Using Ground Microtremor Data in Advanced Rockfall Early Warning Systems and Predicting Spatiotemporal Characteristics of Rockfall Hazards

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Research Article

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Abstract

Identifying cliffs that are prone to fall and providing a sufficient lead time for rockfall warning are crucial steps in disaster risk reduction and preventive maintenance work, especially that led by local governments. However, existing rockfall warning systems provide uncertain rockfall location forecasting and short warning times because the deformation and cracking of unstable slopes are not sufficiently detected by sensors before the rock collapses. Here, we introduce ground microtremor signals for early rockfall forecasting and demonstrate that microtremor characteristics can be used to detect unstable rock wedges on slopes, quantitatively describe the stability of slopes and lengthen the lead time for rockfall warning. We show that the change in the energy of ground microtremors can be an early precursor of rockfall and that the signal frequency decreases with slope instability. This finding indicates that ground microtremor signals are remarkably sensitive to slope stability. We conclude that microtremor characteristics can be used as an appropriate slope stability index for early rockfall warning systems and predicting the spatiotemporal characteristics of rockfall hazards. This early warning method has the advantages of providing a long lead time and on-demand monitoring, while increasing slope stability accessibility and prefailure location detectability.

Main Text

Rock cliffs are usually unstable and may lead to catastrophic collapse that seriously threatens the construction of slope engineering and the safety of passengers in vehicles on the slope[1,2]. Only a few papers about rockfall prediction have been published, and no clear precursors before rock collapses have been detected1[1,3–6]. Kinematic and deformation analysis methods, including the limit equilibrium method[7], numerical simulation method[1,8,9], fuzzy theory[10,11] and acoustic emission[12], are used in the stability evaluation of unstable rock slopes. These theoretical tools can analyse the spatiotemporal characteristics of rockfall hazards and are suitable for the assessment of the damage level of rock slopes but not for the accurate monitoring and early warning of a rockfall. Currently, the technologies used for rockfall monitoring mainly include laser scanning methods, light detection and ranging systems (LiDAR), GPS receivers, geographical information systems (GISs), video image recognition systems and interferometric synthetic aperture radar (InSAR)[4,13–16]. Although the InSAR and differential interferometric synthetic aperture radar (D-InSAR) techniques have been developed to identify potential landslides for early landslide detection[17–18], these remote image analysis techniques still provide uncertain forecasting rockfall locations and short warning times[5]. A rockfall always occurs suddenly. Before a rockfall occurs, the displacement index of the unstable rock does not change enough for remote imaging sensors to detect[1]. Although another landslide early warning system based on rainfall monitoring can lead to a longer warning time of days[19], this system can be applied only over specific regions and for rainfall-induced landslides.

With the advancement of electronic technology, some researchers have started to monitor unstable rock slopes and indicated that the landslide seismic response and vibration signal monitoring index can offer a foundation for the early warning of rock collapse[8,20,21]. The ground vibrates before collapse due to crack nucleation and propagation in the unstable rock. The vibration amplitude and fundamental vibration frequency can record failure precursors in unstable rocks[22]. When a rock slope becomes dangerous, the measured seismic response exhibits strong directional amplification[23,24]. Compared to displacement analysis, these results show that vibration analysis signal characteristics can be used to improve early warning approaches of rock collapse[2,3]. However, seismic monitoring has temporal and spatial limitations because it can record signals after a seismic event in only a seismic zone. For monitoring and early warning of rockfall hazards, choosing an appropriate technique for rockfall hazard assessment is therefore necessary.

Microtremors are small-scale vibrations of the ground caused by natural phenomena and have been applied to study sedimentary thickness, evaluate local site effects and locate weathered bedrock depths and landslide areas[25–27]. In this study, we introduce ground microtremor signals for early rockfall forecasting and conduct in situ and laboratory experiments to study the relationship between microtremor characteristics and slope stability. We then compare the effects of three early warning detection systems based on microtremor, displacement and crack generation characteristics. Our analysis demonstrates that microtremor characteristics provide the earliest precursor of rockfall and are remarkably sensitive to slope stability. To this end, we apply a microtremor-based rockfall warning method on a mountain highway in central Taiwan to identify cliff areas that are prone to fall and provide appropriate warnings according to the estimated slope stability.

