Reply to Referee Comments

(C and R denote comment and reply, respectively)

We would like to express our sincere gratitude to you for your careful reading of our manuscript and for providing insightful and constructive comments. We have carefully considered all the comments and revised the manuscript accordingly. Below, we provide a detailed response to each comment raised by the referee.

Referee #2:

General comments:

C1: The authors demonstrated detection of debris flows in Wenchuan area, China using a self-designed system, and analyzed the data to obtain important characteristics of the debris flow with the goal of establishing “a cost-effective, dependable, and convenient approach for monitoring debris flows in intricate mountainous terrains”.

The data itself is unique and valuable; however, I have significant concerns about the seismic processing approach and remain unclear about the monitoring system's effectiveness for early warning.

R1: Thank you very much for your valuable comments. In response to the reviewer's suggestions, we have revised the focus of the study so that we now concentrate on analyzing the seismic signal characteristics of debris flows and reconstructing the process, rather than focusing on debris flow monitoring and early warning. In addition, we have provided a detailed explanation of the methods used in this study to process seismic signal data. Further details on the specific changes can be found in the following replies.

C2: The rationale behind the compensation step is not understood, especially when there is a large uncertainty in attenuation or the Q factor, and therefore the reconstruction of the signals. In addition, most of the detection analyses would not need to compensate for Q and the reconstruction, especially if the debris flow monitoring system is so close to the source. This problem is compounded in the power spectral density (PSD) where the equation has already accounted for attenuation and therefore is contributing to conflicting values.

R2: Thank you very much for your valuable comments. We used a linear viscoelastic compensation function for plane waves to compensate for the loss of high-frequency energy in seismic signals. This helps to partially restore the different degrees of attenuation in different frequency bands during propagation, thereby improving the accuracy of the PSD analysis. The PSD calculated using equation 6 (Eq.1) based on forward modeling takes into account parameters such as the epicentral distance and the attenuation coefficient and thus corresponds to the compensated PSD. After compensating the seismic signal with the compensation function, the PSD calculated from the seismic signal using equation 5 (Eq.2) also represents partial compensation. This approach is more effective in eliminating the propagation effects on the seismic frequency characteristics. In our study, the Q value (representing attenuation) remained constant during the calculation of the PSD and compensation of the signals to ensure consistent compensation across all signals. This approach helps to ensure the reliability of subsequent comparisons of the parameter characteristics of debris flows.

C3: On Section 3.2 Cross-correlation and for Section 4.2 Debris flow analysis: What part of the recording is cross-correlated: the seismic power, absolute amplitude, envelope of the amplitude in time-domain? And if you use the whole debris flow signal, or just the onset. My concern is that the high frequency recording is complex and will generally give poor cross-correlation value. The peak frequency (in equation 6) can be used as a proxy to distance too, and can be used to calculate flow velocity and cross-check with the velocity obtained from cross-correlation.

R3: Thank you very much for your valuable comments. We used the amplitude method to process the entire debris flow signal. This approach helps to eliminate high-frequency noise and provides a more stable representation of the amplitude of the seismic signal. Using the entire debris flow signal, we calculated the average flow velocity based on the time delay and distance between the peak amplitude differences of the signals from two measurement points. This method effectively captures the flow characteristics by focusing on the peak amplitude differences between the measurement stations. As follows:

Lines 614 to 618

The sampling rate for seismic signal monitoring is 100 Hz. The average amplitude for each second of seismic data is calculated using the amplitude method (Arattano, 1999), whereby 100 seismic signals are recorded within each second and their amplitudes are averaged. This method helps to smooth out high-frequency noise and provides a more stable representation of the amplitude of the seismic signal.

C4: On Section 4.3.3: seismic power spectral density (PSD) curves: Is this analysis done on the raw data or the compensated data? Equation 6 has accounted for attenuation. The analysis is only done for one station, but given the setup of dual monitoring systems and that most parameters like grain size would be the same, it would be useful to perform the analyses on both stations and explore the effectiveness and value in having a dual monitoring system.

