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Low frequency acoustic signals associated with rock falls, thunderstorms, and wind turbulences in field environment

Xing Zhu [a,b], Qiang Xu [a,*], Zhiye Zhao [b], Tiantao Li [a]

[a] State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China
[b] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore

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ABSTRACT

This paper characterized the observed low frequency acoustic signals generated by rock falls, thunderstorm, and wind turbulence in large rocky landslide. A digital infrasonic recording system was deployed on site to capture real-time low frequency acoustic signals associated with rock falls. An advanced non-stationary signal analysis method, i.e. Empirical Mode Decomposition (EMD), was applied to get insight to the characteristics of the low frequency acoustic signals induced by the hazards. Joint time–frequency distribution spectra technique was used to detect distinctive features of the events. The study shows that the low frequency acoustic signals can be excited by rock falls, thunderstorm and wind turbulence in the field environment, but the signal varies in both time domain and frequency domain with different patterns depending on the physical processes. The results demonstrated that the EMD-based signal processing technique is capable of extracting distinctive features to differentiate acoustic signals in real environment.

1. Introduction

Rock fall and landslide poses significant risk to the mountainous areas strongly affected by large earthquakes. For example, ground motion induced by the Wenchuan Earthquake triggered tens of thousands of landslides and rock falls in southwest of China [1]. Understanding the failure mechanism of large rock fall is critical for assessing the risk, but such events are sometimes difficult to identify and document [2]. Geo-hazard mapping based on eyewitnesses often resulted in underestimation in the volume of the displaced material, which may not provide accurate feedback for understanding the characteristics and mechanism of the event. Therefore, a tool capable of passive monitoring for rock falls, such as acoustic or seismic technique, yields great benefits in studying rock fall activities [3]. Zimmer et al. [2,3] deployed seismic and infrasound sensors in Yosemite Valley for rack fall detection, and the study focused on seismic data analysis in time and frequency domain for individual rock fall occurring at short distances (<1 km). Pankow [4] found that instead of a large earthquake triggers landslides, a large landslide can trigger several small earthquakes. Defined as sub-audible or low frequency acoustic wave with frequencies ranging from about 0.001 Hz to the lowest frequency of the human hearing limit (20 Hz or cycles/s) [5–7], infrasound has been employed as a passive monitoring and detecting technique in many applications, including snow avalanches [8,9], volcanic eruptions [10], and debris flow [11], as it can propagates over long distance with little attenuation and the signals are not sensitive to high noise disturbance in the field. Researches on infrasound signals generated by natural and artificial sources are available in previous literatures [3,12–15]. However, a few studies focused on the low frequency acoustic measurements for rock falls in field, or on the difference between acoustic signals induced by rock falls and other natural sources.

A digital infrasound detecting equipment was implemented at the north-west cliff of the Daguangbao landslide in China to study the characteristics of the infrasonic signals associated with rock falls occurred at a distance less than 2 km, and the results demonstrated the potential for using such techniques for real-time rock fall monitoring. Meanwhile, low frequency acoustic signals generated by thunderstorm and wind turbulences are detected in the real environment. The advanced digital signal processing and analysis methods are applied to the detected data to distinguish the rock fall from other natural sources on the basis of different signal features registered in the time and frequency domain.

This paper characterizes acoustic signals associated with rock falls, thunderstorm and wind turbulence to demonstrate the potential applications of low frequency acoustic monitoring

* Corresponding author.
E-mail address: xuqiang_68@126.com (Q. Xu).

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technique for real-time rock fall detection and risk assessment in complex geological conditions. The methodology section of briefly introduces the study area, instrument implementation, and data mining methods for signal processing and features extraction. The monitoring dataset section presents some of the original data and processed results for three natural acoustic signal sources. Future work and concluding remarks are included in the discussion and conclusion sections.

2. Methods for acoustic signal processing and analyzing

2.1. Study site and acoustic monitoring

On 12 May 2008, Wenchuan Earthquake (Ms7.9) hit the Sichuan Province in southwest China. The earthquake was the largest seismic event in more than 50 years in China, and the earthquake triggered more than 60,000 landslides [16]. The Daguangbao landslide was the largest landslide triggered by the Wenchuan Earthquake, of which the displaced material converse an area of 7.8 km^2 with the estimated volume of 7.5×10^8 m^3 [1,17]. The location of the landslide and the epicenter of the earthquake are shown in Fig. 1(a). The landslide is located on the hanging wall of the Yingxiu–Beichuan Fault (YBF) in Anxian town with the distance to fault of 7 km [17]. As shown in Fig. 1(b), the north boundary of the Daguangbao landslide is characterized by deep and high cliff with an average slope gradient of 65°, and the maximum vertical height of the cliff is 1200 m varying between 1850 m and 3000 m a.s.l [17]. A long narrow tensile cracks zone along the boundary was formed by the strong and long-lasting ground shaking. Rock falls occurred frequently along the ridge of high cliff because of the non-stable geological conditions after the earthquake with additional environmental factors such as rainfall, wind and thunderstorm. Base on the field investigation, many talus cones (i.e. rock falls and rock mass collapses) are distributed in the bottom of the cliff with the width of 300–400 m, as shown in Fig. 1(d). The northern boundary of the landslide is an ideal field observation site for the preliminary study of the infrasonic signals generated by rock falls because of its remote location with minimal urban noises. To study the characteristics of acoustic signals associated with the geo-disasters, a digital infrasonic monitoring system was employed and deployed in the Daguangbao landslide area as shown in Fig. 1(c), detailed description of the system can be found in previous study [5]. In this study, the sampling frequency of the acoustic monitoring system was 100 Hz. Fig. 1(d) shows the detached rock blocks during the monitoring period.

