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The seismic signatures of the surge wave from the 2009 Xiaolin landslide-dam breach in Taiwan

Zheng-yi Feng*
Department of Soil and Water Conservation, National Chung Hsing University, Taichung 402, Taiwan

Abstract:

The catastrophic Xiaolin landslide occurred on 9 August 2009, after Typhoon Morakot struck Taiwan. This landslide formed a dam that subsequently breached, burying and flooding the village of Xiaolin. Seismic signals were induced by the landslide and dam breaching and recorded at the Jiaxian broadband seismic station in Taiwan. The time-frequency spectra for the data from this station were analysed to extract the seismic characteristics of the landslide and to deduce the timing of processes associated with the landslide dam-break flooding. The duration of the river blockage, the time of the dam breach, the duration of the surge wave and the mean speed of the surge wave were estimated, and the hydrological implications of the flood behaviour were interpreted. The spectral characteristics of the different stream discharges were also studied. Stream water level/discharge is closely related to the frequency of the seismic signals. The broadband stations are particularly useful for flood monitoring due to their ability to continuously record measurements and their high sensitivity. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS dam breach; seismic; Xiaolin; landslide; flooding; surge wave

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INTRODUCTION

The catastrophic Xiaolin landslide (23·16 °N, 120·65 °E) occurred at 06 : 16 local time on 9 August 2009 (22 : 16 UTC on 8 Aug.), after Typhoon Morakot struck Taiwan. A natural landslide dam was created that blocked the Qishan River with the debris from the landslide (Figure 1). The landslide and the subsequent dam-breach flooding events wiped out the village of Xiaolin and caused several hundred casualties. The deep-seated Xiaolin landslide was primarily triggered by the large amount of precipitation in the area (approximately 1,676 mm in three days) and the dip-slope geological features (Tsou *et al.*, 2010). Debris from the Xiaolin landslide fell about 830 m from the head scarp (Tsou *et al.*, 2010), and the debris travelled nearly 2·83 km (Figure 1). The landslide volume was estimated to be 25·5 million m^3, and the landslide area was approximately 252 ha (Chen and Wu, 2009a). The landslide debris also blocked the Qishan River by forming a natural dam approximately 53 m high, 350 m wide and 600 m long, with a dam volume estimated at 10·5 million m^3. The area of the landslide-dammed lake was approximately 922 ha, and the volume of water temporarily withheld by the dam was 19·5 million m^3 (Chen and Wu, 2009b). The resulting reservoir was approximately 3·6 km long. The landslide dam failed within 1 h and 24 min of forming due to erosion caused by overtopping water. The surge wave caused by the breaking dam arrived at the Shanlin stream station, 30·5 km downstream from Xiaolin, between 08 : 40 and 10 : 10 on 9 August 2009.

The sliding mass of 25·5 million m^3 generated by the Xiaolin landslide caused shaking that was equivalent to an approximate surface magnitude Ms of 4·6 earthquake (Cheng-Horng Lin, 2010, personal communication). The seismic signatures of the dam-break flooding surge wave and the landslide were recorded at the Jiaxian broadband station, Station Code SGSB. The SGSB is located 500–600 m from the Qishan River, and this station was able to record clear signals during the dam-break flooding. The stations in the Broadband Array in Taiwan for Seismology (BAT) record continuous seismic signals at 200 Hz and are able to detect very weak signals, unlike the short-period instruments (accelerometers) used in Taiwan that are triggered by seismic signals exceeding an amplitude threshold.

Seismic signals are often used to monitor natural hazards other than earthquakes, such as rock avalanches, debris flow and flooding. The monitored waveforms are then analysed to understand the frequency content and characteristics of the event. Generally, the frequency of ground vibrations associated with debris flow ranges from 10 to 150 Hz, which is caused by debris loads impacting riverbeds (Huang *et al.*, 2008). De Angelis *et al.* (2007) observed that large pyroclastic flows descending the slope of a volcano produce seismic signals from 1 to 25 Hz. Observations of the time-frequency spectra of a snow avalanche by Suriñach *et al.* (2005) indicated that a time-frequency spectra with a triangular shape are caused by a sliding mass due to an increase in high-frequency energy

* Correspondence to: Zheng-yi Feng, Department of Soil and Water Conservation, National Chung Hsing University, Taichung 402, Taiwan. E-mail: tonyfeng@nchu.edu.tw

