



Quantitative Analysis of Landslide Processes Based on Seismic Signals—A New Method for Monitoring and Early Warning of Landslide Hazards

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Abstract

Effective monitoring and early warning methods can greatly reduce the threat of sudden landslide damage to lives and property in mountainous areas. Seismic monitoring is a newly developing remote monitoring method that can make up for the shortage of on-site data obtained from traditional methods. This review article summarizes the authors' recent developments involving the combination of band-pass filter, empirical mode decomposition, and fast and short-time Fourier transform methods to deduce event sequences of actual landslides. Two case studies of landslides in Xinmo and Shuicheng, China are used to follow the methodology development. Through seismic signal processing, seismic signals caused by the two landslides are extracted and successfully denoised, and the time-frequency characteristics of the seismic signal in each stage are analyzed in detail. The results show good correspondence between each seismic signal stage caused by the landslide and the field investigations.

This further demonstrates the feasibility of applying monitoring and early warning methods based on seismic signals.

Keywords

Seismic signal • Monitoring and early warning • Signal extraction and identification • Landslides process

Introduction

Major landslides are often called “secondary hazards” triggered by another disaster such as an earthquake or rainstorm. In addition to directly inflicting casualties, landslides can also block transportation lines, destroy buildings, and damage pipeline systems, resulting in severe economic losses. The effective monitoring and early warning of landslides are therefore of great significance to preparation measures for hazards associated with sudden disasters.

Conventional landslide monitoring and early warning require two types of information: (1) degree of deformation regarding surface and interior displacement of a landslide mass, which allows deduction of the creep and deformation mechanism; and (2) hydrological factors, such as pore pressure, precipitation, soil water content, and groundwater level (Wang et al. 2008; Yin et al. 2010). Different models lead to different early warning results. For example, setting too high of a threshold value can lead to failure in issuing a timely alert, whereas setting too low of a threshold can lead to a false-positive alert (Cui et al. 2019).

Landslides can generate ground vibrations, which can be recorded by seismic stations. Recorded signals can vary in amplitude, duration, and frequency components depending on their origin direction and size of the responsible landslide (e.g., volume, dimensions). Processing of such landslide-induced seismic signals provides important information for understanding how the particular landslide event

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occurred and how the detached soil mass was transported. Several previous studies have proposed seismic monitoring techniques for landslides. A broadband seismic network can be used to record and analyze landslide-induced ground tremors over a wide frequency range, which makes up for the typical information deficit from on-site observations (Yamada et al. 2012). This review article summarizes the authors' recent attempts to process seismic signals to deduce event sequences of actual landslides that occurred in Xinmo (Yan et al. 2020a) and Shuicheng, China (Yan et al. 2020b). The seismic signal processing includes the extraction and denoising of seismic signals caused by two landslides and time-frequency analysis of signals. Combined with field investigations, the entire landslide process is explained and the movement characteristics of each stage are summarized. Based on the seismic signal reconstruction of the landslide process, this review verifies the feasibility of using seismic signals for landslide monitoring and early warning.

Recent Advances in Seismic Monitoring of Landslides

Among the common methods of landslide monitoring developed over the past two decades, seismic monitoring has received increasing attention because of its potential for remotely monitoring hazards (Moore et al. 2017). Through seismic signal processing, the dynamics of large-scale landslides (e.g., occurrence time, duration) can be quickly obtained, which can be further used for interpreting the landslide movement process (Zhang et al. 2019).

Time-frequency analysis of seismic signals is a common method presently used to study landslide dynamics. The results show that seismic signals related to landslides, including high-frequency and low-frequency landslide components, can reflect the dynamic characteristics of landslides. (Li et al. 2017). However, the scale, velocity, and track of landslides remain difficult owing to the complexity and fast attenuation of high-frequency signal components (Zhang et al. 2019). The common method is therefore to invert signals based on the long-period monitoring signal. The force-time function is first obtained followed by a quantitative analysis of the landslide kinematic parameters. The date and occurrence time of the Todagin Creek landslide were extracted from its seismic signal (Sakals et al. 2012). Based on analysis of the seismic signal amplitude produced by the Baige landslide, Zhang et al. (2019) determined the landslide occurrence time and, combined with the force-time function, spectrogram, and field investigation, discussed the sliding process and movement mode. Fuchs et al. (2018) developed a simple and fully automatic processing chain for

the location and classification of rockfalls, landslides, and other hazards. Through comprehensive analysis of the characteristic parameters of seismic signals (e.g., peak degree, maximum amplitude), natural hazards such as landslides can be automatically identified. Kuo et al. (2018) proposed rainfall warning thresholds for different scale landslide events based on the analysis of seismic signals of landslides in Taiwan.