R4: Thank you very much for your valuable comments. Indeed, Eq. 6 (Eq. 1) includes a compensation term. We initially performed signal compensation to facilitate PSD analysis without considering the effects of absorption. Without compensation, when comparing PSD curves at different times or from different stations, we would first need to account for the absorption and attenuation effects on our signals. Furthermore, the $\cdot\frac{f^{3+5\xi}}{v_c^5 r_0} e^{-\frac{8.8 f^{1+\xi} r_0}{v_c Q}}$ term in Eq. 6 (Eq. 1) is relatively complex. By minimizing this effect in the seismic signal, the PSD curve simplifies to $PSD \approx 1.9 \cdot LWD^3 u^3$, allowing us to focus solely on the influences of particle size, epicentral distance, and velocity. This approach makes the analysis more straightforward and focused on the relevant parameters.

C5: In the context of "Subsequent debris flow detection, early warning, and inversion", It would be helpful to discuss how effective the system is in dealing with false detections such as local earthquakes or quarry activities. The emphasis on early warning is compelling and clearly important, yet the discussion on how the system or its processing steps contribute to early warning is quite limited.

Another point is on cost-effective, which brings the question of why we need a two-station monitoring system. Presumably for redundancy, but this design choice warrants a longer discussion, especially considering their proximity (less than 1 km apart) and most of the calculations can be done with a single station.

R5: Thank you very much for your valuable comments. Based on the expert's comments, our monitoring devices were unable to transmit data in real time due to network problems, which prevented the implementation of real-time monitoring and early warning. As a result, we shifted the focus of the study from monitoring and early warning to analyzing the seismic signal characteristics of debris flows and reconstructing the process. Therefore, in this study, we no longer focus on the monitoring and early warning functions of the monitoring system, nor do we focus on its cost-effective aspect.

Specific comments:

C1: Highlights:

- Real-time monitoring of debris flow kinematics based on seismic signals.
- Extraction of debris flow characteristics (e.g., peak velocity) over space/time.
- Provides a framework for upscaling debris flow monitoring networks.

These highlights are not reflected in the manuscript. As written in the text, the monitoring is not done in real-time. Similarly, the term 'Peak velocity', is only mentioned once in this highlight and not in the text. The manuscript mostly demonstrated the data analyses and there are little to no discussion on the framework for upscaling.

R1: Thank you very much for your valuable comments. Based on the reviewers' comments, we have adjusted the content of this study and revised the highlights of the research as follows:

Lines 32 to 43

Highlights:

- By analyzing the characteristics of seismic signals, the study successfully reconstructed the entire process of the second debris flow event at Futangba Gully by utilizing features such as the time series, flow velocity, particle characteristics, and surge variations of the debris flow.
- The seismic signal characteristics of the debris flow showed rapid excitation and slow attenuation. Even after removing propagation effects, significant differences in amplitude and frequency were observed at different monitoring stations, indicating changes in the dynamic parameters of the debris flow.
- The time-frequency characteristics of seismic signals reflect the evolution process of debris flows, with a corresponding relationship between the power spectral density and debris flow characteristics.

C2: Abstract: "Our analysis of infrared imagery and power spectral density showed a strong correlation between debris flow seismic energy and its frequency spectrum, supporting the accuracy of using seismic signals to reconstruct debris flow events."

- This is ambiguous. Which observable is strongly correlated to which physical properties of the debris flow?

R2: Thank you very much for your valuable comments. Due to adjustments in the research content, we have revised the abstract as follows:

Lines 15 to 29

Abstract

Rainfall-induced debris flows are highly destructive due to their abrupt onset, rapid movement, and high sediment transport capacity, all of which can lead to significant loss of life and damage to infrastructure. However, a comprehensive analysis of their dynamic evolution remains limited by the scarcity of in-situ monitoring data. In this study, we utilized near-field seismic data recorded by acquisition instruments deployed in Wenchuan, China, combined with images and post-event field investigations to reconstruct the second debris flow event in Fotangba Gully. Seismic signal attenuation was compensated, and time-frequency analysis and power spectral density (PSD) calculations were conducted. The results reveal pronounced differences in signal amplitude and frequency content across stations, reflecting spatial heterogeneity in flow dynamics. We identified flow velocity and grain concentration as the dominant factors affecting the PSD curves. This research provides a framework for extracting debris flow kinematics characteristics from seismic signals and offers new insights for hazard evaluation and the design of mitigation strategies.