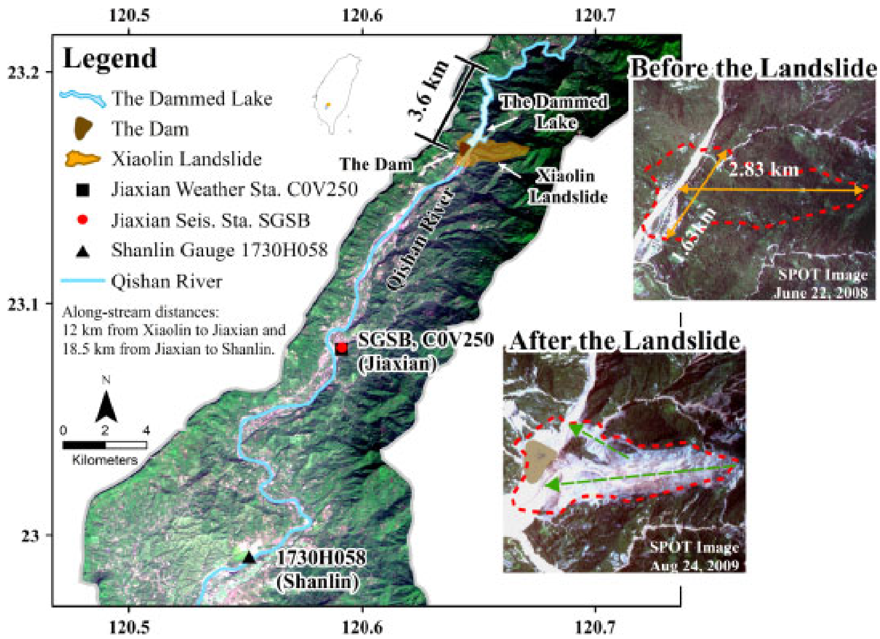

Figure 1. Map of the Xiaolin landslide, the landslide dam, the landslide-dammed lake and the Qishan River

transmitted to the seismometer as the sliding mass (or flow) approaches it. In this study, a trapezoidal shape of the time-frequency signature is observed for the surge wave caused by the dam breach passing the seismic station.

Amitrano *et al*. (2007) indicated that the frequency range of 0·1–1 Hz is the most sensitive to mudslide velocity and that the frequency range of 0·01–10 Hz is associated with landslide deformation. These frequency ranges are close to those found for the Xiaolin landslide in this study. Costa and Blanchard (2008) found that floods may induce ground vibrations with frequencies greater than 100 Hz, and Newman and Bennell (2002) inferred that stream flow may be related to vibrations caused by the flow of water. While considerable literature exists regarding the frequency content of landslide and debris flow, there are fewer studies related to the frequency contents associated with floods, particularly for dam-breach surge waves. The frequency range analysed for the Xiaolin surge wave in this study is much lower than that reported by Costa and Blanchard (2008), and the spectrogram of the dam-break process is interpreted in detail.

To understand the seismic signatures of the Xiaolin landslide and the dam-break flooding, empirical mode decomposition (EMD) was used to obtain the intrinsic mode functions (IMFs), and the Hilbert-Huang transform (HHT) was used to obtain time-frequency spectra (Huang *et al*., 1998). The characteristics of the HHT time-frequency spectra recorded at SGSB during several other river stages were also studied. The SGSB seismic signals were used to explain the timing of the landslide and the dam-break flooding and to relate them to the stage records from the Shanlin gauge station (1730H058).

DATA AND METHODS

Seismic station SGSB, Jiaxian

For the Xiaolin landslide, the vertical-component seismic signals from 06 : 16 to 06 : 18 on 9 August 2009 were analysed for SGSB station. The intrinsic mode functions and time-frequency spectra from SGSB were obtained by EMD and HHT to observe the characteristics of the signals generated by the landslide.

Continuous 4-h vertical waveforms at SGSB from 06 : 00 to 10 : 00 on 9 August were investigated to observe the flow behaviour of the Qishan River before and after the breaking of the landslide dam. The time-frequency HHT spectra recorded during this 4-h period were examined in detail, and the signals induced by the dam-break flooding surge wave were observed. The seismic signals were recorded at 200 Hz and were down-sampled to 100 Hz before performing EMD and HHT.

To investigate how the seismic characteristics at SGSB relate to the flooding levels of the Qishan River, data from SGSB were retrieved for three periods: a period with an average stream water level, a period during peak rainfall, and a period with a high stream water level.

