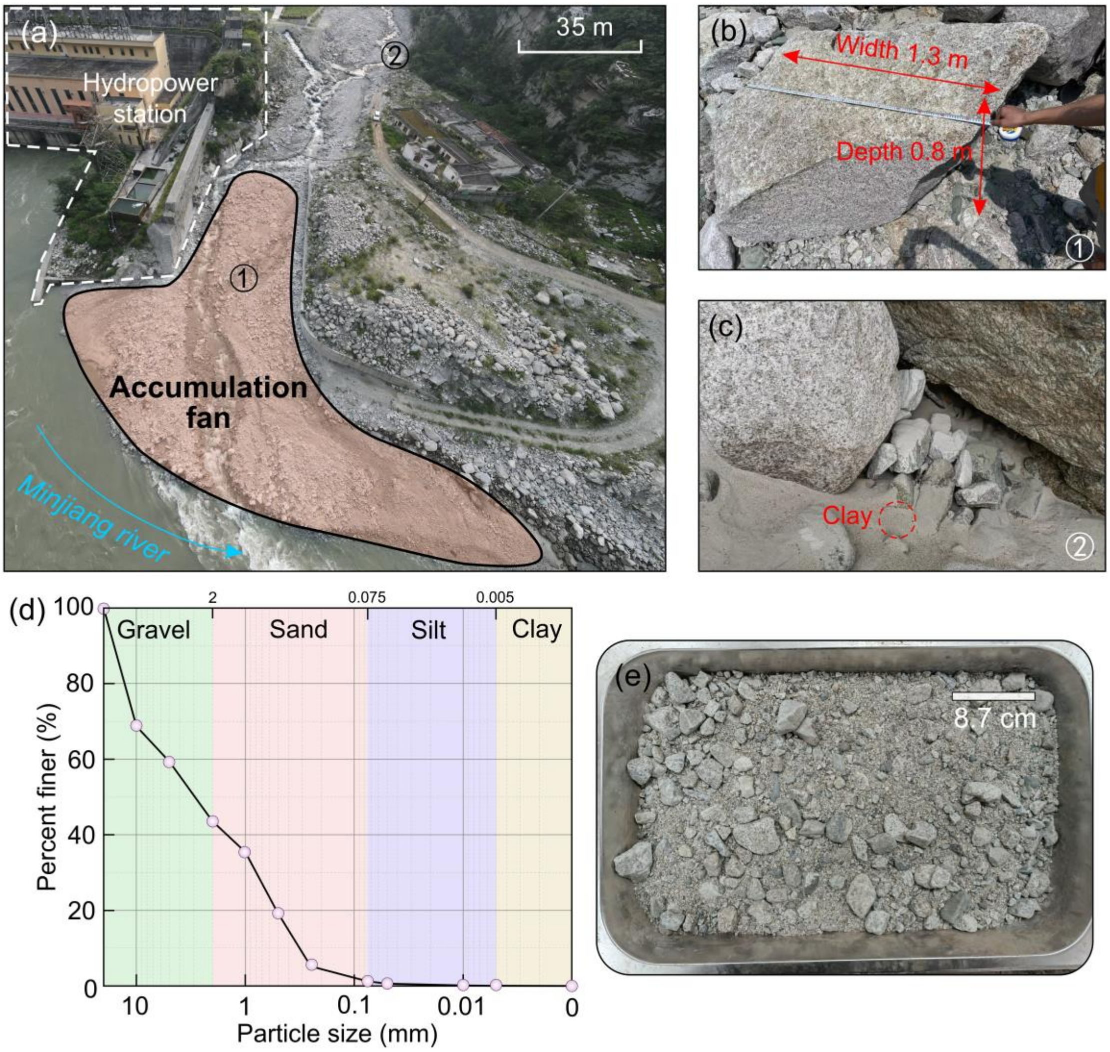


Fig. 8. Post-event field survey of accumulation fans in Fotangbagou Gully. (a) Aerial view of the Fotangbagou gully fan; (b) Largest particle on the Fotangbagou gully fan, marked ① in image (a); (c) Thin layer of clay covering the accumulation surface in Fotangbagou gully, marked as ② in image (a); (d) Particle size distribution for Fotangbagou gully sediment samples; (e) Fotangbagou 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.

We explain how different diameters were used, as follows:

Lines 637 to 642

We conducted debris flow seismic Power Spectral Density (PSD) forward modeling (Fig. 9b), employing Eq. (7) with key parameters derived from observations of the 2nd debris flow in Fotangbagou. *D* was determined based on 94% of the particle size, resulting in values of 0.01 m, 0.015 m, 0.02 m, and 0.025 m, respectively. The velocity *u* was consistent with the mean velocity described in Section 4.3, which was set at 2 m/s, 4 m/s, and 6 m/s.

Reference

Allstadt, K.E., Farin, M., Lockhart, A.B., McBride, S.K., Kean, J.W., Iverson, R.M., Logan, M., Smith, J.B., Tsai, V.C., George, D., 2019. Overcoming barriers to progress in seismic monitoring and characterization of debris flows and lahars. Association of Environmental and Engineering Geologists, Special Publication 28.

Arattano, M., Cavalli, M., Comiti, F., Coviello, V., Macconi, P., Marchi, L., 2015. Standardization of methods and procedures for debris flow seismic monitoring. In: Lollino, G., Arattano, M., Rinaldi, M., Giustolisi, O., Marechal., J.-C., Grant, G.E. (Eds.), Engineering Geology for Society and Territory-Volume 3: River Basins, Reservoir Sedimentation and Water Resources. Springer International Publishing, Switzerland, pp. 63-67.

Bessason, B., Eiríksson, G., Thorarinsson, Ó., Thórarinsson, A., Einarsson, S., 2007. Automatic detection of avalanches and debris flows by seismic methods. J. Glaciol. 53(182), 461-472.

C3: My second concern is the reliability of the analyses, since I cannot say whether all the methods are applied correctly. As an example, the method for the compensation of seismic energy dissipation is not clear to me. The authors should provide more thorough explanations, as almost all references are not present or not accessible. Similarly, the choice of the parameters used in most of the equations ((5), (6), (8), (9), and (10)) is vague and not straightforward. How do you estimate the channel slope and roughness, and the flow lengths and heights? You only briefly mention the procedure in the results section without details, and most importantly you often do not show the values. What about the seismic parameters (attenuation factor Q, Rayleigh wave velocities and seismic travel time)? It is understandable that you couldn't estimate them in the field, but you should at least give some references and discuss the errors associated with your choices, as your conclusions rely on them. Moreover, I find most of the interpretations of the results as speculative, meaning I often barely see what the authors claim to observe in the figures.

R3: Thanks a lot for your suggestions sincerely**.** During the propagation of seismic in the crust, the energy of seismic will be converted into thermal energy, which is always called absorption attenuation. The magnitude of the absorption attenuation is positively related to extend of formation consolidation. However, debris flow monitoring site is usually located at the surface of earth and made up of loose deposit. It is the strongest absorption attenuation at this moment. It is difficult to estimate accurately most of parameters like L, W, u, v_c, r_0, in Eq. (7). However, semi-quantitative analysis has been carried out according to guiding of Eq. (7) when we use this equation. For the same debris flow at the same monitoring station, its static parameters almost keep invariable, and dynamic parameters will vary. It will make us achieve semi-quantitative analysis under the condition of indeterminate parameters. Related parameters in Manning formula have been explained how we get the values in Section 3.3. Seismic parameters mentioned by you have been explained how we get the values in Section 3.4 and 3.5.

The choice of parameters has been modified in the section methodology, as follows:

Lines 322 to 346

To verify the reliability of the velocity calculations based on the cross-correlation function, mean velocity was also determined using the Manning formula (Eq. (5)), which was originally developed for hydraulics problems (Rickenmann, 1999). The formula is used to calculate the mean 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):

$$v = \frac{1}{n} J^{\frac{1}{2}} R^{\frac{2}{3}}, \tag{5}$$

where v represents debris flow velocity, n represents the roughness coefficient of the channel, J is the slope of the section in percentage instead of a degree, and R represents the hydraulic radius, calculated by dividing the area of the monitoring section (as determined by the DSM) by the wet perimeter, denoted as χ (Fig. 4). Channel parameters were extracted from cross-sections at the monitoring stations (Fig. 4). A key element of the Manning formula is the channel roughness coefficient n (Smart, 1999), which was determined as 0.05 (Xu and Feng, 1979) for the Fotangbagou gully. The gradient ratio J of the monitoring section was determined using the digital surface model (DSM) output of the UAV aerial survey. The values for two cross-sections are 0.13. χ can be employed as a means to estimate the cumulative bed length and lateral depth of the channel that is inundated by debris flow within the cross-section. For the cross-section of monitoring station 1, the area of the monitoring section and the wet perimeter χ are 17.7 m^2 and 14.2 m, respectively. For another cross-section, the two values are 27.5 m^2 and 21.6 m, respectively. Thus, two values of the hydraulic radius R are 1.25 m and 1.27 m for the two monitoring stations.

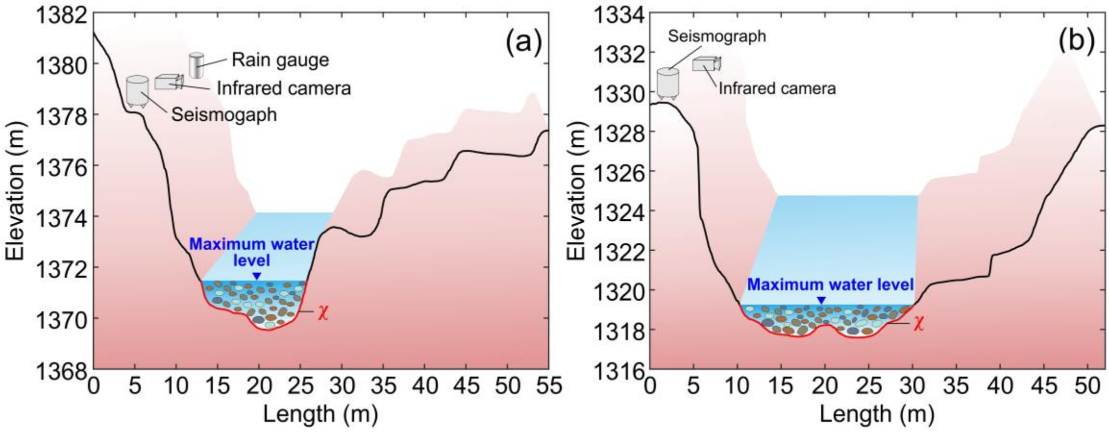


Fig. 4. Cross-sections of Fotangbagou gully showing maximum water level used in calculation of mean velocity by the Manning formula. (a) Monitoring station 1; (b) Monitoring station 2.

Lines 349 to 377

Power spectral density (PSD, Eq. (6)) 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.

$$PSD_{f_{\min}\sim f_{\max}}(t)=\frac{1}{(f_{\max}-f_{\min})}\times\sum_{f=f_{\min}}^{f_{\max}}X(t,f)\,, \qquad (6)$$

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). 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. (7) 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.

$$PSD\approx 1.9\cdot LWD^3u^3\cdot\frac{f^{3+5\xi}}{v_c^5 r_0}e^{-\frac{8.8 f^{1+\xi}r_0}{v_c Q}}\,, \qquad (7)$$

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). Width W of the river channel is about 10 m. We will take the monitoring station as the center, the upstream and downstream 10 m range of the river as the main source of the monitoring station; Then, the river channel is divided into 200 segments at an interval of 0.1 m, and the travel time from each segment to the station is calculated respectively. Then, the geometric average value of the 200 segment travel times is calculated, which is taken as the average value of the travel time. Using the second Fotangbagou debris flow as an example, Q is 4 and 2.4 for monitoring points 1 and 2, the horizontal distance between the channel and monitoring station is 15 m and 25 m, and the Rayleigh wave velocities of 800 m/s and 500 m/s at 1 Hz, respectively (Guo et al., 2023). So, the seismic travel time of 0.02s and 0.04s respectively. Eq. (6) is used to compute the PSD and Eq. (7) is used to analyze velocity and grain size with PSD of the debris flow between the two stations due to lack of data of continuous time series between the two stations.

Lines 379 to 399

Elastic wave travel makes energy and velocity smaller, the two effects are a function of frequency and are mathematically expressed by Eq. (8) with some parameters (Kjartansson,1979; Futterman, 1962; Strick,1967). It can be used to restore a part of energy loss as:

$$h(t, f) = e^{-\frac{\pi f t}{Q}\left|\frac{\omega_0}{\omega}\right|^{\frac{2}{\pi}\arctan\left(\frac{1}{2Q}\right)}}, \tag{8}$$

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. (7), Q represents attenuation factor quantitatively depicting the absorption attenuation, and ω_0 and ω are reference angular velocity at 1 Hz (ω_0=2π) and angular velocities, respectively. Eq. (8) is used to characterize the attenuation of plane waves absorbed by the earth. In this equation, t represents the propagation time of the seismic wave, a key parameter Q represents the attenuation factor quantitatively depicting the absorption attenuation, $h(t,f)$ represents the relative amplitude attenuation at the frequency-domain spectrum of the original seismic wave at a certain frequency f after the propagation time t. When the amplitude at a certain frequency has decayed more, a compensation function (Eq. (9)) can be used to restore the part of the signal decaying at that frequency range (Liu et al., 2013):

$$\Gamma(t, f) = \frac{h(t, f) + \sigma^2}{h^2(t, f) + \sigma^2}, \tag{9}$$

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. (9) better with a comparison of Eq. (8). Because the seismic signal of debris flow belongs to a high-frequency signal, we always use Eq. (9) at all the frequencies of 1 Hz to 50 Hz actually.

This part has been used to explain the limitation, as follows:

Lines 843 to 852

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 are able to 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, on the basis of this study, we expect to improve the monitoring and analysis based on seismic signals for subsequent debris flow detection, early warning, and inversion.

Reference

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

Futterman, W. I., 1962. Dispersive body waves. J. Geophys. Res. 67(13), 5279-5291.

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 (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.

Kjartansson, E., 1979. Constant Q-wave propagation and attenuation. J. Geophys. Res.-Solid Earth 84(B9), 4737-4748.

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.