Microtremor monitoring of rock slope

An in situ test was conducted on Provincial Highway No. 8 (also known as the Tai-8 highway, Central Cross-Island Highway) in central Taiwan to analyse the slope stability using microtremor monitoring (Fig. 1). The Tai-8 highway runs through an extremely unstable and rugged region of the Central Mountain Range. Heavy rain from monsoons and typhoons and considerable shocks by earthquakes often cause substantial rockfall damage to highways and other transportation infrastructures[28]. The microtremors at the ground level (G1-G4) of a rerouted section of the old Tai-8 highway, neighbouring lateral slope walls (W1 and W2) and overhanging cliffs (W3, W5, W4 and W6) were recorded by triaxial accelerometer sensors (Figs. 1a, b). All the sensors were installed along two synchronous monitoring routes (Fig. 1a). The fast Fourier transform (FFT) was employed to transform the microtremor signal into the frequency domain. Two synchronous microtremor data sets in the vertical component are shown in Fig. 1c. W1 and W2 reflect similar ground microtremor patterns as those of the signals observed at the ground level (G1-G4), which shows that the fundamental frequency in this area is in the range of 6–10 Hz and that the amplitudes are below 1.3 μm. Along the routes, the amplitudes of the microtremors recorded at W3 and W5 became larger, and the frequency ranges decrease. The outermost cliffs, W4 and W6, located at the end of routes, show higher amplitudes of up to 4 μm and relatively low dominant frequencies of 1–3 Hz. These results imply that the microtremor characteristics may be highly sensitive to the stability of rock wedges and can indicate the location of unstable rock wedges on slopes before they occur. To evaluate the relationship between microtremor characteristics and slope stability, a series of laboratory tests were conducted.

Microtremor characteristics

We designed a series of laboratory tests for monitoring the microtremors of overhanging rock (experiment setup shown in Extended Data Fig. 1). The factor of safety (FS) of an overhanging rock was calculated according to cantilever beam theory. In the laboratory tests, a main block with an overhanging block made of plain concrete was prepared to model the bedrock slope and overhanging rock wedge. Three different contact areas between these blocks were considered. First, the overhanging block was supported by a 200 x 63 mm junction to the main block without an upper trench (Fig. 2a). Second, an 18 mm-deep trench was cut artificially at the top of the junction (Fig. 2b). Third, a 32 mm-depth upper trench was considered (Fig. 2c). The calculated FSs for these three conditions are 38.58, 19.13 and 8.85. The narrow contact surface with a lower FS reflects a relatively unstable rock slope. The microtremor signals in the vertical component of the overhanging blocks and the FFT patterns are shown in Fig. 2. This result implies that as the overhanging block became unstable, the amplitude of the vertical microtremor signal was relatively large, and the energy in the time domain was concentrated in the lower frequency band of the 2–6 Hz range (Fig. 2a). Current early warning methods can warn of a rockfall when the FS is close to 1.0. The results of laboratory tests indicate that ground microtremor signals are remarkably sensitive to rock slope stability, even when the FS of the rock slope is greater than 8. This finding demonstrates that ground microtremors are an early precursor of rockfall and have the potential to determine a rock slope stability index.

Stability related analytical frequency

The weight and size of unstable rock cliffs vary, which may interfere with the identification of unstable rock slope derived from microtremor characteristics. To extract the rock stability-related signal information, we designed a laboratory test to reduce the signal information caused by rock mass (Extended Data Fig. 1). To simulate varied rock wedge masses, we added progressive loading on the overhanging block supported by the junction with a 32 mm-depth upper trench (Fig. 3a). The block finally fell when the load was increased to 1440 kN. We assumed that the FS was 1.0 when the overhanging block fell and then obtained the FSs in all statuses of the overhanging specimen according to the ratio of the maximum flexural stress based on cantilever beam theory. Fig. 3b shows the three components of the microtremor signals of the overhanging block. Before the block fell, the microtremor amplitude increased and the microtremor frequency decreased as the designed loads increased. However, the weight/load of the block mass also contributed similar characteristics to the block vibration. To amplify the microtremor characteristics and reduce the mass-induced vibration effects, we added the signals in the horizontal component towards the main block (Y-axis) and the vertical component (Z-axis) and then divided them by the horizontal tangential component, towards the X-axis. The microtremor signal in the horizontal tangential component, towards the X-axis, is the only signal component that does not reflect the block stability but has the same mass component as the others. Therefore, we chose this component as a divisor to remove the mass-induced vibration effects and extract the features of rock slope stability from the microtremor signals. The feature extraction results are presented in Fig. 3c. With increasing rock mass/load, the amplitude ratio increased sharply from 500 to 3000, and the analytical frequency shifted from 6 Hz to 1.5 Hz.

Figure 4a shows the effect of this rock slope stability extraction method. With the FS of rock slope, power spectrum of the original microtremor signals in the vertical component from the overhanging block varies remarkably. Red dotted lines and white asterisks show the analytical frequency using the extraction method. The analytical frequency clearly decreases compared to the original signals as the block becomes unstable, especially when the FS is lower than 2.0. This indicates that the rock slope stability extraction method enhances the sensitivity of ground microtremor signals to slope stability and can help to more accurately detect the location of unstable rock slopes in the field and provide more lead time for landslide remediation works.