Quantitative Analysis Method Based on Seismic Signals

The quantitative analysis steps of the landslide movement process based on seismic signals is shown in Fig. 1 (Yan et al. 2020b). Effective seismic signals of landslides are extracted using short-time Fourier transform (STFT) and band-pass (BP) filter methods, followed by empirical mode decomposition (EMD) methods for denoising. Fast Fourier transform (FFT), STFT, and power spectral density (PSD) are used to analyze the time-domain and frequency-domain characteristics, compare with the field investigation, reconstruct the entire landslide process, and obtain the movement characteristics of every stage of the landslide. The following is a brief introduction to the principles of these main methods.

BP-filtering is a method of filtering interference signals. Interference and effective signals are usually emitted in different frequency bands. The interference signal is separated by setting the frequency amplitude within the interference signal bandwidth to zero and keeping the effective signal amplitude unchanged. The EMD method focuses on denoising to improve the signal-to-noise ratio. A set of different frequency and amplitude intrinsic mode functions (IMFs) are decomposed from a non-linear and non-stationary signal.

STFT is a method to obtain information regarding the time and frequency distribution of seismic signals. A 128-point length Hanning window is selected as a window function, which is considered static over a relatively short time. Equation 1 shows the transform equation:

$$STFT\{x(n)\}(m, \omega) \equiv X(m, \omega) = \sum_{n=-\infty}^{\infty} x[n]\omega[n-m]e^{-j\omega n} \quad (1)$$

The power of each frequency unit corresponding to each frequency range component at a certain time can be estimated according to the power spectral density of the seismic signal in the frequency domain. In this study, we integrate the PSD model along F and D to obtain the sum of PSD energy at different frequencies at one time.

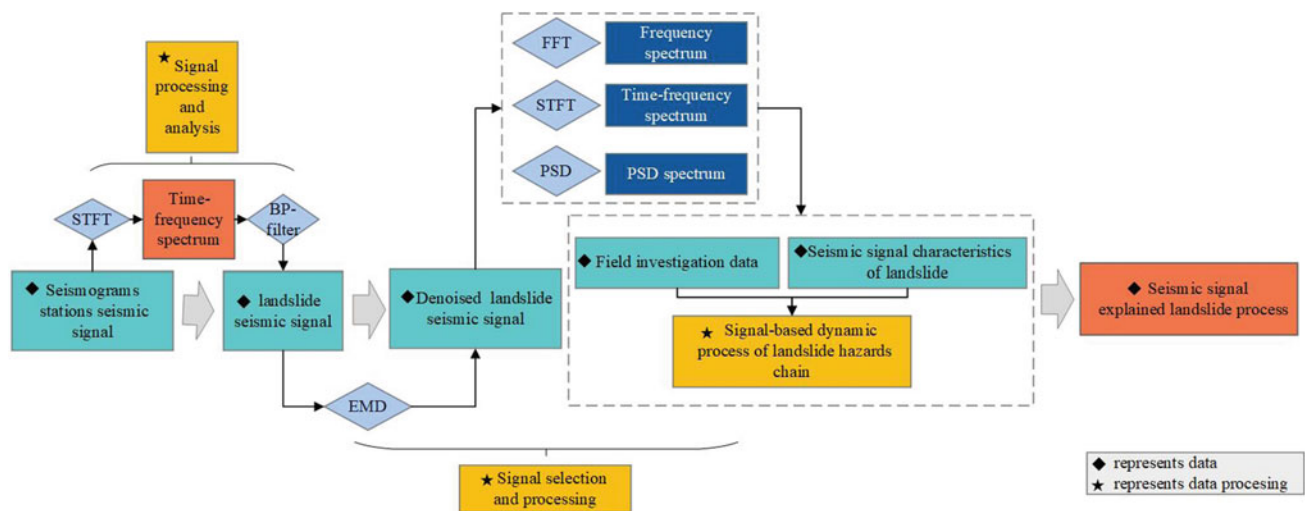


Fig. 1 Flow chart of seismic signal extraction and analysis (Modified after Yan et al. 2020a)