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

Smart, G.M., 1999. Coefficient of friction for flow resistance in alluvial channels. Proc. Inst. Civil Eng.-Water Marit. Energy 136(4), 205-210.

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.

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 (in Chinese).

Rickenmann, D., 1999. Empirical relationships for debris flows. Nat. Hazards 19, 47-77.

Roth, D. L., Brodsky, E. E., Finnegan, N. J., Rickenmann, D., Turowski, J. M., Badoux, A., 2016. Bed load sediment transport inferred from seismic signals near a river. J. Geophys. Res.-Earth Surf. 121(4), 725-747.

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.

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.

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.

Yu, G., Lim, S.Y., 2003. Modified Manning formula for flow in alluvial channels with sand-beds. J. Hydraul. Res. 41(6), 597-608.

C4: Finally, I agree with the other reviewer that the quality of the writing should also be strongly improved. In several parts it is hard to follow the text, the vocabulary is not correct and some physical quantities are called with different terms along the manuscript. A thorough revision is therefore required, and I believe this could improve the clarity of the work.

R4: We thank the reviewer for this helpful comment. We have improved the quality of the writing. Besides, we changed some expressions and corrected terms in the manuscript. The clarity of expression has been improved in this manuscript. Take the abstract as an example, the abstract has been improved the clarity, which is shown in R1 from lines 25 to 51 for general comments of reviewer 2.

C5: For all these raisons, I recommend major revisions before this manuscript can be considered for publication. I think that an important effort must be made by the authors in order to address these points. My opinion is that the authors have the data to write a nice contribution, but most of the analyses need to be revised and the structure redesigned.

R5: Thank you for your constructive comments. We have changed structure of the manuscript, which has been explained as shown in R1 for the general comments of reviewer 1 and R1 for the general comments of reviewer 2. We have changed the structure of the manuscript to deleted the section of debris flow scale analysis by seismic signal. The content about methodology has been removed to the section “methodology”.

C6: My main suggestion is to change the aims of this work. Since I find it too speculative to invert the debris flows dynamic parameters in this context, this manuscript should be rather presented as a “case study” where to show the preliminary results of two new monitoring stations in catchments prone to debris flow events. To do so, the authors could first compare the debris flows they observe with existing observations in the same catchments (e.g. Guo et al, 2016), for example with respect to the triggering rainfall, and underline the potential additional information gathered with the seismic sensors (e.g., without the seismic sensors, how do we know if debris flows occur in these catchments? This is not clear to me and should be clarified). Within this new structure, I believe that some first inputs for the development of early warning for the study areas would fit better. I suggest the authors to analyze the seismic signals associated with rainfall events that did not trigger debris flows. In this way they could propose some seismic thresholds (e.g. Coviello et al., 2019). Regarding this latter point, the authors should not over-interpret the seismic signals, frankly acknowledge the limitations of the monitoring stations, and discuss what could be improved (e.g. are the authors sure that the camera frame rate is high enough to get the debris flows dynamics? Why didn’t the camera work well at night? Could it be possible to install flow height sensors in such gullies?,…). Some of these limitations appear in the discussion section, but if the authors were really aware of them, several analyses shouldn’t have been carried out. Comparisons with other studies on the seismic monitoring of debris flows are not present in the discussion section, yet I consider them as necessary. I acknowledge that to follow my suggestions all the structure of the manuscript has to be modified, and it may require a huge work by the authors, but I honestly believe that this is still the simpler way to valorize their findings. This is also in line with the criticisms raised by the other reviewer.

Below are my specific comments to the authors on the different sections of the manuscript.

R6: We are thankful to our reviewer’s encouraging comments on the scientific contents of the present study. As your suggestions are mentioned, we have changed our aim in this study. Our research purpose has been changed that we proposed a low-cost, reliable, convenient method to monitor debris flow based on seismic signal in complex mountainous areas where is lack of enough sunlight to offer enough solar energy to make monitoring equipment work normally. We did not quantitatively invert the debris flows dynamic parameters. Semi-quantitative analysis can be achieved, which can help for other researchers to offer a case to monitor debris flow in complex mountainous areas. Guo et al. (2016) and Cui et al. (2018) proposed the research about rainfall thresholds based on rainfall monitoring data for a same study area, Ergou gully, but our purpose is not based on rainfall. We aimed to do research in seismic signal monitoring of debris flow. We did not aim to offer seismic thresholds or development of early warning for the study areas. Instead, we only proposed semi-quantitative analysis. Dynamic analysis based on images from cameras is only semi-quantitative, which can be combined with seismic signal to achieve semi-quantitative analysis. Because our study gullies are lack of enough sunlight, which is difficult to offer enough solar energy to make camera or video with high resolution or strong infrared shooting function work normally. We would use camera for 5-min interval shooting, it has a lower power consumption. The camera we installed has a poor infrared function and its infrared shooting distance is shorter than the distance between camera and debris flow, so the camera works bad at night. In the subsequent research, we will consider installing flow height sensors to enrich data of debris flow. Indeed, there are limitations about our previous analysis, so we changed the structure of the manuscript to offer a simpler method. In addition, the title of the manuscript has been modified as “Monitoring, analysis and application of debris flow based on seismic signal”.

Reference:

Cui, P., Guo, X., Yan, Y., Li, Y., Ge, Y., 2018. Real-time observation of an active debris flow watershed in the Wenchuan Earthquake area. Geomorphology 321, 153-166.

Specific comments:

C1: I think that the abstract should be re-written and shortened. Although it is important to explain the methods, the main findings of the work should appear more clearly and not only in 3-4 lines at the end of it (lines 48-52).

R1: Thank you for the useful advice. We have rewritten and shortened the abstract. We also have improved expression and writing quality of the methods, the main findings of the work. The main findings have been rewritten at the end of the abstract. The abstract has been modified, which is shown in R1 from lines 25 to 51 for the general comments of reviewer 2.

C2: Lines 27-28: these lines are not clear to me, because in my view early warning is a consequence of monitoring. I would say that it is important to monitor debris flows to better understand their dynamics and also define thresholds for early warning systems.

R2: We thank the reviewer for this comment. We have rewritten and shortened the abstract, which is shown in R1 from lines 25 to 51 for the general comments of reviewer 2.

C3: Lines 28-29: I would change "non-contact observations" with "remote observations"

R3: We totally agree with suggestion of the reviewer. It has been modified in the related mistake part, as follows:

Lines 141 to 143

The main advantages of the approach are long-distance, remote monitoring and rich information on event dynamics (Arattano and Marchi, 2008; Hübl et al., 2013; Kogelnig et al., 2014) .

Reference

Arattano, M., Marchi, L., 2008. Systems and sensors for debris-flow monitoring and warning. Sensors 8(4), 2436-2452.

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.

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.

C4: Lines 31-37: according to my general comment, the scientific questions and aims of the work should be soften. The main subject could be the Wenchuan area and the high frequency of debris flows events, which need to be monitored.

R4: Thank you for your constructive comments. There is a gap between the scientific questions and aims of the work. Our research purpose has been changed that we proposed a low-cost, reliable, convenient method to monitor debris flow based on seismic signal in complex mountainous areas where is lack of enough sunlight to offer enough solar energy to make monitoring equipment work normally.

It has been modified, as follows:

Lines 33 to 37

Given that environmental seismology has proven to be a powerful method for monitoring debris flows and other geohazards, our study aims to establish a debris flow monitoring system based on the core of seismic monitoring which is proven to be cost-effective, reliable, practical, and monitored three debris flows of different scale in Wenchuan, China.

C5: Line 32: what do you mean by “imagery”?

R5: We thank the reviewer for this helpful comment. “Imagery” means monitored imagery of debris flow. It is image shot by infrared camera. It has been modified, as follows:

Lines 37 to 39

We comprehensively analyzed seismic signals and infrared images gained by the system with other post-event field investigations to obtain basic parameters such as debris flow velocity and grain size.

C6: Line 34: what do you mean by “basic parameters”? Please tell us which ones

R6: Thank you for professional comment. “Basic parameters” means basic parameters (e.g., velocity, grain size and so on). It has been modified, which is shown in R5 for the specific comments of reviewer 2 from lines 37 to 39.

C7: Line 35: I propose to change “other” with “additional”

R7: Thanks a lot for the constructive comment. We have rewritten and shortened the abstract. “Other information” has been deleted.

C8: Line 38: “absorption attenuation effect” is a bit hard to digest. I would simply talk about the energy loss of the seismic signal during propagation in the ground

R8: Thank you for the helpful advice sincerely. During the propagation of seismic in the crust, the energy of some seismic will be converted into thermal energy and lost. It is always called absorption attenuation. The magnitude of the absorption attenuation is positively related to extend of formation consolidation. However, debris flow monitoring site is usually located at the surface of earth and made up of loose deposit. It is the strongest absorption attenuation at this moment. The sentences above are too long to be written in the abstract.

C9: Line 39: what do you mean by “as far as possible”?

R9: Thank you so much for the comments. "As far as possible" has an error of expression. We have rewritten and shortened the abstract. The words have been deleted.

C10: Line 41: what is the "test rain"? Do you mean the rainfall observed?

R10: We thank the reviewer for this comment. There is an error during typing. Actually, it is not "test rain" but "rain". The word "test" has been removed in the manuscript.

C11: Lines 41-43: I'm not sure that this is shown in the text. Please see my comments on the result section

R11: Thank you for the useful advice. It has been modified, as follows:

Lines 46 to 47

The three debris flows were analyzed to show the seismic characteristics of rapid excitation and slow decay.

C12: Lines 43-48: I find these lines not clear. I would remove the part which starts from "clarify the feasibility".

R12: We thank the reviewer for this comment. In order to improve clarify the feasibility of this part, it has been modified, as follows:

Lines 42 to 47

Second, we comprehensively analyzed the infrared imagery, the power spectral density (PSD) and the PSD forward, and revealed that the debris flow seismic energy and its frequency spectrum characteristic are highly correlated with the development process of the debris flow; and the three debris flows were analyzed to show the seismic characteristics of rapid excitation and slow decay.

C13: Line 48: instead of saying "fast excitation and slow recession" I would be more clear, saying that the seismic signature of the debris flows is characterized by an abrupt increase of seismic power and a slower decrease. Is the increase in seismic power related to the passage of the front? This aspect needs to be discussed later on.

R13: Thank you for the professional comment. As reviewer 1 said, "fast excitation and slow recession" about seismic signal is not our research contribution, but I would leave the sentence and modified the context of the sentence, which is shown in R12 for reviewer 2.

C14: Line 49: it is too strong to say "verifying Manning's formula", also because in the text you seem to say the opposite (the Manning's formula confirms the cross-correlation). I would rather say that you estimate velocities with two independent methods

R14: Thank you for your constructive comments. As you said, it is too strong to say "verifying Manning's formula", which is an error of expression. Thus, we have modified the previous sentence, as follows:

Lines 47 to 49

Finally, the cross-correlation function is used to calculate the maximum velocity of 7.0 m/s of the second debris flow, which was confirmed by the Manning formula.

C15: Line 50: three significant digits seem to many to me, given the errors associated with the method. I would also remove "maximum" velocity, since it is more a mean velocity

R15: We thank the reviewer for this helpful comment. Three significant digits has been modified into a significant digit. The velocity is mean value between the two cross-sections indeed. All the maximum velocities should be modified the mean velocities. It has been modified, as follows:

Such as lines 316 to 317

This method has been used to objectively calculate the mean velocity of debris flows (Coviello et al., 2015).

Reference

Coviello, V., Arattano, M., Turconi, L., 2015. Detecting torrential processes from a distance with a seismic monitoring network. Nat. Hazards 78, 2055-2080.

C16: Lines 52-55: this end should be modified if you follow my suggestion

R16: Thank you for spending the time to review and assess our manuscript. Our main finding has been modified as R1 for reviewer 2 has been shown, as follows:

Lines 177 to 182

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, where insufficient sunlight impedes the normal functioning of solar-powered monitoring equipment.

C17: Keywords: I would put seismic methods instead of seismic wave

R17: Thanks a lot for the constructive comment. The keywords "seismic wave" has been modified into "debris flow seismic".

C18: Lines 60-61: I would make the distinction between mobilization from landslide or surface runoff. Please add some references

R18: We deeply appreciate the reviewer for the comment. The distinction between mobilization from landslide has been added, as follows:

Lines 61 to 64

Landslides involve the movement of rock and soil masses on a slope, which slip along a shear failure surface (Yan et al., 2020); debris flows unlike landslides comprise a solid-fluid mixture that, under heavy rainfall (Iverson, 1997), can generate massive surges that cause damage and loss of life.

Reference

Iverson, R.M., 1997. The physics of debris flows. Rev. Geophys. 35(3), 245-296.

C19: Lines 66-68: "disaster reduction measures" is too vague to me, since it would also include check dams and deposition basins. I suggest you to be more explicit, here and along the text.

R19: Thank you so much for the comments. It has been modified, as follows:

Lines 68 to 71

Given the significant hazard potential of debris flows, there is considerable interest in disaster reduction measures, particularly in instruments based on seismic and flow depth monitoring. Currently, the most widely used approaches are monitoring and early warning systems.

C20: Line 68-70: the sentence is a bit repetitive. Please reformulate with something like "On-site monitoring provides information on the triggering mechanisms (e.g. rainfall events) and the characteristics of debris flows such as flow depth, …, which can be used to develop warning systems". I don't see how flow velocity can be used for early warning systems

R20: We thank the reviewer for this comment. Flow velocity monitoring can help us to study evolution characteristic of debris flow. Maybe it can contribute to exploring the early warning of debris flow. The sentence has been modified, as follows:

Lines 72 to 75

On-site monitoring provides critical insights into the triggering mechanisms of debris flows, such as rainfall events, and key characteristics like flow depth and velocity. This information is essential for developing effective warning systems (Tecca et al., 2003; Suwa et al., 2009; Hürlimann et al., 2019).

C21: Line 102: remove "or so"

R21: Thank you for the useful advice. The words "or so" have been removed.

C22: Line 104: please comment briefly on how environmental seismology works, saying that natural processes generate ground vibrations

R22: We thank the reviewer for this comment. It has been modified, as follows:

Lines 135 to 137

Natural events, such as hazards, can induce ground vibrations that are detectable as seismic signals by instruments used in environmental seismology.

C23: Line 109: I propose you to change "non-contact monitoring" with "remote monitoring". What do you mean by "rich information"? I would remove it.

