Quantitative Analysis of Landslide and Debris Flow Based on Seismic Signal

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Abstract. Landslides and debris flows are occasionally explosive and extremely destructive. In recent years, satisfactory results have been made in studying these hazards based on environmental seismology and using seismic signals to monitor and analyze the evolution of hazards. In this study, the quantitative analysis of landslide and debris flow based on seismic signals is summarized and analyzed. It includes the analysis of seismic signal characteristics of different hazards, the reconstruction analysis of landslide, debris flow and hazard chain, and further combined with the dynamic inversion of seismic signals and numerical simulation method, the reconstruction method system of hazards evolution process is constructed. In view of the current research progress, the direction of future research is proposed. These methods provide new ideas for the study of landslides and debris flows, and provide theoretical guidance for future monitoring and early warning and hazard prevention and mitigation.

Keywords: Seismic signal · Landslide · Debris flow · Quantitative analysis

1 Introduction

Landslide and debris flow, as the most typical and common geological hazards, present characteristics of sudden and hidden. It is difficult to achieve active monitoring and early warning, causing the most serious damage and high cost of project management. (Cui et al., 2019; Shugar et al., 2021). Understanding the physical and mechanical mechanisms of the evolution, initiation, and movement of landslides and debris flows is of great significance for building effective hazard prevention and mitigation projects and improving the level of hazard prevention and mitigation technology.

In recent years, with the development of environmental seismology, the existing high-precision seismometer can record the seismic signal accompanying the movement of landslide and debris flow. Seismic signal is gradually becoming a new way to monitor and analyze the physical characteristics of landslide and debris flow hazards (Chmiel et al., 2021; Cook et al., 2022). How to quantitatively analyze the characteristics of

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these seismic signals and establish the physical model of seismic source is the key problem for the rapid identification of hazard. Scholars analyzed the characteristics of seismic signals of different hazards through the data of seismic signals recorded by seismometers during the movement of landslides and debris flows (Dammeier et al., 2015; Loew et al., 2017). The location and duration of landslide or debris flow can be conveniently calculated according to information such as the start time of hazard seismic signals, wave propagation speed, and the duration recorded by multiple seismic stations in different locations (Iverson et al., 2011; Hu et al., 2011; Bugnion et al., 2012). Furthermore, according to the energy characteristics of seismic signals, scholars have established a theoretical model for estimating the volume and scope of landslides, and established a connection between seismic signals and the scale of hazard events (Kean et al., 2015; Hibert et al., 2017). In recent years, many researchers have devoted themselves to mining more information about hazard dynamics parameters by using seismic signals (Cook et al., 2022). Zhang et al. (2019) reproduced the complete dynamic process of landslide by combining the long-period seismic signal of landslide, force-time function, and the field investigation, and estimated the dynamic characteristics of landslide such as friction coefficient and acceleration. By reducing the force of debris flow on the channel bed to the sum of the impact force generated by particles' vertical impact on the channel, the distribution characteristics of the vertical impact force are calculated, and a power spectral density model is proposed (Tsai et al., 2012), and the connection between seismic signal characteristics and the kinematic characteristics of the hazard is gradually explored and established (Lai et al., 2018; Farin et al., 2019). However, the correlation between seismic signals and hazard dynamic behavior has not been solved.

This paper mainly summarizes and analyzes the inversion and quantitative analysis of landslide and debris flow based on seismic signals. Taking physical parameter - mechanical process - seismic signal characteristics as the main line of the research, proposes development ideas in view of the existing problems in the current research, to clarify the direction of further research.

2 Methodology and Data Source

2.1 Methodology

Firstly, STA/LTA method (Stevenson, 1976) was used to extract seismic signals of hazards from the recorded seismic signals, and the signals were denoised by BP-filter. Then use EMD to separate the main feature components. Finally, using Fast Fourier transform (FFT), short-time Fourier transform (STFT), power spectral density (PSD), and other methods to quantitatively analyze the time-frequency of seismic signals, the characteristics of seismic signals are obtained.