C3: Introduction: "Landslides involve the movement of rock and soil on slopes, slipping along shear surfaces (Yan et al., 2020)."

- This first sentence is not related to the overall manuscript. Please remove self-citation.

R3: Thank you very much for your valuable comments. We have deleted this sentence.

C4: Line 68: Alternative approaches use flow velocity and depth as primary indicators for monitoring and early warning

- This is ambiguous. Is it debris flow velocity and depth?

Line 76: showcasing the effectiveness of ultrasonic and radar devices for monitoring.

- Similarly, this is ambiguous. From the sentence it is unclear if it is actually effective or not.

R4: Thank you very much for your valuable comments. Due to the adjustment in the research content, we have revised the Introduction section. The content you mentioned has been removed as per your suggestion. This modification aligns the introduction with the updated focus of the study.

C5: Line 84: Belli et al. (2022) found that physical parameters of debris flows correlate positively with seismic signal amplitudes.

- Which physical parameters?

R5: Thank you very much for your valuable comments. We've made some changes, as follows:

Lines 121 to 122

Belli et al. (2022) found that physical parameters (front velocity, maximum flow depth and density) of debris flows correlate positively with seismic signal amplitudes.

C6: Line 208: …. successfully recorded debris flow events.

- Ambiguous. Did all the instruments in the monitoring system recorded the event?

R6: Thank you very much for your valuable comments. Due to the miscellaneous content of the article, we have adjusted the content and the relevant expressions have been modified. The details are as follows:

Lines 192 to 207

We have installed a near-field debris flow observation system at locations along the debris flow channels with unobstructed views. The system includes seismic monitoring devices, infrared cameras, and rain gauges. The main function of the system is to comprehensively monitor the debris flow process through seismic signals and infrared camera images, while the rain gauges provide real-time precipitation data. The Fotangba Gully observation stations 1 and 2 are located 3,260 meters and 2,740 meters from the canyon entrance, respectively, while the Er Gully 0bservation stations 1 and 2 are located 4,130 meters and 3,670 meters from the entrance (Table 1, Fig. 2). The distance between the two monitoring stations in Fotangba Gully and Er Gully is 520 meters and 460 meters, respectively. Both monitoring stations are installed on rocky platforms on the left bank of the river. The two observation stations in Fotangba Gully are located approximately 20 meters and 15 meters from the centerline of the river. However, due to the lack of a network signal, real-time transmission of the recorded data via the Internet/GSM is not possible. The seismic monitoring devices operate at a sampling frequency of 100 Hz, and the infrared cameras are set to take images every 5 minutes. The specific parameters are listed in Table 1.

C7: Figure 4. error in captions and lettering in the figure.

- Which station is which panel?

R7: Thank you very much for your valuable comments. We modified Fig. 4, added the station information for each panel.