R23: Thank you for your professional comments. "Rich information" refers to seismic characteristics and dynamic parameter features of geohazards in seismic signals. The sentence has been modified, as follows:

Lines 141 to 143

The main advantages of the approach are long-distance, remote monitoring and rich information on event dynamics (Arattano and Marchi, 2008; Hübl et al., 2013; Kogelnig et al., 2014).

C24: Line 111: if I'm correct, Marchetti et al. (2019) use infrasound measurements

R24: Thank you for your constructive comments. Indeed, Marchetti et al. (2019) use infrasound measurements. This reference has been removed here, which is shown in R23 for the specific comments of reviewer 2.

Reference

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.

C25: Line 115-119: if you want to talk about debris flow models, you need to introduce all of them and not only the one by Lai et al. (2018). Please see Farin et al. (2019), Zhang et al. (2021)

R25: We thank the reviewer for this helpful comment. Two sentences have been added, as follows:

Lines 149 to 155

Farin et al. (2019) introduced a physical model that addresses the high-frequency (>1 Hz) spectral distribution of seismic power produced by debris flows, which aims to estimate parameters, such as effective grain size and mean flow velocity. Meanwhile, the model presented by Zhang et al. (2021) proposed that the ratio of single-particle to multi-particle contributions significantly influences the non-linear relationship between the flow depth and the magnitude of high-frequency seismic signals.

Reference

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. 44(13), 2529–2543.

Zhang, Z., Walter, F., McArdell, B. W., Haas, T., Wenner, M., Chmiel, M., He, S., 2021. Analyzing bulk flow characteristics of debris flows using their high frequency seismic signature. J. Geophys. Res.-Solid Earth 126(12), e2021JB022755.

C26: Line 122: flow is not a parameter

R26: Thank you for spending the time to review and assess our manuscript. We use the word mistakenly. It has been modified, as follows:

Lines 157 to 162

Current research on seismic monitoring and debris-flow early warning concentrates on event timing (Walter et al., 2017; Huang et al., 2020; Beason et al., 2021), location (Walter et al., 2017; Lai et al. al., 2018), evolution of parameters such as velocity and discharge (Arattano, 1999; Lai et al., 2018; Andrade et al. 2022; Schimmel et al., 2022), and detection (Bessason et al., 2007; Schimmel and Hübl, 2016; Huang et al., 2020).

C27: Line 123: what do you mean by “identification”?

R27: Thanks a lot for the constructive comment. The word means detection of debris flows. According to R103 for reviewer 1, “identification” has been modified into “detection”, which is shown in R26 for reviewer 2.

C28: Line 132: please change “comprising” with “composed of”

R28: Thank you for the professional advice. The sentence has been rewritten, as flows:

Lines 172 to 175

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.

C29: Lines 131-134: these sentences are repetitive. Please change them with “The in-gully monitoring systems are composed of seismic sensors, rainfall gauges, and infrared cameras.

R29: Thank you so much for the comments. The sentence has been modified, which is shown in R28 for reviewer 2.

C30: Lines 134-137: following my general comment, these lines are too strong. At this stage, this study cannot offer “a framework for establishing a debris flow identification, monitoring, and early warning systems”. In my view, several aspects of your monitoring systems can be improved, and there is no mention about early warning in the current text.

R30: We thank the reviewer for this comment. We have modified the sentence mentioned by you, which is shown in R16 from lines 177 to 182 for reviewer 2.

C31: Line 151: please add some references about the occurrence of debris flows in this area

R31: Thank you for the useful advice. It has been modified, as follows:

Lines 197 to 201

Notable incidents include 17 occurrences documented by Guo et al. (2016) in Table 2, along with specific events such as the debris flow in Ergou on July 10, 2013 (Guo et al., 2016), in Fotangbagou on the same date (Cao et al., 2019), and another in Ergou on July 5, 2016 (Cui et al., 2018), among others.

Reference

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

C32: Figure 1: I'm not sure that Figure 1c is necessary, since you do not mention the geology of the area with this precision. If you remove the panel and all the legend, Figure 1a and 1c could gain some space. In the caption of the figure, say that the catchments of interest are in red. I don't get Google Earth 2015/2018: why these two years?

R32: We thank the reviewer for this comment. We also think Figure 1c is unnecessary, so Figure 1c, the panel and all the legend were deleted. The catchments of interest in red also have been explained in legend. Satellite images in 2015 and 2018 are the newest availably for the study area. Because the area is too broad, satellite images of this area in 2015 or 2018 are incomplete. Thus, Figure 1b is drawn from the combination of two satellite images of 2015 and 2018. The figure has been modified, as follows:

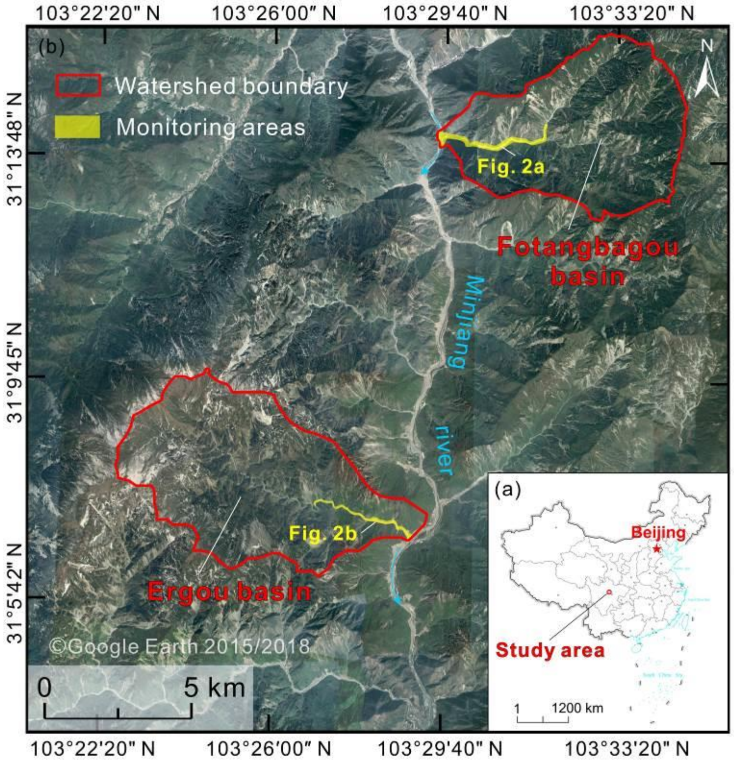


Fig. 1. Overview of the study area. (a) Location of the study area within China; (b) The two study catchments, Ergou and Fotangbagou, on the Minjiang River, Wenchuan, Sichuan, China.

C33: Lines 163-164: “a narrow and winding channel” before “abundant water sources”

R33: We totally agree with suggestion of the reviewer. The sentence mentioned by you has been modified, as follows:

Lines 210 to 212

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.

C34: Line 161-164 and so on: please decide between degrees and percentage for the slope

R34: Thank you for your constructive comments. We chose degree for the slope. It has been modified, as follows:

Line 212

The average slope is 10.5°.

C35: Line 171: what are “adequate” water sources?

R35: We thank the reviewer for this helpful comment. “Adequate” in “adequate water sources” means rich, abundant. It has been modified, as follows:

Lines 218 to 219

The gully has abundant water sources, with steep walls and a wide and gently winding channel.

C36: Line 172: what is the “average slope ratio”? Isn’t it just “slope”?

R36: Thank you for spending the time to review and assess our manuscript. Indeed, “average slope ratio” refers to “average slope”. It has been modified, as follows:

Line 219

The average slope is 6.1°.

C37: Line 181: please remove “etc.”: either you mention all the quantities measurements, or you mention only what you use in this work

R37: Thanks a lot for the constructive comment. We have removed “etc.”, as follows:

Lines 254 to 256

In Fotangbagou Gully, seismographs from Chengdu Baixinyuan Science Technology Company Limited were used for seismic monitoring; these incorporate velocity sensors, acceleration sensors, with a sampling frequency of 100 Hz.

C38: Line 182: “seismic monitoring” is better than “seismic signal monitoring”

R38: We deeply appreciate the reviewer to review it. It has been modified, as follows: It has been modified, as follows:

Lines 256 to 260

In Ergou Gully, seismic monitoring (Geophone) and acquisition (Data-Cube) equipment, provided by the Helmholtz Potsdam Center and German Geoscience Center, was used with a sampling frequency of 100 Hz and an eigenfrequency of 4.5–150 Hz, i.e., ground velocity response of signal output.

C39: Line 185: it is not clear to me what is the eigenfrequency of 150 Hz, given that your sampling frequency is 100 Hz

R39: Thank you so much for the comments. Sample frequency of 100 Hz represents 100 times in a second. Eigenfrequency is characteristic of an instrument, which can be considered that the equipment can clearly record range of frequency such as 4.5~150 Hz. It indicates that this equipment can receive seismic wave of frequency range of 4.5~150 Hz, but the equipment cannot record seismic signal below 4.5 Hz and over 150 Hz, which is like that ears of human cannot hear ultrasound or infrasonic waves. It has been modified, which is shown in R38 for reviewer 2.

C40: Line 189: “other data” is too vague. I would say that infrared cameras give insights on the debris flow processes. Also “verify the seismic reconstruction” is a bit too strong. I would say rather say “compare with the seismic observations”

R40: We thank the reviewer for this comment. It has been modified, as follows:

Lines 261 to 264

Each observation station was also equipped with an infrared camera to record the images of the debris flow at 5-minute intervals in real time to provide particle size data and insights on the debris flow processes to compare with the seismic observations.

C41: The workflow in Figure 3 is not clear to me. Please follow the suggestions of the other reviewer

R41: Thank you for the useful advice. We have modified this workflow and added some simple explanation of the workflow in the beginning of the methodology. It has been modified, as follows:

Lines 279 to 295

To extract information on debris flow evolution, debris flow seismic signals were processed and interpreted by following the procedure in Fig. 3. Absorption attenuation compensation is first to be processed for each frequency of the extracted seismic signal of debris flow to restore the different energy loss caused by different propagation, which was aimed to obtain the seismic signal of debris flow that is not affected by sensors installation location. Then, the seismic spectrogram is from compensated seismic signal based on short-time Fourier transform, characteristic analysis of debris flow evolution has been done by computing power spectral density of keyframe and the absolute value of time-domain amplitude, the evolution analysis result has been verified based on infrared imagery and post-event field investigation. Finally, the maximum velocity of debris flow has been estimated by computing the absolute seismic amplitude of different monitoring stations based on the cross-correlation function, which has been verified by the Manning formula. The key steps are outlined below in Fig. 3. Amplitude method in this figure is used to get the absolute value of time-domain amplitude in this figure. After this method, the signal processed by us is called a simplified signal.

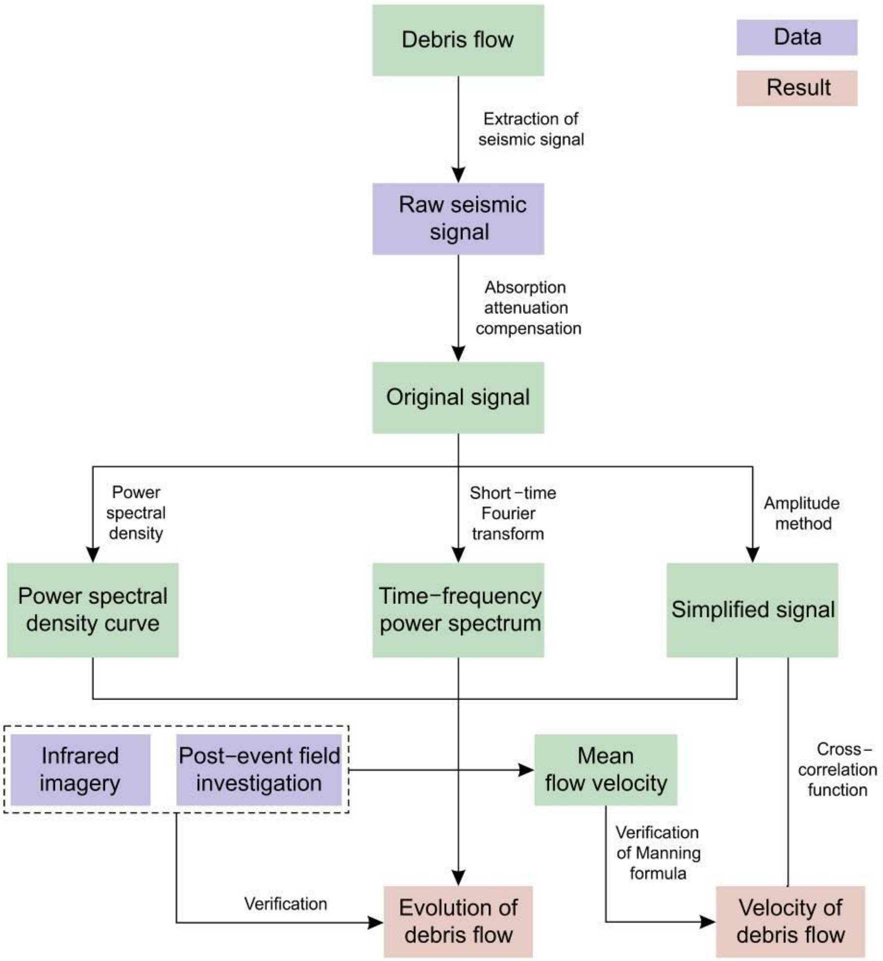


Fig. 3. Research methodology for processing and analysis of debris flow seismic signal.

C42: Line 206-2012: I'm not sure if all these details are needed because the short-time Fourier transform is a common method in signal processing. I propose to just mention the language you use

R42: We thank the reviewer for this comment. We think it is necessary to show all the details of the short-time Fourier transform, because the purpose of using this method and the related parameters are also shown. It has been modified, as follows:

Lines 298 to 306

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:

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

where X and x are 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.

C43: Lines 214-222: this part can be misleading. You need to clarify that you are talking about seismic signals, since the works by Arattano and Marchi (2005) and Comiti (2014) apply this method also to flow stage measurements. I suggest you to take inspiration from Arattano and Marchi (2005) to be more clear in the explication.

Have you computed the signal time delay with equation (4), and then you divide by the distance between the stations? Please be more explicit at line 221. Have you considered the distance between the stations along the channel or the straight distance?