Empirical Green's function is used to deconvolution seismic signals to reconstruct the landslide force-time function (Li et al., 2017; Allstadt et al., 2020), and then the dynamic parameters of the landslide are estimated, and the basic characteristics of the hazard are inverted by combining the field survey data. The inversion results can then be used to constrain the numerical simulation of landslide to improve the accuracy of numerical simulation, and finally realize the reconstruction of the whole hazard process (Li et al., 2023) (Fig. 1).

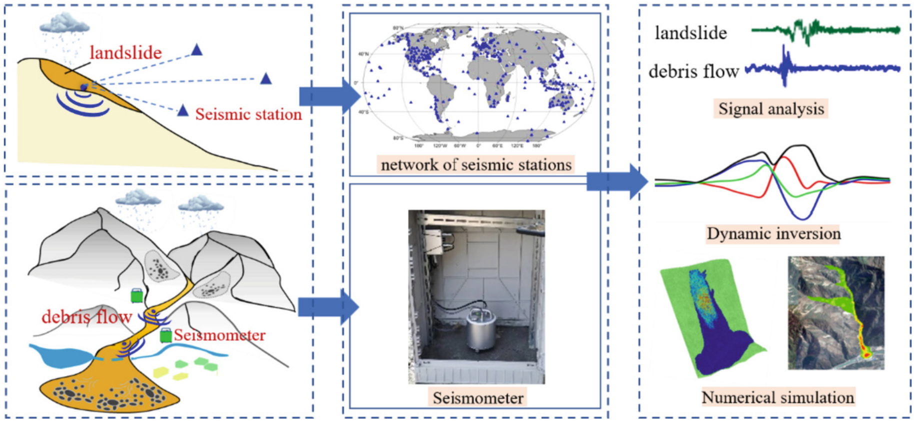

Fig. 1. Hazard process reconstruction flow chart based on seismic signal.

2.2 Data Source

The low-frequency seismic signals generated by landslides in the process of movement can be recorded by seismic stations dozens of kilometers away from the hazard, which is the data source. By using the seismometers independently deployed near the debris flow channel, the relatively high frequency seismic signals caused by the debris flow can be monitored at close range. And the network can be used to transmit real-time monitoring seismic signals to achieve rapid analysis of debris flow.

3 Result and Analysis

3.1 Seismic Signal of Landslide and Debris Flow

Time-frequency analysis of a large number of seismic signals from landslide and debris flow hazards shows that the complete landslide signals are usually presented in the shape of a double spindle or a single spindle in the time domain, and the time-frequency characteristics also show a bimodal or unimodal shape (Tsou et al., 2011; Yan et al., 2020a, 2020b), and the frequency of seismic signals from landslide hazards is usually low. Compared with landslide, the frequency range of debris flow seismic signal is mainly high frequency (Huang et al., 2020), and in the time domain, in addition to the characteristics of the spindle, it is usually accompanied by micro-amplitude seismic of the tail, and in the time-frequency characteristics, the tail energy is weakened or the bandwidth is narrowed (Schimmel et al., 2018; Suriñach et al., 2005). Based on these characteristics of the shape and frequency range of hazard seismic signals, specific hazard types can be identified (Fig. 2).

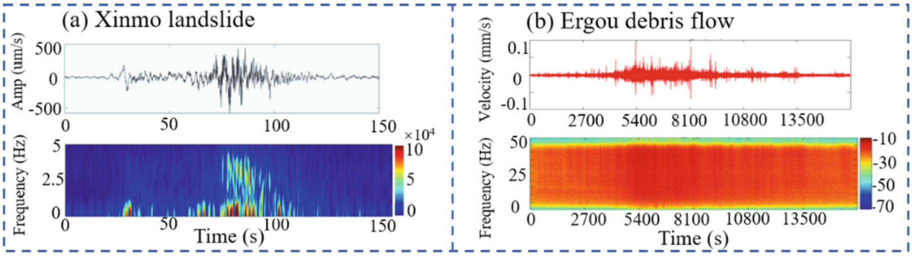

Fig. 2. Seismic signal characteristics of hazards. (a) Xinmo landslide, Sichuan; (b) Ergou debris flow, Sichuan