Signal-Based Dynamic Processing of Landslides

Xinmo Landslide

In our recent study of the Xinmo landslide, EMD, STFT, and PSD methods were used to process the seismic signals (Yan et al. 2020a). The EMD method decomposed the signals into 10 IMFs (IMF1–IMF10). The IMF4 of the MXI station and IMF5 of the PWU station are considered the principal components of the seismic signal, as shown in Fig. 2c. From the time-domain perspective, the signals include two parts: the 1st and 2nd main signals. The amplitude and duration of the 2nd main signal are considerably longer than those of the 1st main signal. The vertical seismic signal decays rapidly after the 1st main signal. The time-frequency spectrum in the three seismic signal directions is shown in Fig. 2d. From the frequency-domain perspective, the signal can also be divided into two parts: the 1st and 2nd principal signals. The peak energy frequency of the 1st and 2nd principal signals is ~ 1 Hz, whereas the 2nd principal signal retains a strong energy frequency up to 4 Hz. The peak frequency of the 2nd principal signal (5 Hz) is slightly higher than that of the 1st principal signal (4 Hz). Because the principal signal magnitude corresponds to the scale of the landslide, the landslide scale corresponding to the 2nd principal signal is larger than that of the 1st principal signal.

By comparing the signal analysis results with the field investigation, the entire physical process of the Xinmo landslide is divided into five stages: stationary, slipping, transition, entrainment-transportation, and deposition, which respectively correspond to intervals A, B, C, D, E in Fig. 2b. The static stage is designated prior to the start of the

landslide from 0 to 18 s. At this stage, the velocity of the landslide body remains close to zero and the displacement is relatively small. The sliding stage lasts from about 18 to 28 s, corresponding to the 1st principal signal. The seismic signal in the middle part of the two principal signals corresponds to the transition stage, lasting from about 28 to 68 s. The entrainment-transportation stage lasts from about 68 to 110 s, equivalent to the 2nd principal signal, and the deposition stage occurs from 110 to 150 s, in which the seismic signal appears after the second peak. The amplitude, peak frequency, and frequency range of the signal decrease gradually. The PSD model used to quantitative analysis of the transition stage shows that the energy on the vertical component first decays and maintains a low value for a certain time, then increases gradually. This may be caused by the entrainment process.

Shuicheng Landslide

In our recent study of the Shuicheng landslide, we used BP-filter, EMD, STFT, and PSD methods to pre-analyze 12 station signals with similar signal characteristics (Yan et al. 2020a). Three BP-filters of 0–10, 10–20, and 20–50 Hz were initially used, and the signal was then passed through a 4.5–6-Hz filter to highlight the continuous energy band of 5 Hz. The EMD method was then used to denoise and enhance the effective signal. The results show that the 4.5–6 Hz signal of the XUW station is the clearest. The STFT method was used to obtain the time-frequency spectrum of the XUW stations in the E, N, and Z directions as shown in Fig. 3d–f. The characteristics of the time-frequency spectrum at different times of the landslide are summarized based on the signal analysis and the seismic signal is divided into four stages