R43: We totally agree with suggestion of the reviewer. Indeed, Arattano and Marchi (2005) and Comiti et al. (2014) use the data of seismic signal, flow stage, respectively to estimate velocity based on the method. The distance between the stations divided by the signal time delay is the maximum flow velocity between monitoring stations. It has been modified, as follows:

Lines 308 to 317

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 that the value of the velocity computation is close to the value of the velocity measurement. In the context of debris flows, the average flow velocity between monitoring 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).

Reference

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.

Comiti, F., Marchi, L., Macconi, P., Arattano, M., Bertoldi, G., Borga, M., Brardinoni, F., Cavalli, M., D'Agostino, V., Pennna, D., Theule, J., 2014. A new monitoring station for debris flows in the European Alps: first observations in the Gadria basin. Nat. Hazards 73, 1175-1198.

C44: Line 225: I think that you must acknowledge that the Manning formula has been originally developed for hydraulics problems (Open channel flow, F.M. Handerson (1966)). Add to the references also (Rickenmann, 1999)

R44: Thank you for your constructive comments. It has been proposed, as follows:

Lines 322 to 324

To verify the reliability of the velocity calculations based on the cross-correlation function, mean velocity was also determined using the Manning formula (Eq. (5)), which was originally developed for hydraulics problems (Rickenmann, 1999).

C45: Line 231: what do you mean by "slope ratio"? Please define the hydraulic radius and tell us how you estimate it

R45: We thank the reviewer for this helpful comment. It has been proposed, as follows:

Lines 328 to 331

Where v represents debris flow velocity, n represents the roughness coefficient of the channel, J is the slope of the section in percentage instead of a degree, and R represents the hydraulic radius, calculated by dividing the area of the monitoring section (as determined by the DSM) by the wet perimeter, denoted as χ (Fig. 4).

C46: Line 233: d50 is the median particle size of the channel bed? I'm not sure that you have used equation (6) to estimate the roughness coefficient, since the n=0.05 you use afterwards corresponds to a d50=1.33 m if I'm not wrong. How have you estimated this d50?

R46: Thank you for spending the time to review and assess our manuscript. Actually, the roughness coefficient is estimated empirically. This equation mentioned by you has not been used for estimation of the roughness coefficient because we only can get d50 of the channel bed for post-event field investigation but the value of the debris flow process. Thus, we use an empirical estimation value. This equation mentioned by you should been deleted.

C47: Equation 7: Is S(t,f) the same as X(n,w) in equation (1)? If yes, please keep the language consistent.

R47: Thanks a lot for the constructive comment. The two equations have been modified, as follows:

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

$$PSD_{f_{\min} \sim f_{\max}}(t) = \frac{1}{(f_{\max} - f_{\min})} \times \sum_{f=f_{\min}}^{f_{\max}} X(t,\ f), \tag{6}$$

C48: Line 239: how do you define fmin and fmax?

R48: We deeply appreciate the reviewer carefully review the manuscript. It has been modified, as follows:

Lines 354 to 355

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 $f_{\max}$.

C49: Lines 242-257: why have you chosen the model by Lai et al. (2018)? Since several models exist, you need to justify your choice (Farin et al., 2019; Zhang et al., 2021)

R49: Thank you so much for the comments. The purpose of our research is to establish a relationship between PSD of seismic signal and dynamic parameters of debris flow. We used simple the model by Lai et al. (2018) to achieve semi-quantitative analysis. However, when we used the model of Farin et al. (2019) to estimate velocity, the estimation has less reliability because of near-field monitoring and difficulty of parameters measurement during propagation. Thus, we didn't mention this result in our study. The mathematical model we observed in the field is further studied in our subsequent research, near-field monitoring used a non-linear solution integration model, which has a difficult computation. We would solve it with artificial intelligence. After that, we can achieve quantitative estimation of velocity and grain size. Similarly, the reason why we don't use the model by Zhang et al. (2019) is consistent with the reason about Farin et al. (2019).

C50: Lines 249-259: as stated in my main comment, this method is not clear to me as most of the references are not accessible. Please add more details, especially on equation (10). From what I understand, you could have estimated the energy loss during propagation through the Green's function as it has been done in several works you mention (e.g. Tsai et al., 2012; Lai et al., 2018). What is the spreading time and what is its value in equation (9)? How have you chosen Q? Is this the same Q you use while applying Lai et al. (2018)? If so, you should call it in the same way. What is sigma in equation (10)? More in general, I haven't understood how you combine equation (9) and (10) to restore the signal. At this stage, I cannot say if I'm convinced by the estimation of the relative magnitude of the events based on these equations.

R50: We thank the reviewer for this comment. We have added the explanation of the method mentioned by you, as follows:

Lines 379 to 399

Elastic wave travel makes energy and velocity smaller, the two effects are a function of frequency and mathematically expressed by Eq. (8) with some parameters (Kjartansson,1979; Futterman, 1962; Strick,1967). It can be used to restore a part of energy loss as:

$$h(t,f) = e^{-\frac{\pi f t}{Q}\left|\frac{\omega_0}{\omega}\right|^{\frac{2}{\pi}\arctan\left(\frac{1}{2Q}\right)}}, \qquad (8)$$

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. (7), 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. Eq. (8) is used to characterize attenuation of plane waves absorbed by earth. In this equation, t represents propagation time of seismic wave, a key parameter Q represents attenuation factor quantitatively depicting the absorption attenuation, $h(t,f)$ represents the relative amplitude attenuation at frequency-domain spectrum of the original seismic wave at a certain frequency f after the propagation time t. When the amplitude at a certain frequency has decayed greater, a compensation function (Eq. (9)) can be used to restore the part of the signal decaying at that frequency range (Liu et al., 2013):

$$\Gamma(t,f) = \frac{h(t,f)+\sigma^2}{h^2(t,f)+\sigma^2}, \qquad (9)$$

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

High-frequency signal can be restored by Eq. (9) better with comparison of Eq. (8). Because seismic signal of debris flow belongs to high frequency signal, we always use Eq. (9) at all the frequency of 1 Hz to 50 Hz actually.

C51: Section 4.1: It is not clear to me if you know that these three debris flows occurred from other independent observations or just from the seismic observations. In the latter case, you should convince the reader that all these events are debris flows and not just intense sediment transport events. It would be also a way to highlight the usefulness of the seismic sensors. Maybe from some critical rainfall thresholds already observed in these catchments? On the other hand, if you know they were debris flows from other observations, please clarify it. For this reason, I should start the section by commenting on the rainfall measurements, and only then on the spectrograms. I propose you to merge Figure 4 and 5 in order to see (or not) the match between rainfall and peak seismic power, because now it is hard to follow your comments.

R51: Thank you for the useful advice. It has been added in the beginning of the section 4.1., as follows:

Lines 403 to 407

We have identified three debris flows by consulting with local residents to confirm the occurrence of these events. Through the methods described above, we can confidently distinguish these three events as debris flows rather than intense sediment transport events. It is important to note that our determination did not rely on critical rainfall thresholds as a method of assessment.

The match between rainfall and peak seismic power in Figure 4 and 5 has been modified in Fig. 5, the previous two figures have been combined to show in Fig. 5.

The figure has been modified, as follows:

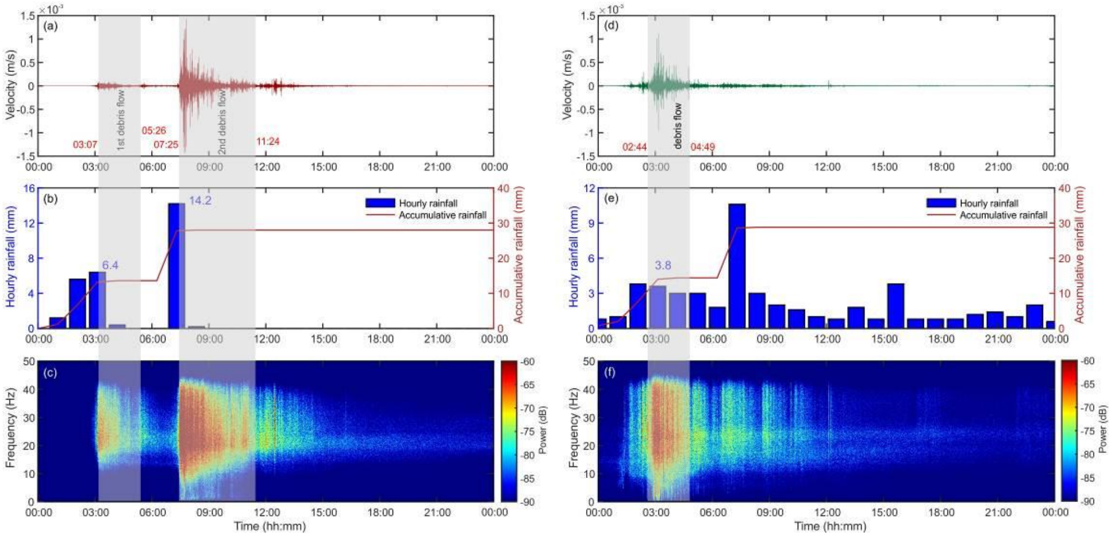


Fig. 5. Vertical seismic, rainfall and frequency spectrum of the debris flows. (a) Raw seismic from Fotangbagou gully debris flow at station 1; (b) rainfall at Fotangbagou gully; (c) spectrogram of (a) by STFT; (d) Raw seismic from Ergou gully at station 2; (e) rainfall at Ergou gully; (f) spectrogram of (d).

C52: Table 2: how do you define the starting and ending time of the debris flows? Please explain your method. For example, an increase of decibels over a certain threshold, a rapid rise, the decrease below a certain threshold. I believe that the times shown are quite approximate (3:00, 7:30, 2:00): can't you be more precise?

R52: We thank the reviewer for this comment. The sentences above have been added in the first paragraph of Section 4.1, which is shown in R51 from lines 403 to 407.

C53: Are you sure that the first peak of seismic power is related to the passage of a debris flow? Shouldn't it be just sediment transport + rainfall (e.g. Rindraharisaona et al., 2022)? That could be the reason why the frequency band is narrower compared to the second event at 7:20, which really looks like a debris flow. More comments are needed on Figure 4. You also never mention the difference between the different parts of a debris flow (front, or body). For instance, the peak of seismic power is usually associated with the passage of the front as it contains the biggest particles. Comments are needed about this aspect. I think that power is more correct than energy next to the spectrogram.

R53: Thank you for the professional comment. The seismic signal of the second debris flow is not from rainfall event because the seismic monitoring equipment has been considered to decrease effect of rainfall with waterproof shelter. The Illgraben debris flows are the most active in Switzerland, transporting a large amount of sediment during the events with viscous much materials because of erosion on the steep lateral slopes (on average 40°) (Rickenmann et al., 2001; Walter et al., 2017). Events observed at Illgraben ranges from granular, muddy, hyperconcentrated debris flows to floods (Badoux et al., 2009). There have been dominated debris flows and partial floods occurring for 27 months between May 2004 and July 2006 at Chalk Cliff, Colorado, American (Coe et al., 2008). Typical debris flows consist of lots of granular surges separated by floods at Chalk (McCoy et al., 2010; 2011). Guo et al. (2016) proposed that a debris flow on July 10, 2013 in Ergou Gully in Wenchuan County, China moved fast initially surges of materials and then transformed each other in flood and debris flow to Minjiang River with a few viscous materials. The debris flows in Wenchuan differ from that in other two basins for property. The first debris flow in Fotangbagou has a narrow frequency band indeed because this event has a smaller scale than the second debris flow. We cannot divide quantitatively front and tail of debris flow from seismic signal because debris flows in our study area is not similar to ones as debris-flow surges in Yunnan Province, China (Yan et al., 2023), Illgraben (Badoux et al., 2009), Chalk (McCoy et al., 2010; 2011). It will become our subsequent research direction.

Reference

Badoux, A., Graf, C., Rhyner, J., Kuntner, R., McArdell, B. W., 2009. A debris-flow alarm system for the Alpine Illgraben catchment: design and performance. Nat. Hazards 49, 517-539.

Coe, J. A., Kinner, D. A., Godt, J. W., 2008. Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central Colorado. Geomorphology 96(3-4), 270-297.

McCoy, S. W., Coe, J. A., Kean, J. W., Tucker, G. E., Staley, D. M., Wasklewicz, T. A., 2011. Observations of debris flows at Chalk Cliffs, Colorado, USA: Part 1, In situ measurements of flow dynamics, tracer particle movement and video imagery from the summer of 2009. Ital. J. Eng. Geol. Env. pp. 715-726.

Rickenmann, D., Hürlimann, M., Graf, C., Näf, D., Weber, D., 2001. Murgang-beobachtungsstationen in der Schweiz. Wasser Energie Luft 93(1/2), 1-8.

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.

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.

C54: Line 266: the subplots are wrong, the frequency bands are visible on the other ones

R54: Thank you for your constructive comments. The subplots are wrong indeed, it has been modified, as follows:

Lines 409 to 411

In each event, seismic amplitude rises rapidly and decreases gradually, and seismic signals are high frequency with wide frequency bands, but the frequency bands differ (Fig. 5c, 5f).

C55: Line 269: here and along the text, I propose you to change "time-frequency spectrum" with "spectrogram" and to keep consistency along the text

R55: We thank the reviewer for this helpful comment. After looking through the whole manuscript, all the related words have been modified, as follows:

Such as lines 413 to 417

By analyzing the amplitude and spectrogram variation, we can roughly get the starting and ending times of each event (Table 2). The beginning time of the events is determined by a sudden increase of the time domain signal and spectrogram, asking locals about the time. Besides, infrared imagery can be considered to confirm the starting time for the second debris flow of Fotangbagou.

C56: Line 291: isn't the cumulative rainfall of the first debris flow event in the Fotangbagou gully 15.6 mm?

R56: Thank you for spending the time to review and assess our manuscript. It was 15.6 mm for the cumulative rainfall of the first debris flow event in the Fotangbagou gully indeed, and 15.6 mm is accumulated from August 18 to the time of the event mentioned by you. We have modified this previous figure and deleted annotation of cumulative rainfall, as follows:

Lines 429 to 432

The rainfall record for Fotangbagou Gully shows hourly rainfall of 6.4 mm and 14.2 mm before the starting time of the first and second debris flows, respectively (Fig. 5b). In Ergou Gully, the hourly rainfall before the debris flow outbreak is 3.8 mm (Fig. 5e).