2.2. Signal processing and data analysis

2.2.1. Brief review of empirical mode decomposition (EMD)

Hilbert–Huang transform (HHT), which was firstly proposed by Huang et al. [18], is a novel method for nonlinear and non-stationary signal processing. As a key and fundamental part of HHT, empirical mode decomposition (EMD) method is an effective way to decompose a signal into a finite number of intrinsic mode functions (IMF) with relatively narrow band signals. An IMF is defined as a function that meets the two requirements [18–20]: (1) the number of zero-crossings and the number of extrema must either be the same or differ at most by one, and (2) the envelopes defined by the local maxima and local minima should be symmetric. The IMFs indicate the inner oscillation modes of the signal.

For a given discrete time series $x(n)$, $n = 1, 2, \ldots N$ (where N stands for the length of this signal), the flow chart of EMD algorithm to decompose a signal into a collect of IMFs is shown in Fig. 2.

The decomposition process of EMD is essentially a sifting process (see Fig. 2). The purpose of EMD is to divide the signal into a collection of IMF components with a narrower frequency range, and thus make further processing easier [21]. After EMD decomposition, the original acoustic signal $x(n)$ can be written as the sum of all the IMF components and the residual as follows:

$$x(n) = C_1(n) + C_2(n) + \cdots + C_k(n) + r(n) = \sum_{i=1}^{k} C_i(n) + r(n) \qquad (1)$$

where C_i is the i-th IMF, and k is the total number of IMF components. r is the residual that does not meet the aforementioned requirements of IMF. The residual r may be a constant value or a monotonic function, which represents the direct current (DC) offset or the average trend of the signal.

Meaningless frequency components in the original signal may increase the complexity of decomposition during the EMD process. As a consequence, excessive decomposition result in boundary error accumulation, which even sabotage the physical meaning of the EMD [22]. Therefore, the original signal should be de-noised

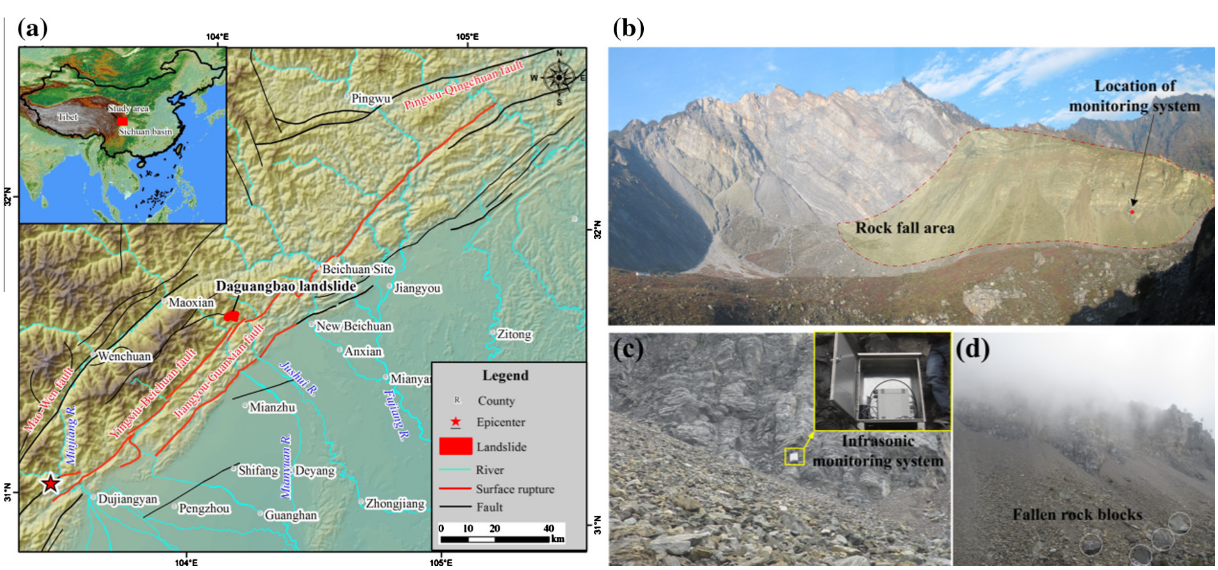

Fig. 1. Study site and field deployment of the monitoring devices (a) location of the Daguangbao landslide; (b) study region and location of the monitoring system; (c) installation of the infrasonic monitoring system in the field; (d) detached rock blocks in the study area.