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Landslide seismic magnitude

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ABSTRACT

Landslides have become one of the most deadly natural disasters on earth, not only due to a significant increase in extreme climate change caused by global warming, but also rapid economic development in topographic relief areas. How to detect landslides using a real-time system has become an important question for reducing possible landslide impacts on human society. However, traditional detection of landslides, either through direct surveys in the field or remote sensing images obtained via aircraft or satellites, is highly time consuming. Here we analyze very long period seismic signals (20–50 s) generated by large landslides such as Typhoon Morakot, which passed though Taiwan in August 2009. In addition to successfully locating 109 large landslides, we define landslide seismic magnitude based on an empirical formula: $\mathbf{Lm} = \log(A) + 0.55\log(\Delta) + 2.44$, where A is the maximum displacement (μm) recorded at one seismic station and Δ is its distance (km) from the landslide. We conclude that both the location and seismic magnitude of large landslides can be rapidly estimated from broadband seismic networks for both academic and applied purposes, similar to earthquake monitoring. We suggest a real-time algorithm be set up for routine monitoring of landslides in places where they pose a frequent threat.

1. Introduction

Catastrophic landslides can not only destroy many human lives, but also have strong economic, social, and political impacts on many countries. For example, a huge number of landslides were triggered by the extremely heavy rainfall (>3000 mm) caused by the synergistic effect of both Typhoon Morakot and the southwestern monsoon in Taiwan in August 2009 (Lin et al., 2010; Tsou et al., 2011; Kuo et al., 2011). One of the most deadly of these landslides buried 474 residents in the Hsiaolin village of southern Taiwan. Based on a detailed investigation (Chen et al., 2011), the disaster process could be clearly divided into two major parts. First, the landslide buried the northern part of the village at around 10:16PM, August 7, 2009 (UTC time) (Lin et al., 2010) and immediately blocked the Cishan River to form a dam. Only a small group of residents (∼40) who lived at the southern part of the village successfully escaped to high land. All others were not so lucky and an hour later, the collapse of the dam completely swept away the remaining parts of the village without any warning (Tsou et al., 2011; Chen et al., 2011). News of the deadly disaster was not conveyed until more than 24 h later, and the premiere of Taiwan resigned several days later because of the delay in the evacuation and rescue work.

At that time, in fact, there was no reliable way to rapidly detect landslide location or seismic magnitude in order to issue a warning of possible dam failure. Traditionally, landslide detection depends on either detailed on-site reports or aircraft and satellite images from space; however, those methods might not help when telephones and other wireless communication systems are not functioning normally and it is impossible to report any survey results from the field. Also, most aircraft and satellite images are obscured when the weather conditions are extreme, for example during typhoon or monsoon periods. In addition to the rapid detection of landslide location, reliable quantitative estimation of landslide seismic magnitude is important for evaluating the possibly complex impact of disasters. Thus, new methods for rapidly detecting large landslide locations as well as their seismic magnitude should be developed to mitigate associated disasters, such as dam damage and downstream floods.

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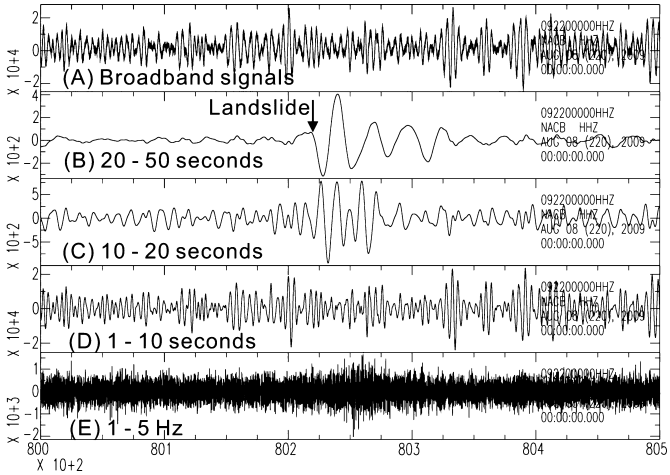

Fig. 1. An example showing the landslide earthquake that occurred at the Hsiaolin village and recorded at a distant station (NACB). The vertical seismograms from top to bottom are (a) original broadband, then band-passes of (b) 20–50 s, (c) 10–20 s, (d) 1–10 s and (e) 1–5 Hz. Landslide energy is clearly marked by an arrow at periods between 20 and 50 s.

In order to rapidly detect landslide seismic magnitude as well as location, we first analyzed all the large landslides that occurred during the period when Typhoon Morakot passed through Taiwan on August 7–10, 2009. We then defined landslide seismic magnitude based on an empirical formula. Similar to determining earthquake magnitude, the landslide seismic magnitude (**Lm**) is simply calculated according to both (1) the peak of seismic displacement recorded at broadband seismic stations and (2) the source distance between the seismic station and the landslide location. Thus, both the location and seismic magnitude of large landslides can be rapidly detected from broadband seismic networks for both academic and applied purposes in the future. Finally, some possible implications of the results of landslide statistics are discussed to improve our understanding of landslide seismology.