C57: Lines 298-321: I must admit that it is really hard for me to follow this part. For what I understand, your idea is to recover the energy loss during the propagation of the seismic wave. If this is true, lines 301-304 are describing another problem, that is the fact that what the sensor records are the seismic waves generated by the entire debris flow (e.g. the front and the body of it), which is not the focus of your approach.

What do you mean by frequency and velocity dispersion at line 299?

What do lines 305-306 mean? What do "river channels are about 10 m around the site during the processing signal" mean? Is 10 m the width?

How have you computed the average the average travel time?

How have you chosen the values of Q and Rayleigh wave velocities and why they change from a site to another? It is crucial to explain your choices, giving references or discussing them.

R57: Thanks a lot for the constructive comment.

1. Debris flow seismic signal of near-field observation is line source, which is not our research emphasis. However, propagation time was considered when we restored power of seismic signal. Importantly, we need to choose accuracy of the propagation time to restore the power. Thus, we estimate appropriate time based on the characteristic of line source.

2. Frequency in "frequency and velocity dispersion" is used to explain attenuation changes with frequency. Velocity dispersion is the attribute of underground medium, we combine the attribute with energy loss model of propagation (Eq. (7)). Thus, we have rewritten this part, as follows:

Lines 442 to 445

When plane waves propagate through the subsurface of the Earth, they exhibit varying levels of dissipation with frequency, as expressed in Eq. (8). To mitigate some of the losses and enhance the fidelity of the seismic signals triggered by debris flow, we employ Eq. (9) to recovery the energy loss with different frequency.

3. This sentence has been modified and moved to Section 3.4, as follows:

Line 365

Width W of the river channel is about 10 m.

4. It has been modified, as follows:

Lines 383 to 387

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. (7), Q represents attenuation factor quantitatively depicting the absorption attenuation, and ω_0 and ω are reference angular velocity at 1 Hz (ω_0=2π) and angular velocities, respectively.

5. There are less researches about Q and Rayleigh wave velocities. We make references from the two values of petroleum seismic prospecting in the earth surface to estimate the two values in our study. However, these references belong to internal data and cannot be offered references in the manuscript. Geology condition of the earth surface around the two monitoring stations are different, so Q and Rayleigh wave velocities are also different. Changes of its carrying capacity, discharge, velocity of the same debris flow are small. Characteristic of seismic frequency, energy and waveform are similar when absorption attenuation was not considered, but seismic signals have a great difference between two monitoring stations due to absorption attenuation. Thus, we determined the value of Q.

C58: Figure 6: more comments are needed for this figure. Why the function h is so different between a site to another? How do you interpret it? Please check the caption, I think that the number of the monitoring stations are not always correct. I also suggest to use spectrogram instead of “time-frequency domain energy spectrum”, which is also different from the vocabulary used in Figure 4

R58: Thank you for your useful advice. Monitoring instruments are installed around the interesting channel, geology condition between the channel and bed are complex. For hard rock especially, surface of earth has a weak absorption attenuation effect for seismic wave, so the value of Eq. (8) is small and Q is small, Eq. (8) is closer to the mathematical derivative state of keeping the attenuation function. Instead, for loose accumulation materials, surface of earth has a strong absorption attenuation effect for seismic wave, compensation coefficient of high frequency signal is big. Signal to noise ratio of high frequency signal of seismic wave is small. The energy with bigger compensation coefficient is dominated by noise after compensation, which would affect the signal to noise ratio, so we add a stability control factor sigma to keep the stability of high frequency part. The number of the monitoring stations in the caption of Fig. 6 are not correct indeed, which has been modified. All the related words “time-frequency domain energy spectrum” have been modified into “spectrogram”.

The figure and caption have been modified, as follows:

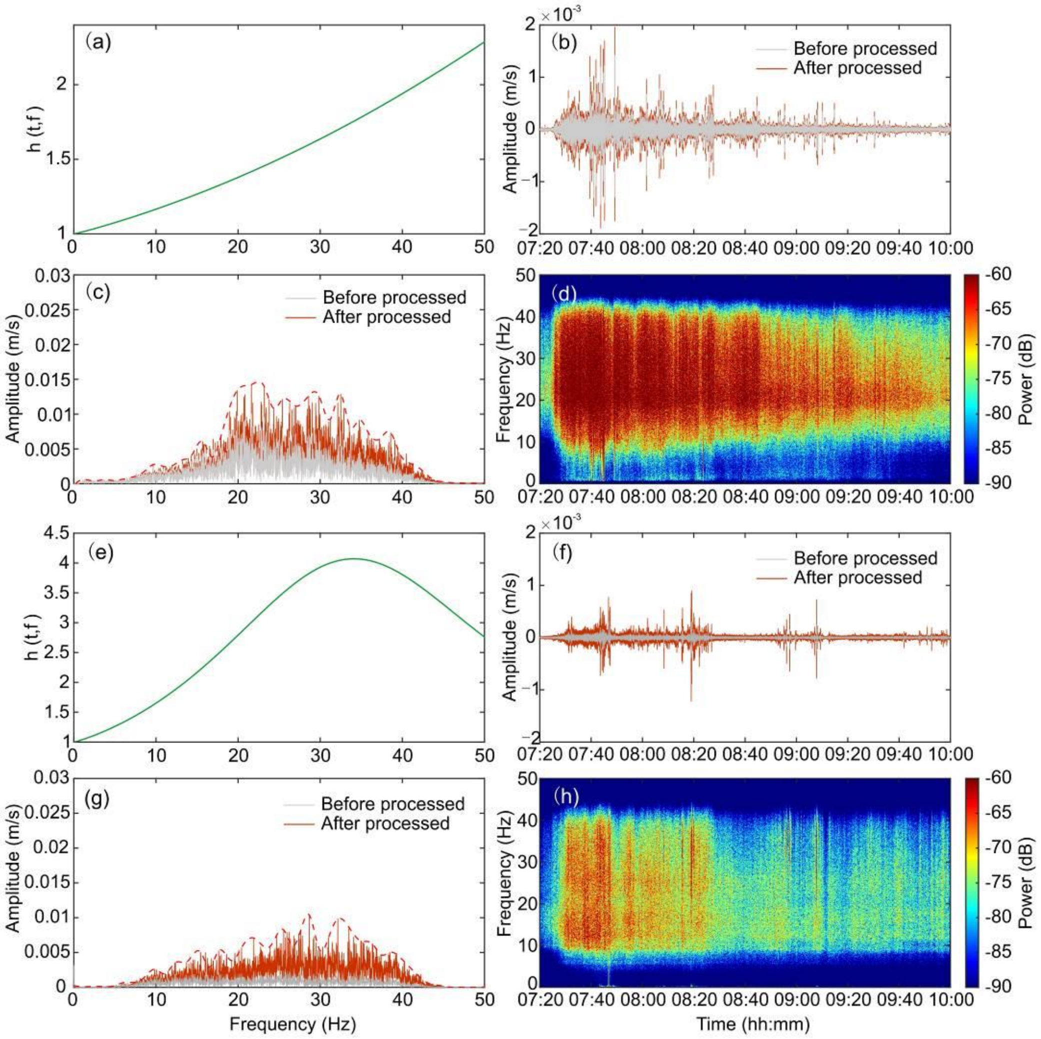


Fig. 6. Restored seismic signal for the second debris flow in Fotangbagou gully. (a) Compensation function curve for monitoring station 1; (b) Time domain signal at monitoring station 1; (c) Frequency domain signal at monitoring station 1; (d) Restored spectrogram for monitoring station 1; (e) Compensation 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.

C59: Line 335: what do you mean by “effectiveness of the debris flow evolution process”?

R59: Thank you so much for the comments. “Effectiveness” means “reliability”, the words mentioned by you have been modified, as follows:

Lines 467 to 469

We will use infrared imagery and grain size data to analyze reliability of the debris flow evolution process.

C60: Lines 340-342: please use the same terminology, you have changed again the term for the spectrogram and it is the first time that you mention the vertical direction

R60: We thank the reviewer for this comment. The related words mentioned by you have been modified, as follows:

Lines 473 to 475

We analyzed the characteristics of the time-domain amplitude curve, the average amplitude, and the spectrogram of vertical direction to reconstruct the debris flow process.

The seismic monitoring instruments triaxial, i.e., northern, eastern, vertical direction, respectively. The seismic signals used are from data of vertical direction. Actually, we have mentioned "the vertical direction" in the caption of Fig. 5.

C61: Section 4.2.1: The subplots in Figure 7 already appear in Figure 6, therefore I would remove this figure and refer to Figure 6. Are the spectrograms computed after restoring the signal? The caption makes the reader think they are.

More comments are needed to present the spectrograms. How have you computed the bandwidths you talk about at lines 347-348? At station 2, the spectrogram has no power under 8 Hz: why does it happen? Is it the result of a filtering process?

Why the seismic power remains relatively high for so much time (until 10:00)? Is it sediment transport?

R61: Thank you for the useful advice.

1. We have deleted previous Fig. 7 and only left Fig. 6. All the spectrograms are computed after restoring the signal, we have modified it in the caption of Fig. 6. The figure and caption have been modified, which is shown in R58 for reviewer 2.

2. Comments about the spectrograms are added. We have modified it about computing the bandwidths in R43 for reviewer 1. At station 2 the reason why the spectrogram has no power under 8 Hz is that distance of 25 m between monitoring station 2 and the channel is bigger than the distance of 15 m between monitoring station 1 and the channel, which caused possibly that the power of the spectrogram under 8 Hz for station 2 is more unobvious and lower than the one for station 2. It is

not the result of a filtering process because we used high-pass filter over 1 Hz. The sentence has been modified, as follows:

Lines 479 to 482

While the frequency associated with high power, represented by the colors red or dull-red, exhibited a rapid increase from 8 to 43 Hz following the initiation of the debris flow and maintained a high power at 22 Hz, indicated by the colors red or dull-red, until 8:45.

3. Guo et al. (2016) proposed that a debris flow on July 10, 2013 in Ergou Gully in Wenchuan County, China moved fast initially surges of materials and then transformed each other in flood and debris flow to Minjiang River with a few viscous materials. The debris flows in Wenchuan differ from that in Illgraben (Badoux et al., 2009) for property. It is possibly the reason why seismic power remains relatively high for so much time

C62: Lines 361-362: if the average amplitude at station 1 is higher than at station 2, it is trivial that the power is also higher, because the power is computed from the signals amplitude.

R62: We thank the reviewer for this comment. As you said, the sentence is description instead of conclusion. Indeed, we would describe seismic signal from time-domain and frequency-domain because expression seismic signal in time-domain and frequency-domain has different meaning.

C63: Section 4.2.2: I find the use of the infrared camera interesting and I acknowledge your effort to get the maximum information possible from the images. However, I find most comments on the figure too speculative. How can you observe an increase in particle content from Figure 8a to 8d? How can you say that the flow velocity increases if images are static? I cannot see signs of erosion of the left bank you mention at line 388, and how can you see that the channel is smooth at point C (line 394)? I don't see a decreasing velocity after 7:39 (line 396), and the presence of a rock at point A is not sufficient to conclude that the transport capacity is low (lines 412-413).

R63: Thank you for the constructive suggestion. We can only achieve semi-quantitatively analysis after changing the structure of the manuscript, so most comments on the figure are a little speculative. We can estimate the concentration of the debris flow and whether flow is torrential or steady in infrared imageries to get the comments mentioned by you. Maybe the point A and C were marked mistakenly so the previous comments were not clear to you. We have changed the location of point A and C in the figure. It has been modified in the section "Infrared imagery analysis", as follows:

Lines 504 to 521

Infrared images were captured at 5-minute intervals between 7:39 and 8:04 (Fig. 7b-7g) during the debris flow event. However, the image quality suffered due to water droplets on the camera lens caused by the passage of the debris flow, resulting in blurry images at station 2. Consequently, we chose to rely solely on the infrared camera at station 1 for our analysis. The early infrared images (Fig. 7b-7g) illustrate a gradual increase in both discharge and particle content of the debris flow, with a peak occurring around 7:54. However, the changes in velocity appeared to exhibit complexity during this phase. In contrast, the later images (Fig. 7e-7g) depict a reduction in particle content, a decrease in flow rate, and lower velocities, with distinct flow characteristics evident towards the end (Fig. 7g). The overall trend in debris flow evolution, as observed through infrared imagery, aligns with the trend observed through seismic analysis. In a macroscopic perspective, seismic signals effectively capture the general development trend of the debris flow. However, it's noteworthy that the peak state time of the debris flow, as indicated by the infrared imagery, does not coincide with the seismic data. To comprehensively analyze this discrepancy, we will delve into a detailed examination of the dynamic features of the debris flow, including discharge, flow velocity, and particle content, as reflected in the imagery. Additionally, in the next section, we will combine this analysis with the PSD forward modeling to gain further insights.

Lines 535 to 559

Regarding flow velocity, it exhibited an interesting pattern, with its highest point observed at 7:39, followed by a gradual decrease as observed at point C, where it remained relatively stable across the six consecutive infrared images. At this location, marked as point C, the flow exhibited maximum turbulence in Fig. 7b, indicating peak velocity, which then gradually declined. In Fig. 7d and 7e, eddies are visible near point A, situated at a higher position, suggesting the possibility of higher flow velocities at both moments. Conversely, the flow pattern at point C, upstream, indicated relatively slower velocities at both instances. Eddies near point C could be attributed to excessive discharge originating from lower elevations.

Analyzing the evolution of the debris flow, we observed a gradual increase in debris flow discharge from 7:39 to 7:59. This increase can be attributed to the relatively high flow velocity during this period, leading to intensified erosion along the course of the rock and soil body adjacent to the accumulation area. As a result, the fluid-solid phase material content increased, leading to a tendency for the flow rate to rise. At 7:59, the flow velocity decreased to some extent, resulting in weaker erosion. The debris flow gradually transitioned into a state resembling a "flood". In Fig. 7f, point A exhibits a stationary stone block that cannot be moved, and in Fig. 7g, the rock bed becomes clearly visible. These observations indicate that the erosion capability and carrying capacity of the debris flow were weak at this moment. This complex behavior in the trend of flow velocity, discharge, and particle composition changes during the debris flow's evolution underscores the inconsistency in their characteristics. In the next section, we will integrate these variables with the seismic PSD forward modeling of debris flow generation to analyze their respective impacts on the signal. This analysis will provide insights into the contradictory peak time observations between infrared imagery and seismic interpretation.