Rockfall predictability

To compare the effects of current early warning detection systems based on slope displacement, crack generation and microtremor characteristics, we used the sensors to monitor the unstable overhanging block (Fig. 4). For a microtremor-based warning system, the energy of the microtremor signal provides the very first precursor of rockfall by concentrating at a low frequency when the FS decreases (Fig. 4a). Both the original microtremor frequency and extracted feature frequency decrease noticeably as the rock becomes unstable, until the block falls. For the displacement-based warning system, the displacement of the unstable block does not change obviously before a rockfall (Fig. 4b). The displacement increases sharply only when the FS drops to 1.11. The corresponding displacement magnitude, smaller than a millimetre, is too small for current remote imaging sensors to detect in the field. The crack-based warning system shows that the acoustic emission event count increases consistently, without a significant change, throughout the experimental process (Fig. 4c). There is no significant validation of precursors for early rockfall warning. Compared with displacement- and crack-based warning systems, the microtremor-based warning method exhibits three main points corresponding to rockfall warnings. One advantage of this system is that the microtremor-based warning method provides the earliest lead time. Second, the stability of the slope can be quantitatively described with the FS from the microtremor frequency of the slope. Three, the microtremor monitoring setup, including accelerometer sensors, is simple, fast, portable and cost-effective. Ground microtremors can be monitored at any time, unlike with the seismic signal-based warning method, which requires monitoring after seismic events. To summarize the above results, the microtremor-based warning method is the most appropriate technique for rockfall hazard assessment.

Microtremor characteristics can assist system managers of government to formulate an efficient multiple rockfall warning system. If the microtremor characteristics of a cliff or rock wedge show that the signal energy is concentrated at a low frequency, a highway administrative unit should decide the warning type, a prerockfall watch should commence, and a rockfall warning system should be utilized according to the corresponding FSs before the rockfall. Taking the mountain slope of the old Tai-8 highway as an example (Fig. 1), both the original microtremor signals and feature extracted signals we analysed at W1 and W2 show that the analytical frequencies are larger than 6 Hz. According to the frequency FS chart (Fig. 4a), the corresponding FSs are greater than 4.5, which means that there is no rockfall risk. The corresponding FSs of W3 and W5 are approximately 4.0, relatively stable according to Bowles safety factor classification[29]. The results of the sensors at the outermost cliff areas, W4 and W6, show low frequencies of less than 2 Hz, and the corresponding FSs are lower than 1.64. The analytical frequency at W4 is nearly 1 Hz. Thus, it is suggested that the highway administrative unit engages in slope protection construction or immediately remove the potentially unstable rock mass at W4 and W6 to prevent a rockfall from occurring to eliminate hazards.

Without a clearly detectible precursor before rock collapse, the predictability of current early-warning systems for rockfall has been limited. Our findings show that the ground microtremor signal is remarkably sensitive to slope stability. We therefore propose that the microtremor characteristics can provide a very early precursor of rockfall to detect unstable rock on slopes early and quantize the stability of slopes. Such microtremor characteristics may be applied to field investigations for slope reinforcement construction. Extending the lead time of microtremor-based warnings will reduce the rockfall hazard risk posed to the safety of not only nearby people but also construction sites.

Methods

To study the microtremor characteristics of mountain slopes, an in situ experiment was conducted with accelerometer sensors. A series of laboratory tests were conducted to evaluate the relationship between the FS and microtremor characteristics of overhanging rock and establish a rock slope stability extraction method.

Microtremor monitoring on a mountain slope

An in situ experiment was conducted on a rerouted section near Taroko, Hualien of the Tai-8 highway of the Central Mountain Range in Taiwan using triaxial accelerometer sensors.

In this experiment, four accelerometer sensors were set to synchronously monitor one ground level monitoring route (G1-G4) and two synchronous monitoring routes at different mountain slope locations (Figs. 1a, b).

Physical rockfall experiment

We executed a series of physical rockfall experiments. A main block with an overhanging block made of plain concrete was prepared to model the bedrock slope and overhanging rock wedge. Extended Data Fig. 1 shows the physical model and measuring system. A strain gauge, three accelerometer sensors and four acoustic emission sensors were set on the overhanging specimen to monitor the displacement, microtremor signal and crack development, respectively.

To study the relationship between the slope stability and the microtremor characteristics, the junction between the overhanging block and main block was cut down gradually (Extended Data Fig. 1d). To quantitatively describe the rock stability on the slope, we added progressive loading on the overhanging block. The microtremor characteristics of the rock were obtained by an accelerometer sensor, and the FSs were obtained through cantilever beam moment calculation.

Declarations

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AUTHOR CONTRIBUTIONS

Y.R. Yang conducted the experiments and compiled the manuscript. T.T. Lee conducted the experiments and carried out the microtremor signals analysis. T.T. Wang managed the study and designed the field and laboratory experiments. Y.R. Yang and T.T. Wang contributed equally to this work.

COMPETING INTERESTS

The authors declare no competing interests.

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