2. Landslide detection

Identification of very long period seismic signals generated by the rebound of the elastic crust after a landslide occurs near the surface provides reliable arrival times to locate the landslide source (Kanamori and Given, 1982; Kawakatsu, 1989; Ekstrom and Stark, 2013; Lin, 2015). After the 2009 Hsiaolin landslide in Taiwan (Lin et al., 2010), we showed that the broadband seismic network, whose original purpose is to routinely study earthquakes, could be useful for locating large landslides. An empirical band-pass filtering from 20 to 50 s (0.02–0.05 Hz) of the broadband seismic data can significantly enhance the seismic signals generated by large landslides. For instance, seismic signals generated by the Hsiaolin landslide and filtered by a variety of bands (0.2–1, 1–10, 10–20, 20–50 s) showed that landslide signals were largely dominated by very long period signals (20–50 s) (Fig. 1). During a 24 h period on August 8 (UTC), we successfully located 52 large landslides in Taiwan (Lin et al., 2010).

To detect more landslides that occurred during the entire period when Typhoon Morakot passed through Taiwan, in this study we have carefully examined all broadband seismic data and then identified all of the larger landslides during the time between August 7 and 10, 2009. Similar to the routine location of earthquakes, we have carefully read the arrivals of very long period seismic signals (20–50 s) at each station (Fig. 2). We have first compared every seismogram recorded at every station and then systematically picked the arrivals at the first maximum (peak) or minimum (trough) of the very long period seismic signals. It is very difficult to "miss-pick" the arrival time at each station because the adjacent maximum (or minimum) is more than 20 s early or late due to the very long period signals. Then we employed a least-square inversion algorithm (HYPO71, Lee and Jahr, 1972) to locate the source. Since the wavelengths of such long-period seismic signals are very long (∼150 km), a simple half-space model with a propagation velocity of 3.4 km/s was employed to calculate the travel-times from the landslide to the broadband seismic stations, based on a previous study (Lin et al., 2010) that showed that the very long period seismic signals are typically surface waves. For example, plots of very long period seismic signals versus station distances clearly show the propagation velocity is about 3.4 km/s in the Taiwan area (Fig. 2).

In fact, landslide events with very-long-period signals are easily distinguished from local earthquakes based on their frequency content as well as their wave propagation velocity (online supplement: Fig. S1). A local earthquake often generates strong high-frequency energy with small long-period signals, but a landslide only produces clear very-long-period energy without any recognizable high-frequency signal. During the period when Typhoon Morakot passed through Taiwan in 2009, no earthquakes were detected by the dense seismic stations in Taiwan as the landslides occurred. The apparent velocities recorded by a seismic network are also different between a local earthquake and landslide. The apparent velocity (∼ 3.4 km/s) of seismic waves generated by landslides (Fig. 2) is significantly less than that of local earthquakes. The very-long-period seismic signals (20–50 s) generated by the Hsiaolin landslide provide one of the best examples to distinguish landslides from earthquakes. In addition, both the location and time of the catastrophic landslide at the Hsiaolin village were clearly identified by eyewitnesses and in the scientific literature (Lin et al., 2010; Kuo et al., 2011; Chen et al., 2011; Tsou et al., 2011; Lin, 2015).

In total, we have detected 109 large landslides from August 7 to 10, 2009. Most of them were clustered in the mountainous area of southern Taiwan (Fig. 3), particularly in the Alishan area, where the accumulated rainfall was extremely high (>3000 mm). The general features of these clustered landslides are similar to previous studies (Lin et al., 2010; Chen et al., 2013). Although the estimated locations might not be exactly at the same sites as indicated from the field or via satellite images (Chen et al., 2013), the differences are relatively small and are acceptable for the purpose of rapid disaster response. For example, we have carefully examined the estimated locations of six larger landslides in this study with those marked by satellite imaging, and found that the errors ranged from 2.69 km to 7.92 km (online supplement: Fig. S2). The error for the Hsiaolin landslide was about 5.69 km.

3. Landslide seismic magnitude

In addition to locating 109 large landslides, we have defined the landslide seismic magnitude based on the relationship between the seismic displacements and source distances at different seismic stations. There are two major parameters for determining the landslide seismic magnitude. One is the maximum seismic amplitude recorded at the seismic stations; the other is the distance from the landslide to the stations. For example, plots of the maximum seismic amplitude recorded at different stations with their source distances on a log–log scale show extremely similar slopes of the regression lines from seven different landslides, as shown in Fig. 4. This result is similar to the seismic energy function of source-station distance obtained in Japan (Yamada et al., 2012).

This is analogous to estimating local seismic magnitude (M_L) at seismic stations (Richter, 1935), and therefore we have tried to formulate a landslide seismic magnitude (**Lm**) as below:

$$\mathbf{Lm} = \log(A) + \alpha \log(\Delta) + \beta \tag{1}$$