C64: I honestly believe that these images can be used to identify the passage of the debris flow, and maybe to get some insights on the flow stage, but any comment on flow velocity and concentration is too vague to me.

Why have you analyzed only images from 7:39 to 8:04 given that the debris flow lasts longer? I think it is crucial to see the condition of the channel before the development of the debris flow. I suggest you to mark different part of the section before the debris flow (e.g. banks, sediment deposits), so that we can better visualize the changes and the magnitude of the event. It is also important to see images after the event: I wonder if the big rocks we see in Figure 8f are carried by the flow or just deposited.

R64: Thank you for your professional comments. We can get the velocity of the flow from the Manning formula, Guo et al. (2016) also used this method to estimate the velocity of the flow. The concentration can be estimated from the amounts of grains and the shade of the color of the flow.

The 6 images from 7:39 to 8:04 correspond to characteristic of the strong time-domain seismic signal at the 6 frames, these images are representative to analyze characteristic of debris flow. We have marking different part of the section before the debris flow (Attached figure 1), this figure is modified from Fig. 7a and not shown to avoid affecting clearness of the figure in the manuscript. Banks of the channel are covered with proluvial, which is from the previous debris flow or collapse. Images before and after the event are shown in Fig. 7a, 7h, which can help us to visualize the changes and the magnitude of the debris flow better. It revealed that the big rocks we see in Fig. 8g are carried by the flow.

Attached figure 1. different part of the section before the debris flow (modified from Fig. 7a)

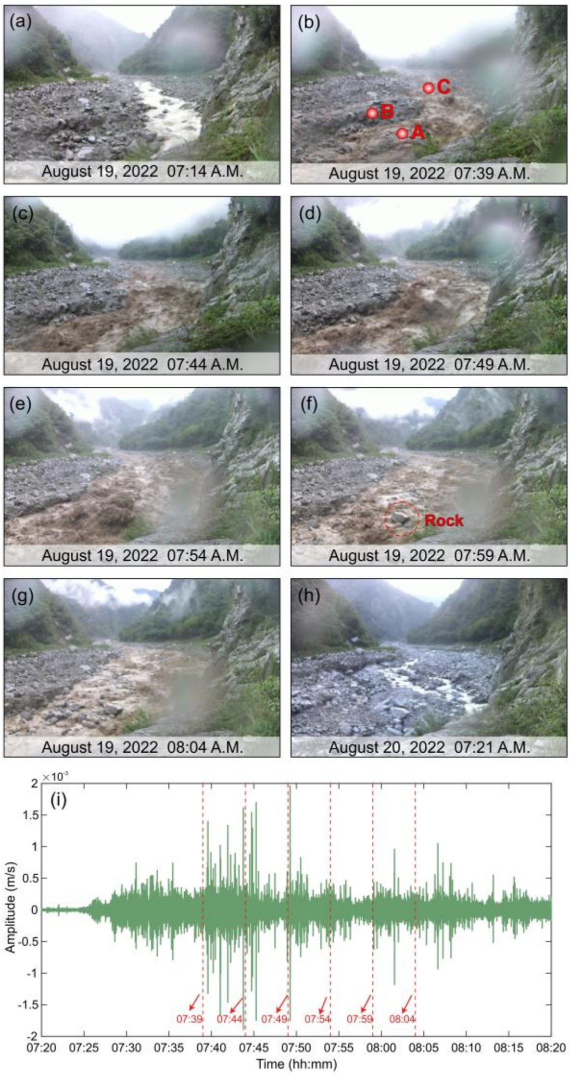


Fig. 7. Infrared camera images and seismic signals were recorded at monitoring point 1 in Fotangbagou Gully during the second debris flow on the morning of August 19, 2022. Images (b)-(g) were recorded every 5 minutes from 7:39 to 8:04: (a) before debris flow; (b) 7:39 frame; (c) 7:44 frame; (d) 7:49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

frame; (g) 8:04 frame; (h) after debris flow. (i) The seismic signal was recorded at the point.

C65: Section 4.2.3: Post-event field investigations are important and it is nice that you made some measurements. However, I don't see where you have used the information you got from the survey and how they can help answering your scientific questions.

R65: We thank the reviewer for this helpful comment. The particle size distribution shows that 94% of the particle size of the sample is 0.018 m, i.e., *D* in Eq. (6). The value helps us to determine grain size of 0.01, 0.015, 0.02 and 0.025 mm in PSD of Fig. 9b, because the four values are determined around 0.018 m. It has been modified, as follows:

Lines 637 to 642

We conducted debris flow seismic Power Spectral Density (PSD) forward modeling (Fig. 9b), employing Eq. (7) with key parameters derived from observations of the 2nd debris flow in Fotangbagou. *D* was determined based on 94% of the particle size, resulting in values of 0.01 m, 0.015 m, 0.02 m, and 0.025 m, respectively. The velocity *u* was consistent with the mean velocity described in Section 4.3, which was set at 2 m/s, 4 m/s, and 6 m/s.

C66: Line 420: where is point C?

R66: Thank you for your useful advice. It has an error here. The words "at point C" has been removed.

C67: Lines 424-426: these sentences are vague. In Figure 9c I still see very big rocks. Moreover, the fact that at a very specific point of the fan there are some small particles, doesn't mean that the carrying capacity of the debris flow sharply decreases. I suggest you to remove this part.

R67: Thanks a lot for the constructive comment. As you said, frontal grains of accumulation fan are small indeed, the sentence cannot verify carrying capacity of the debris flow sharply decreases. Thus, these sentences have been deleted.

C68: Lines 427-438: please specify that from your sample you can only quantify the small fraction of the deposit. For the same raison, it is not correct to say that the 94th percentile of the grain size distribution in 0.018 m: look at the big rocks in the photos.

Are you sure that you have used this value for equation (8)? In the following section you use much bigger values.

R68: We deeply appreciate the reviewer carefully went through the manuscript line by line.

1. This part can explain the grain about the sample we collected from the accumulation fan instead of the debris flow. It is correct that the 94th percentile of the grain size distribution is 0.018 m for the sample because the big rocks are not in the sample.

2. The particle size distribution shows that 94% of the particle size of the sample is 0.018 m, i.e., *D* in Eq. (6). The value helps us to determine grain size of 0.01, 0.015, 0.02 and 0.025 m in PSD of Fig. 9b, because the four values are determined around 0.018 m. We used much bigger values in the previous manuscript. In order to get close to 0.018 m, we have modified grain size of 0.5, 0.55 and 0.6 m into grain size of 0.01, 0.015, 0.02 and 0.025 m.

C69: Figure 9: In Figure 9a you use “deposition fan”, in the caption you use “accumulation fan”. Please choose one of them.

R69: Thank you for your useful advice. The figure has been modified, as follows:

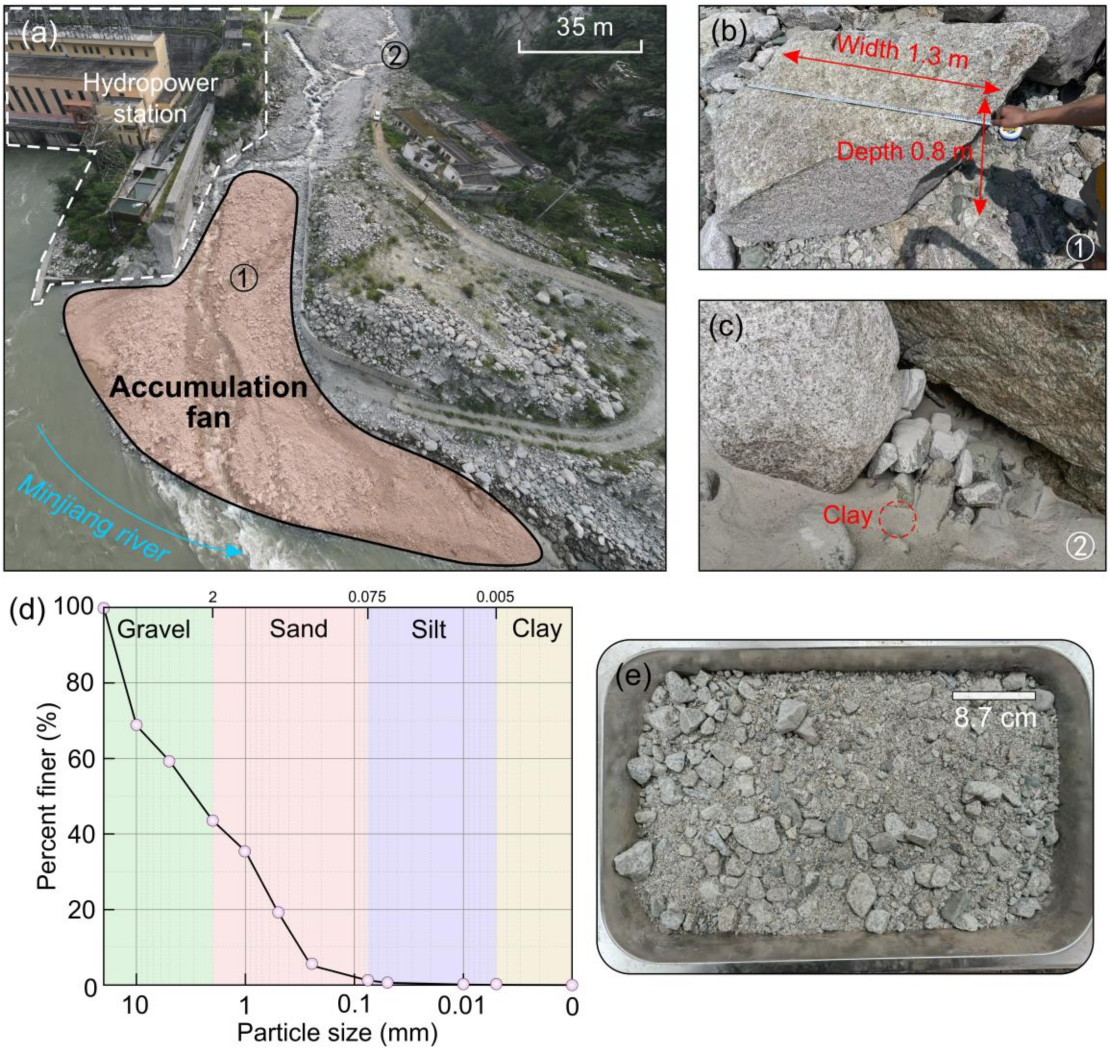


Fig. 8. Post-event field survey of accumulation fans in Fotangbagou Gully. (a) Aerial view of the Fotangbagou gully fan; (b) Largest particle on the Fotangbagou gully fan, marked ① in image (a); (c) Thin layer of clay covering the accumulation surface in Fotangbagou gully, marked as ② in image (a); (d) Particle size distribution for Fotangbagou gully sediment samples; (e) Fotangbagou gully sediment sample. Clay has not been marked in the subplot (d) because of the particles with grain size less than 0.005 mm.

C70: Section 4.2.4: I'm sorry but I'm not sure about the need of this section. The changes you claim to see in Figure 10 are really small, especially from 7:44 to 08:04, maybe less than 1 decibel. I believe that this can be within the errors associated with your computations. If you want to investigate the variation of frequency over time, maybe you could compute the frequency peak or the mean frequency as in Farin et al.

(2018). However, it should be done continuously and not only for the 6 time intervals as you do.

R70: We thank the reviewer for this comment. Actually, the changes of PSD of different grain sizes and velocities are small at low frequency, great at high frequency. The frequency peak or the mean frequency versus time cure can reflect the change of frequencies in the evolution of debris flow. We cannot explain the purpose of the section clearly in the previous manuscript. We would get characteristic of PSD for every frequency at different frames to analyse characteristic of velocity, discharge and grain size of debris flow. We have divided the figure into two subplots and rewritten this part, as follows:

Lines 615 to 690

Eq. (6) was employed to calculate the seismic Power Spectral Density (PSD) curves for the six-time points corresponding to the infrared images (Fig. 9a). Notably, the maximum energy within the main frequency band (15~30Hz) exhibited a gradual decline from 7:39 to 8:04, evident from the discernible trend in dot changes depicted in Fig. 9a. The width of the PSD spectrum demonstrated an initial increase, followed by a subsequent decrease, showing distinct trends between the low-frequency and high-frequency bands. Specifically, the high-frequency band (>30Hz) experienced a gradual reduction from 7:39 to 8:04, characterized by a rapid decrease from 7:39 to 7:49 and a relatively slower decline from 7:54 to 8:04. Conversely, the low-frequency band (<15Hz) exhibited a substantial increase from 7:39 to 7:44, followed by a more substantial decrease leading up to 7:54, after which it roughly remained unchanged. These varying characteristics among different frequency bands underscore the need for a deeper understanding. In the subsequent sections, we will employ a debris flow seismic PSD forward model to gain a more comprehensive insight into these observations.

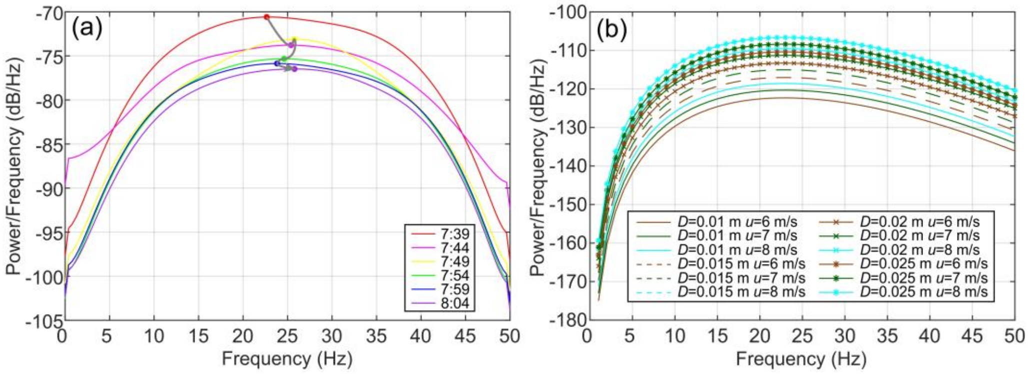


Fig. 9. Characteristic change of power spectral density (PSD). (a) Evolution of PSD during the second debris flow in Fotangbagou Gully on the morning of August 19, 2022, from 7:39 to 8:04; (b) Comparison of PSD for different grain sizes (*D*) and velocities (*u*). Each curve represents PSD frequency over 60 s. 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).