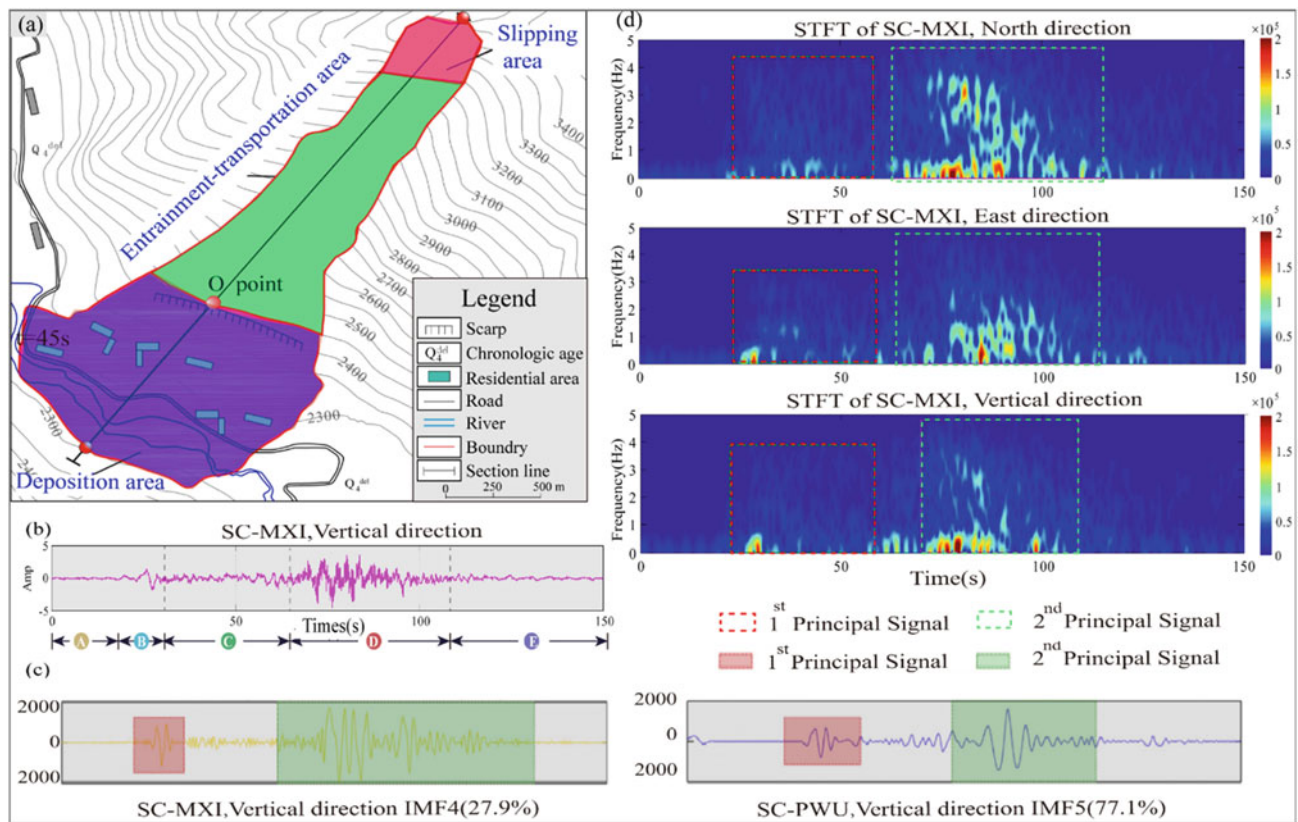


Fig. 2 Contour map of the Xinmo landslide area and signal time-frequency spectra. **a** Contour map of the Xinmo landslide area. **b** Time spectrum of the MXI station in the vertical direction. **c** Vertical

seismic signal of IMF4 of station MXI and IMF5 of station PWU. **d** Three direction time-frequency spectra of the MXI station obtained by short-time Fourier transform (Modified after Yan et al. 2020b)

(Fig. 3e, f). The spectrum of the XUW station in the E, N, and Z directions shows that the four peak frequencies form an inverted W-shaped curve. In the first stage, the seismic signal in the E, N, and Z directions is relatively small. In the other stages, the signal is stronger than the first stage and substantially stronger than the background noise.

Through the comprehensive analysis of rainfall, geological survey, and seismic signal, the landslide evolution is determined to consist of four stages: fracture-transition; accelerated initiation; bifurcation-scraping; and deposition (Fig. 3a). These four stages correspond to the four stages of the seismic signal one by one. In the fracture-transition stage, owing to increased soil moisture content, small-scale landslides occurred and local collapse reduced the stability of the landslide area. In the fracture-transition stage, under the action of landslide mass accumulation, the weathering layer in the wide platform and its surroundings gradually destabilized and began to move. Two natural debris flow gullies were distributed on the eastern and western sides of the broad platform. At this stage, the velocity of the main body of the landslide increased and reached the bifurcation of the gullies. In the bifurcation-scraping stage, the landslide divided into two parts and entered the valley on the western

and eastern sides of the platform. Owing to the main body of the landslide on the eastern side, the volume and kinetic energy of the landslide in the eastern valley were larger than those on the western side. Some landslide fragments then passed through the western slope, the landslide velocity rapidly decreased, and deposition occurred. In the last (deposition) stage, the landslide body gradually extended to both sides and the constraint of the river valley on the landslide decreased. The entire landslide was ultimately deposited on the bottom of the canyon.

Outlook and Prospect

The method of seismic signal analysis is very promising within the study of landslides and has been well applied to the Xinmo and Shuicheng landslides. This method for remote hazard monitoring is safe, stable, and maintains data integrity. Broadband seismic networks are relatively dense in China and are optimal for establishing rapid monitoring and early warning systems of large-scale landslides based on seismic signals, including determination of the occurrence time, duration time, location, and landslide volume.