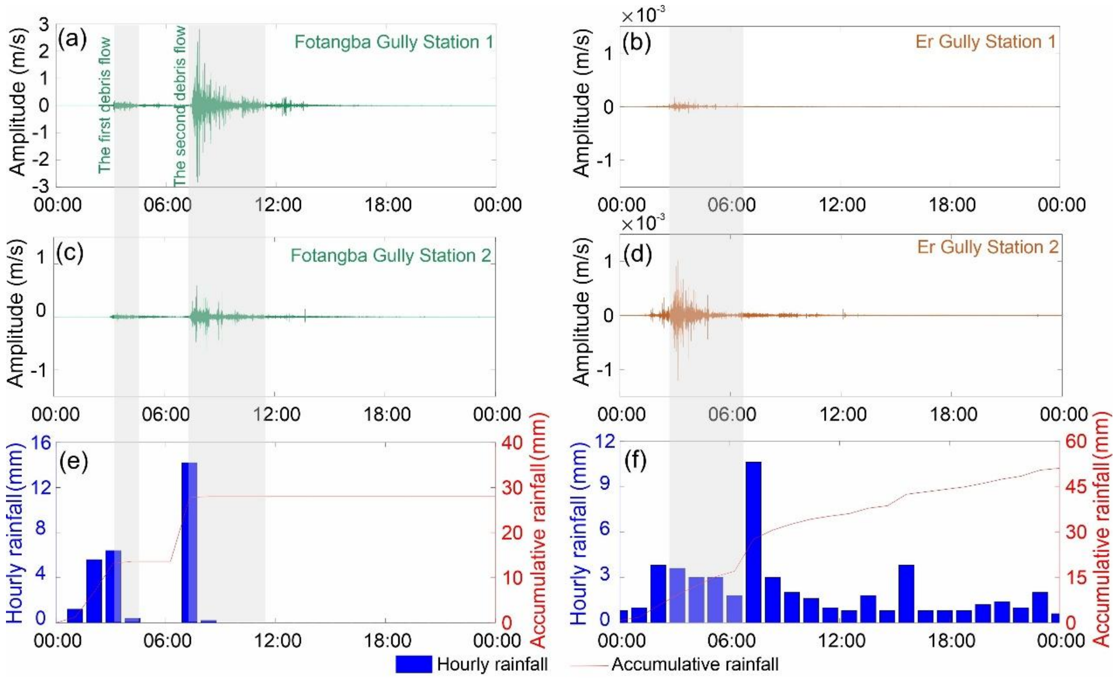

Fig. 4. Raw seismic signals and rainfall data. (a) and (c) represent monitoring station 1 and station 2 in the Fotangba Gully; (b) and (d) represent monitoring station 1 and station 2 in the Er Gully; (e) Rainfall at Fotangba Gully; (f) Rainfall at Er Gully.

C8: Line 387; From the compensation spectrum curve, the high-frequency components have been significantly restored, and both sites show similar improvements in their spectrum curves (Figure 5).

- What has changed in the spectrum curves for the raw and compensated signals, and why is it considered improvements?

In Figure 6, is the data raw or 'restored'?

R8: Thank you very much for your valuable comments. Through the seismic wave absorption and attenuation characteristics, we know that the amplitude attenuation of seismic waves during propagation follows a negative exponential relationship with frequency and propagation distance, with the high-frequency energy loss being much greater than that of the low-frequency end. Restoring the high-frequency energy is an important task in our data processing process. After compensating the signals from two stations, the comparison of the compensated curves shows that the red signal (after compensation) is more concentrated, and the signal trends tend to align more consistently (Fig.5c and 5g). Fig.6 shows the original signal, and since Fig.6 is mainly used to reconstruct the debris flow temporal process, which largely overlaps with Fig.4, we have deleted Fig.6 to avoid redundancy.

C9: For Table 2, what data went into determining the times? The point of the detection is to use the monitoring station independent of other sources (like local villagers reporting) to obtain the start time. I recommend listing the start times estimated from all the instruments in the monitoring system (seismic, infrared), and then comment on how these times match or differ with those from the local villagers and/or other types of observations.

R9: Thank you very much for your valuable comments. We define the start of a debris flow event based on the rapid increase in signal amplitude and energy. However, since our images were taken with a time-lapse camera at 5-minute intervals and raindrops impaired the camera's view in the Er Gully, errors may occur when determining the start and end of the debris flow based on the images. Nevertheless, the images can serve as auxiliary data for reference. In addition, debris flows differ from floods, making it difficult to directly determine the start and end based on the images. As shown in Fig. 7, the debris flow began at 7:14 a.m., but the water flow did not stop until around 7:21 a.m. the next day. Therefore, we used seismic signals to analyze the start and end of the debris flow.

C10: Line 438 to 462. It is very hard to understand the process from the writing. Suggest using a schematic or timeline instead. Also, it is unclear what "number of waves" is.

In Figure 7, please show the raw data as well like in Figure 5.