We conducted debris flow seismic Power Spectral Density (PSD) forward modeling (Fig. 9b), employing Eq. (7) with key parameters derived from observations of the 2nd debris flow in Fotangbagou. D was determined based on 94% of the particle size, resulting in values of 0.01 m, 0.015 m, 0.02 m, and 0.025 m, respectively. The velocity u was consistent with the mean velocity described in Section 4.3, which was set at 2 m/s, 4 m/s, and 6 m/s. The seismic propagation distance r_0 was determined by measuring the distance between Point 1 and the central channel of the 2nd debris flow in Fotangbagou gully. All other parameters in Eq. (7) remained consistent with those used for seismic signal recovery, as detailed in Section 4.1.

As depicted in Fig. 9b, it is evident that the velocity of the debris flow significantly determines the energy level of the PSD, while the particle size exerts a comparatively weaker impact on energy levels than flow velocity. Specifically, for a debris flow with the same particle radius, the energy across the entire frequency band experiences a sharp increase with higher flow velocities. In contrast, the increase in energy within each specific frequency band remains relatively modest when varying particle size at a consistent flow velocity.

The impact of flow velocity is more pronounced at the high-frequency end compared to the low-frequency end. This suggests that variations in flow velocity can be effectively discerned by analyzing the energy at the high-frequency end of the PSD curve. When examining the PSD curves for the six-time points corresponding to the infrared images, it becomes evident that the high-frequency end of the curve gradually decreases. This decrease signifies a gradual reduction in the debris flow velocity. Notably, the velocity decline is relatively rapid from 7:39 to 7:59 and then exhibits a slower rate of decrease. These observations align with the inferences drawn from the analysis of flow rates based on the infrared imagery.

In the low-frequency range, velocity has a notable impact on energy. When velocity decreases, the energy corresponding to a single frequency also decreases, albeit with a relatively small amplitude compared to the high-frequency range, as illustrated in Fig. 9. Notably, there is an observable increase in the low-frequency end at 7:44 in contrast to 7:39, which contradicts the analysis of the high-frequency range. Fig. 7c displays an infrared image indicating a relatively high concentration of particles within the debris flow at 7:44. This observation suggests that the strong energy observed at the low-frequency end in this timeframe may be attributed to the presence of these particles.

The peak frequency is influenced by both particle size and flow velocity, as demonstrated in Fig. 9b. When examining the relationship between particle size *D* and flow velocity *u*, it becomes evident that a smaller particle size and higher flow velocity result in a larger peak frequency in this debris flow, and vice versa. This phenomenon is attributed to the combined effects of particle size and flow velocity. Additionally, it's worth noting that particle content, including flux and concentration, plays a significant role in affecting the energy of seismic signals. Therefore, when considering the model described in Eq. (7), it is imperative to account for the influence of particle concentration. Analyzing the peak frequency of seismic signals from debris flows captured between 7:39 and 8:04, as shown in Fig. 9, reveals an interesting pattern. Initially, the peak frequency increases, then decreases, and eventually rises again. This behavior can be attributed to the comprehensive response of particle size and flow velocity to the PSD. Specifically, when flow velocity decreases, the particle size of debris flows transported by the debris flow increases. It's important to recognize that significant changes in flow velocity should be accompanied by corresponding alterations in sediment concentration.

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 4.2.2 and confirms that the trend of the debris flow can be determined from the time-frequency characteristics of the seismic signals.

C71: Similarly, the application and interpretation of the model by Lai et al. (2018) is vague to me. How have you got D=0.5-0.6 m if the 94th percentile of your sample is just 0.018 m? Why have you chosen velocities ranging between 2 and 6 m/s? Have you taken these values from the literature? This choice looks weird also because later you do estimate the velocity, so why haven't you tested your estimation? Maybe it would be interesting to test the model by Lai et al. (2018) with the velocity you estimate, and see what is the diameter that gives you a seismic power similar to observations. However, some issues still remain as it is not clear to me how you can estimate the debris flow length and the seismic parameters in equation (8). I believe that the uncertainties on these parameters are too high to interpret the result of the modelling.

R71: Thank you for the useful advice. *D*=0.5-0.6 m and *u*=2-6 m/s were incorrect. We determined *D*=0.01-0.025 m and *u*=6-8 m/s that are around the 94th percentile of your sample, 0.018 m and the flow velocity estimated based on cross-correlation function, 7.0 m/s. It will help to use 0.018 m and 7.0 m/s to analyse PSD. Effective length of Eq. (7) is that main contribution length which monitoring stations record seismic signal.

We can estimate 15 m and 25 m that are distances between the monitoring station and the channel with measurement. Thus, we continued to use the length during forward analysis.

C72: The interpretation of your results looks also incorrect to me. In equation (8), both diameter and velocity are to the third power, therefore you cannot say that particle size has a minor effect than velocity. Your interpretation is due to the fact that the velocities you have tested vary much more than the diameters (you triple the velocity from 2 to 6 m/s, but the diameter only varies by a factor of 1.2 between 0.5 and 0.6 m) (lines 479-484). Moreover, at line 502 you say that “the particle content in one of the factors affecting the energy of seismic signals”, but the model by Lai et al. (2018) makes the opposite assumption of constant particle content. If you believe that particle content plays a role, why have you used this model?

R72: We thank the reviewer for this comment. D=0.5-0.6 m and u=2-6 m/s were incorrect. We determined D=0.01-0.025 m and u=6-8 m/s that are around the 94th percentile of your sample, 0.018 m and the flow velocity estimated based on cross-correlation function, 7.0 m/s. It will help to use 0.018 m and 7.0 m/s to analyse PSD. Indeed, particle size and velocity are three cubed, but magnitudes of particle size and velocity change differently. In our research, magnitude change of velocity is bigger than magnitude change of particle size, because particle size is affected by velocity and discharge in non-Newtonian fluid, which caused that change of particle size is relatively lagging behind change of velocity.

C73: For all these raisons, I would remove this section, unless you can solve the points I have raised.

R73: Thank you for the professional advice. We have solved the points you have raised. This section is important to analyse PSD at different time frames combined with grain size, velocity and infrared imagery, which can help to analyse the influence of different factors on characteristic of seismic signal of debris flow.

C74: Line 518: what do you mean by “horizontal distances”?

R74: Thank you for your constructive comments. “Horizontal distances” means distance between the channel and the monitoring station along horizontal direction. It has been modified, as follows:

Lines 693 to 696

The horizontal distances, representing the separation between the channel and the monitoring station in the horizontal direction for Ergou Gully, are 13 m and 7 m for monitoring points 1 and 2, respectively.

C75: Line 519: Why have you chosen a gain factor of 1.8? Is it the sigma of equation (10)? Are the spectrograms resulting from the seismic signal restoration? If not, I don’t see how the restoration is useful here given that all your comments concern the spectrograms.

R75: We thank the reviewer for this helpful comment. A gain factor of 1.8 is Q of equation (8) indeed, which cannot be obtained accurately but estimated empirically. We make references from the two values of petroleum seismic prospecting in the earth surface to estimate the two values in our study. However, these references belong to internal data and cannot be offered references in the manuscript. Geology condition of the earth surface around the two monitoring stations are different, so Q is also different. Changes of its carrying capacity, discharge, velocity of the same debris flow are small. Characteristic of seismic frequency, energy and waveform are similar when absorption attenuation was not considered, but seismic signals have a great difference between two monitoring stations due to absorption attenuation. Thus, we determined the value of Q.

As you said, the spectrograms resulting are from the seismic signal restoration indeed.

C76: Lines 522-537: it is really hard to see what you observe in the figures. I propose to show the different times with lines in the spectrograms.

R76: Thank you for spending the time to review and assess our manuscript. We have added the different times in the spectrograms of this figure, as follows:

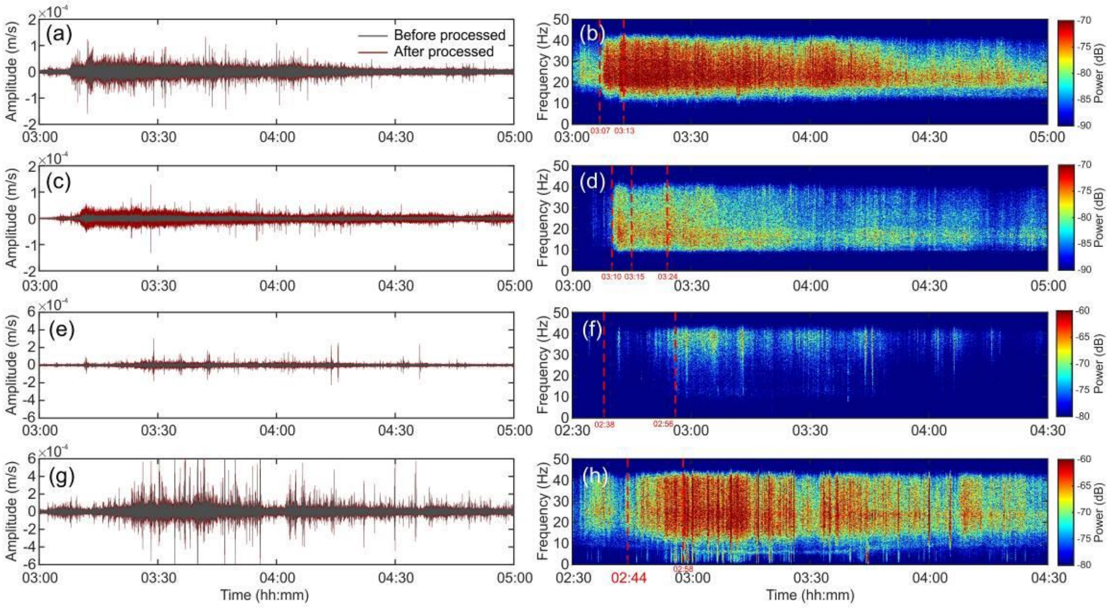


Fig. 10. seismic and its spectrogram of the first debris flow in Fotangbagou gully and debris flow in Ergou gully. The first Fotangbagou debris flow's Seismic recorded at monitoring stations 1 (a) and station 2 (c), and (b) and (d) is its spectrogram respectively; The Ergou debris flow's Seismic recorded at monitoring station 1 (e) and station 2 (g), and (f) and (h) is its spectrogram respectively.

C77: Figure 11: more comments are needed. As I have already said, why in Figure 11b and 11d the seismic power is zero below 10 Hz? Is the signal filtered or a different characteristic of the instruments compared to the ones in the Ergou gully? In both cases, this is an important aspect to clarify since it affects all the interpretation about the frequency bands. Again, there are no comments about the passage of the debris flow front: you assume that the first peak in seismic power is related to the passage of the debris flow, but it could also be the front approaching towards the seismic station. Finally, are you sure that in Figure 11f we see the seismic signature of a debris flow? It could be rainfall in my opinion (Rindraharisaona et al., 2022).

R77: Thanks a lot for the constructive comment. The reason why the seismic power of the two subplots is zero below 10 Hz is that the seismic power below 10 Hz is small, inobvious and close to the power that is blue in colorbar. It is not the result of a filtering process because we used high-pass filter over 1 Hz. The first debris flow of Fotangbagou has smaller time-domain amplitude than the debris flow of Ergou, so the former is more inobvious than the latter. Events observed at Illgraben ranges from granular, muddy, hyperconcentrated debris flows to floods (Badoux et al., 2009). Guo et al. (2016) proposed that a debris flow on July 10, 2013 in Ergou Gully in Wenchuan County, China moved fast initially surges of materials and then transformed each other in flood and debris flow to Minjiang River with a few viscous materials. The debris flows in Wenchuan differ from that in other two basins for property. The first debris flow in Fotangbagou has a narrow frequency band indeed because this event has a smaller scale than the second debris flow. We cannot divide quantitatively front and tail of debris flow from seismic signal because debris flows in our study area is not similar to ones as debris-flow surges in Yunnan Province, China (Yan et al., 2023), and Illgraben (Badoux et al., 2009). It will become our subsequent research direction. Figure 10f show different signature of a debris flow because the distance of the station 1 for Ergou is longer than others possibly. Maybe there are other reasons, and it is a problem to solve subsequently.

C78: Lines 550-552: the two sentences repeat the same concept

R78: We deeply appreciate the reviewer carefully went through the manuscript line by line. The two sentences have been modified, as follows:

Lines 730 to 732

In contrast to Fotangbagou Gully, the seismic signal was stronger at monitoring point 2 than at monitoring point 1, and the energy generated by the movement of the debris flow increased between the two monitoring points.

C79: Line 556: I cannot see the decay towards 23 Hz. Can you explain this comment?

R79: Thank you so much for the comments. It has been modified, as follows:

Lines 736 to 738

Throughout the entire event, there is a gradual energy decay towards 23 Hz, representing the dominant frequency range with high power, indicated by red or dull-red colors in the color bar, observed at the conclusion of the debris flow in Ergou.

C80: Section 4.3: as I said before, I’m not convinced about the method you have used. However, I will make some comments on the text.

R80: We thank the reviewer for this comment. After consideration, we deleted Section 4.3 “debris flow scale analysis by seismic signal” because the part is not strongly convincing.

C81: Lines 569-571: please try to be more clear. The decay of seismic power is not a problem by itself. You should say that you need to take into account the distance between the sensors and the debris flow if you want to estimate the relative magnitude of the events.

R81: Thank you for the constructive advice. After consideration, we deleted Section 4.3 “debris flow scale analysis by seismic signal” because the part is not strongly convincing.

C82: Line 575: what are these values? m/s? You should also mark the peaks in the figures (and mention the figures where you can see these values). Which station have you considered? This must be clarified

R82: We thank the reviewer for this comment. After consideration, we deleted Section 4.3 “debris flow scale analysis by seismic signal” because the part is not strongly convincing.

C83: Lines 576-578: how do you compute the frequency bands? How can you use the frequency bands to get the magnitude of the debris flows? The larger the frequency band, the bigger? Who says that?