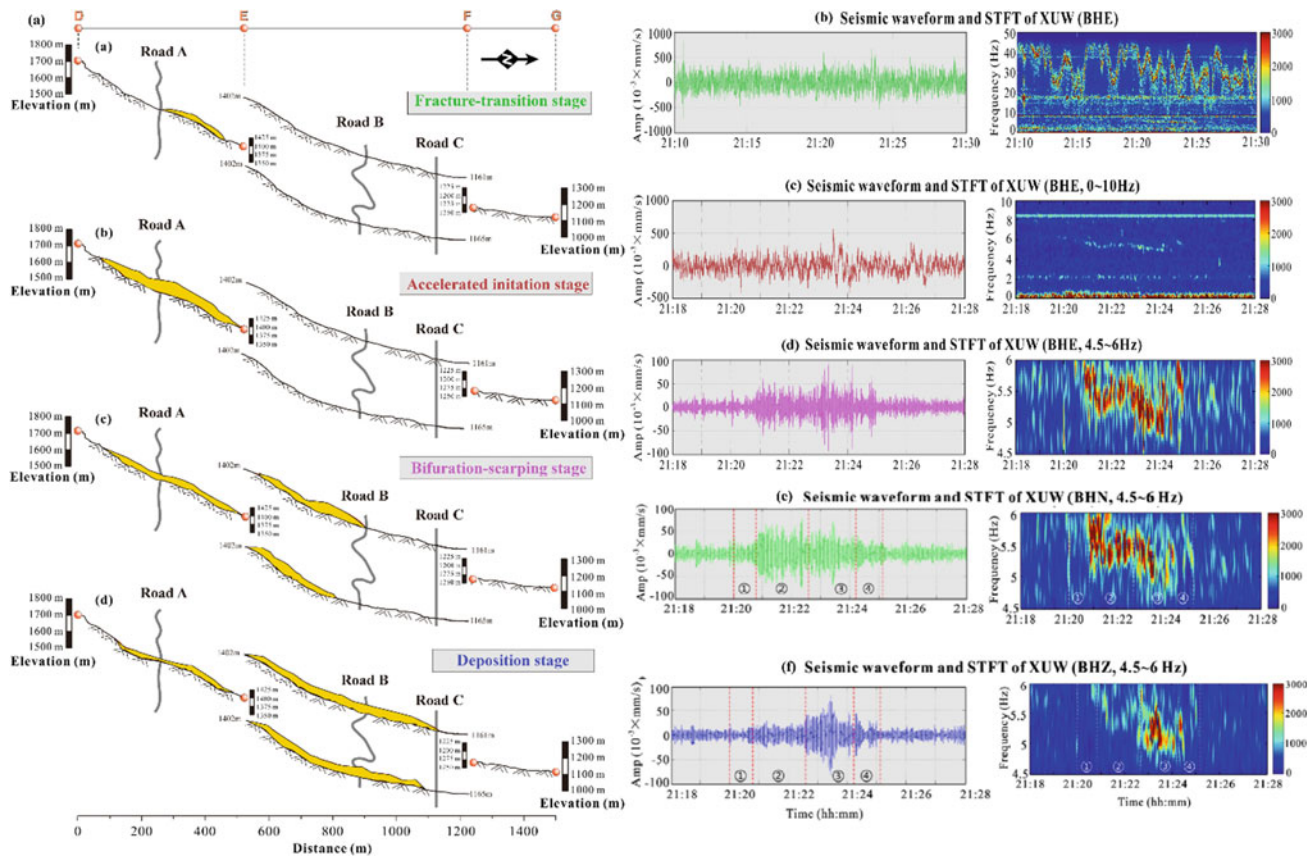


Fig. 3 Schematic diagram of the Shuicheng landslide and signal time-frequency spectra. **a** Schematic diagram of the Shuicheng landslide in stages. **b** Seismic signals of station XUW. **c**–

f Time-frequency spectra of the XUW station in 0–10-Hz and 4.5–6-Hz frequency bands in the E, N, and Z directions (Modified after Yan et al. 2020a)

However, the study of seismic signals remains relatively new with only a few case studies. We therefore aim to propose a universal monitoring and early warning method in the future based on more samples and in-depth analyses.

The methods presented here can be combined with numerical simulation methods, which can be used to more accurately estimate the location, time, and scale of landslide hazards with the help of seismic network data. The monitoring and early warning of landslide hazards based on seismic signals will then be fully realized. There is no relatively clear distinction between landslide signals and other emergencies (e.g., earthquakes, debris flows, man-made blasting), and the identification of landslide signals is mostly based on the experience and knowledge of involved researchers. Ideally, a description of waveform characteristics of landslide seismic signals and other types of seismic signals can be used to establish a classification standard for landslide signals and achieve their rapid recognition. Such results combined with the rapid assessment of landslide scale will provide a more timely and accurate reference basis for the rapid identification and assessment of landslide hazards to improve the speed and target of rescue measures.

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