3.2 Reconstruction of Hazard Process

Reconstruction of Landslide. According to the seismic signal data of the Shuicheng landslide (Yan et al., 2020b) recorded by seismic station, the time-frequency characteristics of landslide signal are obtained by weak signal processing and analysis. Here STFT and BP-filter are used to process and filter the signals to identify and extract the signals generated by landslides, and then Empirical Mode Decomposition (EMD), FFT, STFT, and PSD are used for further analysis and processing. Based on field investigation, combined with the results of seismic signal analysis, which realized the reconstruction analysis of the Shuicheng landslide process. It is important to understand the complicated process of starting and moving of landslide.

In the study of the Xinmo landslide (Yan et al., 2020a), the seismic signals of several stations are jointly analyzed and analyzed respectively from the perspective of time domain and frequency domain. It is found that the landslide signals are composed of the first and second main signals, and the frequency ranges of the two main signals are 0–2 Hz and 0–4 Hz respectively. At the same time, a micro-seismic signal was detected between the two main signals, with a frequency of smaller than 1 Hz. Combined with field investigation and numerical simulation, we call it a transition stage in the landslide process. Therefore, the whole complex process of the Xinmo landslide is divided into stationary stage (0–18 s), slipping stage (18–30 s), transition stage (30–65 s), entrainment-transportation stage (65–110 s), and deposition stage (110–150 s). This is the first time to discover the transition stage between the two main landslides, which is of great significance for landslide monitoring and warning.

Reconstruction of Debris Flow. Through the seismometers deployed in advance in the Ergou and Fotangba Gully in the Minjiang River Basin, we recorded two seismic signals of the debris flows that erupted in the two channels on August 19, 2022. By denoising and filtering seismic signals, and using STFT and amplitude method for calculation and analysis, the characteristics of high-frequency seismic signals during the formation and evolution of debris flow are obtained. Combined with field investigation, the preliminary identification of debris flow events based on seismic signals is realized. And the cross-correlation algorithm is used to calculate the velocity of debris flow. Further, based on the analysis of the gravity acceleration variation characteristics and energy presentation in the time-frequency domain diagram, the debris flow hazard characteristics and other information are judged. Combined with the rainfall monitoring data and the real-time video of the hazard process taken on site, the quantitative analysis of the debris flow process in Wenchuan earthquake area is realized. It also lays a theoretical foundation for establishing the method of debris flow identification, inversion, monitoring and early warning based on seismic signal.

Reconstruction of Hazard Chain. Taking the hazard chain of Danba quake Lake in Xiaojinchuan River in 2020 as the research object (Yan et al., 2021), the seismic signals recorded from June 17 to 20 by XJI station, which is closest to the hazard point, are selected, and the signal extraction and noise attenuation of the seismic signal data are carried out by BP-filter, EMD, and STFT. A program of weak seismic signal recognition for geological hazards is established.

The whole process of hazard chain is reconstructed by analyzing seismic signals. The first stage is the debris flow in Meilonggou, and its effective signal frequency is less than 0.1 Hz. However, we identified the debris flow by the relative magnitude of the amplitude in the signal processing results, and divided the debris flow into three stages by combining the time-frequency spectrum, the first stage is the initial stage, the increase of flow velocity and debris volume by channel entrainment is increased, manifested as the trend of earthquake amplitude increase. The second stage is the evolution stage, the flow velocity becomes fast, and the corresponding signal also shows strong amplitude. The last is the deposition stage, the signal characteristics show weak amplitude. Then there was the outburst of the barrier lake formed by the accumulation of debris flows, and the signal frequency range of the flood stage was 0–40 Hz, with typical broadband characteristics. The flood erosion caused the instability of the ancient landslide downstream, which triggered the landslide in Aniangzhai. According to the signals of the entire physical process of landslide, it is divided into three stages: initial stage, continuous collapse stage, and gradual stabilization stage. The continuous occurrence of landslides led to the formation of a new barrier dam. However, due to the low stability of the accumulation body, it caused a second flood. This is the evolution pattern of the whole hazard chain.