R10: Thank you very much for your valuable comments. Based on your suggestion, we have revised this section to make it simpler and clearer for better understanding. Additionally, since Fig.7 and Fig.5 were repetitive, we have removed Fig.7. As follows：

Lines 442 to 466

At monitoring point 1, the signal amplitude and frequency range rapidly increased when the debris flow occurred. The frequency range primarily concentrated between 8 Hz and 43 Hz. During the debris flow event, the energy initially concentrated and then gradually decreased, with a range between -120 dB and -60 dB. The data from monitoring point 2 was essentially consistent with that from monitoring point 1, recording the debris flow starting at 7:26 AM, with a peak amplitude observed around 7:45 AM, followed by a gradual decline. However, there were minor differences in the frequency bandwidth at monitoring point 2, which concentrated between 10 Hz and 40 Hz. The energy variation trend and range were almost the same as those at monitoring point 1. Throughout the entire debris flow event, the observed peak frequencies at the two monitoring points were 21.6 Hz and 28.6 Hz, respectively. The frequency evolution between the two points indicates an increase in the peak frequency, which may be related to changes in particle impacts and scale. Factors such as rock falls and channel erosion might also influence the peak frequency. To reflect the surge wave characteristics, we used the upper envelope of the signal waveform (Fig. 5b and 5f). The surge waves corresponded with the wave characteristics of the debris flow, and the number of surges matched the number of waves. The flow depth between the surge waves was significantly discontinuous, with a sudden increase in flow depth from one surge to the next, similar to the characteristics of the surge flow. Monitoring point 1 observed about 8 significant surge waves, while monitoring point 2 recorded 7. Additionally, we noticed that monitoring point 2 recorded two significant surge waves around 9:00 AM, while monitoring point 1 did not observe any significant surges at the same time. This indicates that the flow dynamics of the debris flow between the two monitoring points along the river channel have changed, possibly due to variations in channel topography and the solid-phase content of the debris flow.

C11: "Infrared cameras are cheap, plus solar energy about $ 78, and Hikvision 's infrared video camera plus solar energy about $ 425."

- Incomplete sentence: Solar power costs about $78….. Also, what is the cost of infrared camera and how is it different from Hikvision's infrared video camera?

"… Around 1693.9 to 1042.2 hours"

- Usually this is written in increasing order. Around 1042.2 to 1693.9.

Line 203: "The earthquake monitoring system was in continuous operation at most from July 2023 to March 2024, which corresponds to a monitoring period of 9 months."

- Don't think you need the phrase "at most" Please use a grammar checker and pick up any missed errors in other sentences

R11: Thank you very much for your valuable comments. Due to the adjustment in the research content, we have removed the relevant sections related to this part.

C12: Line 216: For better readability: However, due to the lack of a network signal, real-time transmission of the recorded data via the Internet/GSM is not possible.

R12: Thank you very much for your valuable comments. We have modified.

Lines 204 to 205

However, due to the lack of a network signal, real-time transmission of the recorded data via the Internet/GSM is not possible.

C13: Line 233: incomplete sentences in section 3.

R13: Thank you very much for your valuable comments. We have revised this section as follows:

Lines 215 to 222

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

C14: Line 374: practical investigations … petroleum seismic techniques

- Ambiguous. Which seismic techniques.

R14: Thank you very much for your valuable comments. What we are primarily referring to here is the surface velocity survey technology used in petroleum seismic exploration. It seems that our previous expression might have been unclear or misleading, so we have rewritten this section for better clarity.

Lines 418 to 421

Under the help of near-surface velocities investigations in using petroleum seismic technique (Liu et al., 2013), we analysis the surface conditions near the second debris flow event in Fotangba Gully and determine the Q values and reference velocities for two specific locations in Fotangba Gully.

C15: Figure 10: missing caption. Where is (h) and (i)?

R15: Thank you very much for your valuable comments. We have modified the captions in Fig. 10 (Fig. 7).

Fig. 7. Infrared camera images taken and the seismic signal recorded at monitoring

station 1 in Fotangba Gully during the second debris flow on the morning of August 19, 2022. Images were recorded every 5 minutes: (a) 7:14 frame (b) 7:39 frame; (c) 7:44 frame; (d) 7:49 frame; (e) 7:54 frame; (f) 7:59 frame; (g) 8:04 frame; (h) August 20, 2022, 8:04 Frame. (i) seismic signal recorded at the point.

C16: Line 723: "many of the analyses in this study are mostly preliminary and lack a certain degree of accuracy"

- This sentence is very unspecific. Which analyses is preliminary, and how inaccurate are they?

R16: Thank you very much for your valuable comments. Based on the reviewer's comments, we have adjusted the research content. As a result, the discussion section has also been revised. The specific changes are as follows:

Lines 779 to 788

5.2 Limitations and future works

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