R83: Thank you for the professional comment. After consideration, we deleted Section 4.3 “debris flow scale analysis by seismic signal” because the part is not strongly convincing.

C84: Section 4.4: This section is interesting, but several aspects must be clarified and you should convince me about the parameters you have used

R84: Thank you for your constructive comments. As you said, we have removed explanations and values of parameters from Section 4.3 “debris flow velocity analysis” to Section 3.3. The related previous explanations have been modified and added, which is shown in R3 for the general comments of reviewer 2 from lines 322 to 346.

C85: Line 580: in my opinion you haven’t estimated the maximum velocity but rather a mean velocity of the debris flow, as you consider all the signal

R85: We thank the reviewer for this helpful comment. The velocity is mean value between the two cross-sections indeed. It has been modified in R15 for reviewer 2 from lines 316 to 317.

C86: Lines 583: even if velocities are shown in the table, you need to recall them in the text. What do you mean by “normal”? Give some references

R86: Thank you for spending the time to review and assess our manuscript. Velocities shown in the table have been recalled. “Normal” means velocities are 0-10 m/s in Table 1 by Arattano and Marchi (2005) and Fig. 10 to Fig. 12 by Cui et al. (2018). The sentence has been modified, as follows:

Lines 743 to 747

The velocity result of 38.3 m/s for Ergou gully is an order of magnitude higher than 3.0 m/s and 7.0 m/s for Fotangbagou gully and is outside the normal debris flow range (Table 3) which indicates the order of magnitude is 1 (Arattano and Marchi, 2005; Cui et al., 2018).

C87: Lines 583-586: from these lines it is not clear to me if you are talking about the cross-correlation method. Comments are needed also for the other debris flows

R87: Thanks a lot for the constructive comment. It is right that we are talking about the cross-correlation method in this part. Comments for the other debris flows have been added, as follows:

Lines 747 to 751

The signal lag time τ in Eq. (4) reflected by the peak amplitude of the second debris flow in Fotangbagou gully is 74 s (Fig. 11), and the distance between adjacent monitoring sections is about 520 m, which gives a mean velocity of 7.0 m/s (Table 3). For the first debris flow of Fotangbagou and the debris flow of Ergou, τ are 173 s and 12 s, mean velocities are 3.0 m/s and 38.3 m/s.

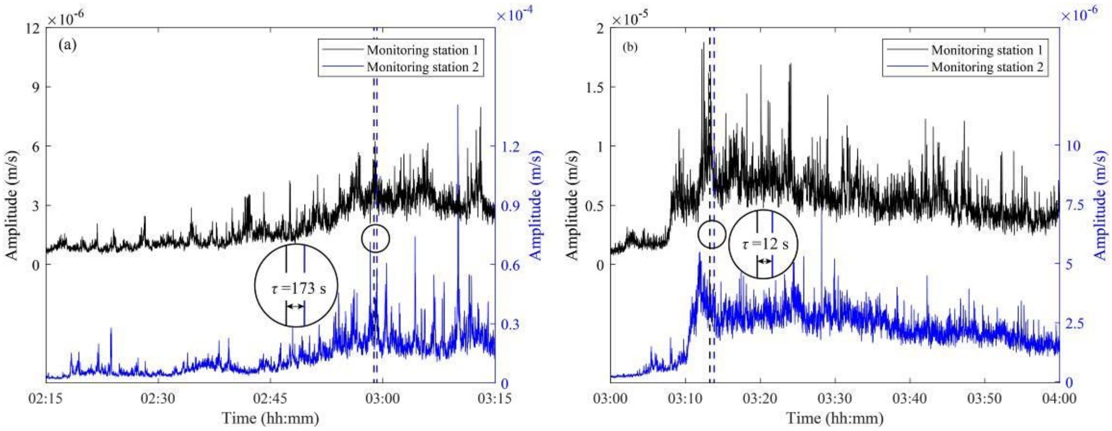
C88: Line 586: three decimal digits seem too many to me given the uncertainties.

R88: We deeply appreciate the reviewer carefully went through the manuscript. Three decimal digits are from the division method of the distance divided by the lag time. The uncertainties come from the division method instead of the cross-correlation function. It has been reduced to one decimal digits, which is the value of “7.0 m/s”. It has been modified, which is shown in R87 for reviewer 2 from lines 747 to 751.

C89: Figure 12: you should show all the three debris flows. It is not clear to me if the curves you show come from the cross-correlation routine or are just the amplitudes

R89: Thank you so much for the comments. After using the cross-correlation function for all the three debris flows, only the result of the second debris flow at Fotangbagou Gully can be thought it is reasonable with comparison of the estimation result of

Manning formula. Thus, it only has a debris flow in Figure 11. The curves I show are just the amplitudes. schematic diagram of the first debris flow in Fotangbagou gully and the debris flow in Ergou gully based on the cross-correlation function is shown as follows (Attached figure 2), the first debris flow of Fotangbagou is shown in Figure 11.



Attached figure 2. Amplitude range of the first debris flow in Fotangbagou gully and the debris flow in Ergou gully based on the cross-correlation function. The signal lag time τ between the two monitoring stations is circled. (a) Amplitude range of the first debris flow in Fotangbagou gully; (b) Amplitude range of the debris flow in Ergou gully.

C90: Line 595: it is a bit strong to say that you use the Manning formula to verify the velocity calculations, because also the Manning formula has its own uncertainties. I would say that you have estimated the velocity with two independent methods

R90: We thank the reviewer for this comment. We use this formula to verify the result of cross-correlation function. It has been added, as follows:

Lines 764 to 767

The Manning formula has its own uncertainties indeed, but Cui et al. (2013), Guo et al. (2016), and Cui et al. (2018) thought it is effective to use this formula to estimate the velocity of debris flows.

C91: Line 599: please be more clear about the estimation of the roughness coefficient. Is it true that you have estimated it with equation (6)? What value of d50 have you used?

R91: Thank you for the useful advice. According to Xu and Feng (1979), the roughness coefficient was estimated to be 0.05. The sentence has been modified, as follow:

Line

A key element of the Manning formula is the channel roughness coefficient *n* (Smart, 1999), which was determined as 0.05 (Xu and Feng, 1979) for the Fotangbagou gully.

Actually, the roughness coefficient is estimated empirically. This equation mentioned by you has not been used for estimation of the roughness coefficient because we only can get d50 of the channel bed for post-event field investigation but the value of the debris flow process. Thus, we use an empirical estimation value. This equation mentioned by you should been deleted.

C92: Lines 604-607: these sentences should appear in the methods. Please tell us more precisely how you have computed the hydraulic radius and the slope, as they are crucial terms in the Manning formula

R92: We thank the reviewer for this comment. It has been modified, which is shown in R3 for reviewer 2 from lines 322 to 346.

C93: Line 611: comments are needed as it means that between the two stations the velocity is quite constant.

R93: Thank you for the professional comment. It has been modified, as follow:

Lines 768 to 770

It indicates that the values of velocities are constant during process between the stations 1 and 2 because of the comparative wide and straight channel possibly.

C94: Lines 611-612: as already said, it is not correct to say that one method verifies the other

R94: Thank you for your constructive comments. We rewrite this sentence, as follows:

Lines 770 to 772

This indicates it is appropriate to use the cross-correlation function to estimate the velocity of debris flow because the two values from cross-correlation and from the Manning formula have a smaller difference.

C95: Figure 13: I’m confused by this figure, since in Figure 2 you show the infrared camera only at station 1. How many infrared cameras do you have on the

Fotangbagou? If two, why have you used only one camera in the previous sections? If one, how have you estimated the flow stage at station 2? Please clarify this aspect

R95: We thank the reviewer for this helpful comment. There are 2 infrared cameras at Fotangbagou. Another unused infrared camera located at station 2. This aspect has been clarified, as follows:

Lines 505 to 508

However, the image quality suffered due to water droplets on the camera lens caused by the passage of the debris flow, resulting in blurry images at station 2. Consequently, we chose to rely solely on the infrared camera at station 1 for our analysis.

C96: Discussion: As a general comment, a better job should be done in this section. The discussion is the place to compare your findings with existing works and you have done it only in section 5.2. If you follow my main suggestion, section 5.3 is good to discuss on the limitations of this monitoring system and on what could be improved, taking advance of the monitoring stations already existing around the world. Comparisons with other works are also needed on the values of velocity.

R96: Thank you for spending the time to review and assess our manuscript. We have modified Section 5.2, as follows:

Lines 818 to 820

Our velocity result of 7.0 m/s is in 3.0-9.1 m/s by Arattano and Marchi (2005) with the cross-correlation function, which makes our velocity result convincing.

C97: Section 5.1: I would remove this section, since you are not adding discussion points but only repeating your findings. Moreover, several parts are not clear to me: at line 633 I don’t see how the kinematic parameters vary with topography; I don’t understand how the distance between the sensor and the channel can affect kinematic parameters (maybe you wanted to say that the distance must be taken into account if one wants to use seismic sensors to estimate kinematic parameters?); at line 639-640, the meaning of “seismic features select representative analysis points” is obscure to me.

R97: Thanks a lot for the constructive comment. After consideration analysis, we would leave this section. We summarize the preceding results and analysis in this section indeed. Two opinions would be explained. Firstly, seismic signals recorded by the different monitoring stations showed difference for the same debris flow. Propagation effect needs to be eliminated appropriately and considered during analysing seismic signals, we use “tendency” to analyse seismic signals. Secondly, seismic signals from different monitoring stations are comprehensive inversion of dynamic parameters of debris flow. It is difficult to analyse change of dynamic parameters based on only seismic signals, but we can consider other information like infrared imagery, post-event field investigation to achieve semi-quantitative analysis.

The content in Line 633 did not show how the kinematic parameters vary with topography, but topography would affect flow velocity and carrying capacity of debris flow, which will be a subsequent research direction. “The distance between the sensor and the channel” is used to explain the distance will affect time-domain amplitude characteristic of seismic signal. The previous expression is ambiguous, so the sentence has been modified, as follows:

For the same debris flow, the kinematic parameters such as flow velocity, particle diameter distribution, concentration, flow rate, etc., vary with the topography (Fig. 4) and the distance of the seismic signal from the sensor is variational with different station, so the signal amplitude recorded at each monitoring point is different.

Line 639-640 mentioned by you is a writing mistake, we rewrite it, as follow:

Lines 799 to 802

When analyzing the change characteristics of PSD curve, it is best to estimate the approximate velocity and particle size of debris flow, because the velocity and particle size change by orders of magnitude, the characteristics of PSD curve will change, and the typical change is that the influence degree of velocity and particle size is greater.

To sum up, we modified the second paragraph, as follows:

Lines 790 to 808

For the same debris flow, the kinematic parameters such as flow velocity, particle diameter distribution, concentration, flow rate, etc., vary with the topography (Fig. 4) and the distance of the seismic signal from the sensor is variational with different station, so the signal amplitude recorded at each monitoring point is different. The time domain seismic changes can roughly reflect the debris flow evolution characteristics, but the analysis of flow velocity, concentration, and flow of the debris flow needs to be combined with the change characteristics of PSD curve for comprehensive analysis. When selecting the analysis time of PSD curve, it is necessary to fully consider the characteristics of debris flow seismic and select representative analysis points. Secondly, when analyzing the change characteristics of PSD curve, it is best to estimate the approximate velocity and particle size of debris flow, because the velocity and particle size change by orders of magnitude, the characteristics of PSD curve will change, and the typical change is that the influence degree of velocity and particle size is greater. We discuss the effect of velocity and particle size on PSD over the range of velocities in the debris flow, and it comes from the fact that the velocity with small changes in this study. Thus, when seismic signals are used for debris-flow evolution analysis, sufficient information on the post-disaster investigation and dynamic parameters of the debris flow, combined with the forward modeling results for the joint analysis, increase the reliability of the analysis results.

C98: Conclusions: The conclusions should be adapted with the respect to the new structure of the manuscript

R98: Thank you for the useful advice. According to your comments, we have changed the structure of the manuscript and modified the conclusions, as follows:

Lines 872 to 902

In this study, the characteristics of the seismic signal from three debris flows on August 19, 2022, in the Wenchuan earthquake area of China are investigated. The three debris flow events studied here were generated under conditions of heavy rainfall. Three debris flows were analyzed that they exhibit the seismic characteristics of fast excitation and slow recession. Even to a large extent eliminating the propagation effect, the seismic amplitude and frequency characteristics of different monitoring stations of the same debris flow have a large difference, which indicates that the dynamic parameters of the debris flow are changing in the evolution process. The change in the flow state of the debris flow results in a different range of frequencies in the energy spectrum at the beginning and end of the debris flow, which is confirmed by our continuous photo analysis, PSD of the current records, and PSD of the forward modeling. At the start of the three debris flows, the energy is strong when debris flow goes through the monitoring point, mainly in the 10–42 Hz frequency range, while later in the event, the main frequency spectrum reduce to 20–23 Hz which roughly reflects the dynamic parameters evolution of debris flow. According to the seismic amplitude and frequency characteristic changes at different monitoring points of debris flows, the relative changes in the debris flow evolution process can be roughly analyzed.

The cross-correlation function can be a good choice to calculate maximum debris flow velocity in relative debris flow with riverbed changing simply. Compared with the result based on the Manning formula, it is reasonable for calculation result of the mean velocity of 7.0 m/s for the second debris flow in Fotangbagou gully. However, in Ergou Gully with relatively complex topography, the cross-correlation function was less successful, probably due to its more complex topographic setting causing strong variations in the kinematic parameters of the debris flow. Hence, the cross-correlation function may be an appropriate approach for peak flow calculation in simple debris flow, but not appropriate in much more complex debris flow.

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

C99: Line 708: you say “large difference”, but at lines 629-630 you seem to say the opposite

R99: Thank you so much for the comments. It is my error of expression. “Large difference” is from comparison of the seismic signal characteristics before and after eliminating the propagation effect, it didn’t point out comparison of time-domain and frequency-domain characteristics for the same seismic signal. Thus, the sentence should be modified into:

Lines 876 to 879

Even to a large extent eliminating the propagation effect, the seismic amplitude and frequency characteristics of different monitoring stations of the same debris flow have a large difference, which indicates that the dynamic parameters of the debris flow are changing in the evolution process.