3.3 Dynamic Inversion and Numerical Simulation

Taking the Baige landslide as an example (Yan et al., 2022), we put forward the combination of signal processing, dynamic inversion, and numerical simulation to reconstruct the hazard evolution process, which can help obtain more reliable landslide simulation results and provide theoretical guidance for the risk prevention and hazards mitigation. The seismic signal of the Baige landslide was quantitatively analyzed by STFT and PSD. The direction of slide and the start and stop time of landslide are determined by a relatively high signal-to-noise ratio of time domain velocity signal. The PSD curve can be divided into three stages longitudinally. According to the results, we divided the landslide into three acceleration and three deceleration stages.

We selected the data from seven stations to invert the landslide dynamic process and obtained the landslide force-time function. By comparing the DEM before and after the landslide, the sliding mass was estimated to be 4.2×10^{10} kg. The acceleration distribution with time was determined, and the velocity distribution with time and the displacement distribution curve with time were reconstructed. The inversion parameters are used to provide verification for landslide numerical simulation. In the end, the time difference between simulation and inversion of peak velocity of landslide is 2.5%, the error of peak displacement is 0.6%, and the error of peak velocity and landslide duration is 33.3%. The accumulation characteristics obtained by simulation are basically consistent with the field investigation.

4 Discussion

4.1 Innovation

Different types, scales and locations of hazards will lead to different seismic signals. The characteristics of seismic signals, such as long propagation distance, fast propagation speed and carrying physical and mechanical characteristics information, can realize long-distance and non-contact monitoring of hazards (Cook et al., 2021). Different from the traditional analysis of debris flow dynamics based on on-site monitoring (Yan et al., 2023), this method is based on the principle that seismic signal generated in the process of hazard initiation and movement and the physical and mechanical characteristics of the signal carrying the hazard, the signal processing and analysis technology can be used to extract the hazard attribute information corresponding to the seismic signal and invert the hazard dynamics parameters, hazard movement, and evolution process.

4.2 Further Research

The impact mechanism of debris flow on the bottom bed is very complicated due to the two-phase property of debris flow. Therefore, it is necessary to carry out flume test based on the range of typical dimensionless numbers of debris flow in the field considering the scale effect (Iverson 2015). To study the influence of the change of physical properties of debris flow on the bottom impact force, analyze the characteristics and mechanism of the generation of seismic signals, and to establish the relationship between physical parameters, bottom impact force, and seismic signal characteristics, for developing a quantitative model of debris flow excitation source.

The near-field monitoring of debris flow is usually characterized by the magnitude of the seismic wave propagation distance and debris flow evolution distance, which approximates debris flow as a "point source". This hypothesis is inconsistent with the actual situation (Gabet et al., 2008; Lee et al., 2012). Therefore, it is necessary to further take the "line source" model as the basic assumption, consider the path effect of seismic signal propagation (Allstadt et al., 2015, 2020; Huang et al., 2020), and quantitatively analyze the calculation error caused by the seismic signal propagation attenuation during hazard motion process. Then improve the empirical green's function to establish a debris flow dynamics inversion model based on seismic signal.

5 Conclusion

With the development of environmental seismology methods, the seismic signal characteristics of landslide and debris flow are obtained by processing the recorded seismic signals. The motion state and key dynamic parameters of landslide and debris flow are calculated in reverse, and the connection between seismic signal and hazard dynamic process is established. The reconstruction of hazard process is realized by combining field investigation and numerical simulation. At the same time, the direction of further research is pointed out, which provides a new idea and method for studying the initiation mechanism and dynamic characteristics of geological hazards by using the relevant theories of seismology and realizing the identification and early warning of hazards.

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