Water-level data for the Shanlin gauge station

The dam break induced a flood surge wave that rapidly increased the water level of the Qishan River. The stage variations were recorded by the Shanlin stage gauging station (1730H058), an automatic ultrasonic stage recorder with a sample rate of one sample per ten minutes. The water level changes indicated the arrival of the surge wave at the Shanlin station, located 30·5 km downstream of Xiaolin along the Qishan River, SSW of Xiaolin. The initial decrease in the water level was due to the landslide dam blockage, while the subsequent sharp increase in the water level was due to the surge wave of the dam-break flood.

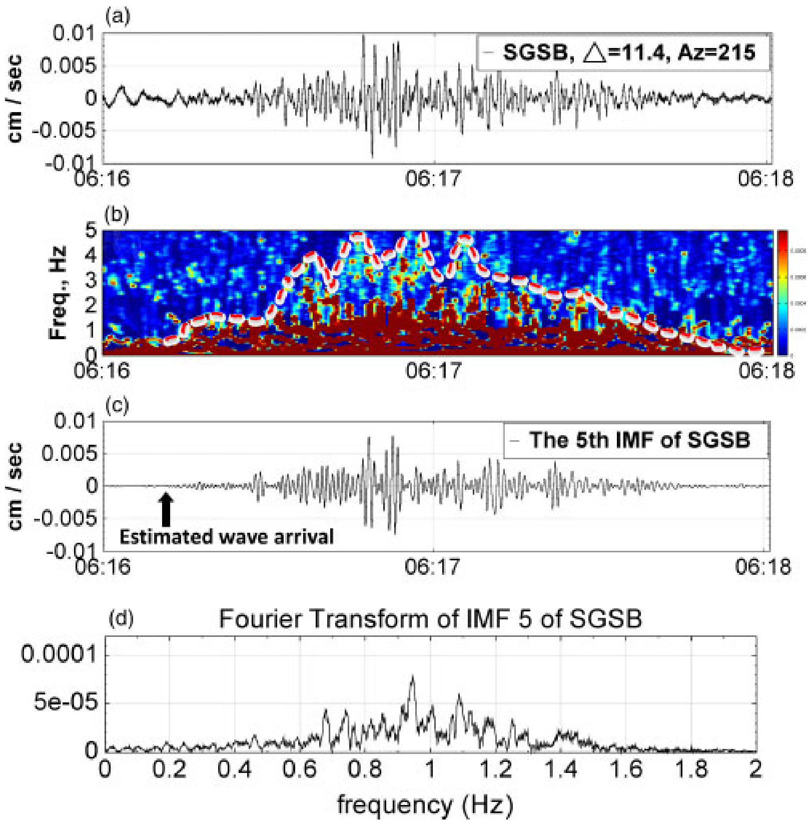

Figure 2. (a) The vertical-velocity waveform caused by the Xiaolin landslide and recorded at SGSB; (b) The HHT time-frequency spectra; (c) The 5th intrinsic mode function (IMF) of the SGSB data in Figure 2(a); (d) The Fourier transform of the 5th IMF in Figure 2(c) (Feng, 2011)

This study calculates the time and duration of the water blockage caused by the landslide dam, the dam-break flooding surge wave, and the approximate flooding speed by examining the seismic signature at SGSB station and the water-level variations at the Shanlin station.

RESULTS AND DISCUSSION

Seismic characteristics of the landslide

The signals from the Xiaolin landslide were easily identified at SGSB because the station is only 11·4 km from the landslide. The vertical component of the seismic wave from the landslide is estimated to have arrived at 06 : 16:11 at SGSB, and the wave coda ended at 06 : 17:49; the signal duration was approximately 98 s. This duration can be used to estimate the average velocity of the landslide. The origin time of the Xiaolin landslide was also reported as 06 : 16 on 9 August 2009, by Lin *et al.* (2010).

The 2-min-long vertical velocity waveform and HHT spectra recorded at SGSB from 06 : 16 to 06 : 18 on 9 August 2009, are shown in Figure 2(a) and (b) (Feng, 2011). The red dashed lines encircle the most significant spectral ranges for the Xiaolin landslide in Figure 2(b). Most of the signal below 0·4 Hz was not induced by the landslide, as a similar signal exists in the time series before and after the landslide. The time-frequency spectrum of the landslide recorded at SGSB is mainly distributed between 0·5 and 5 Hz. In Figure 2(b), higher frequencies (3–5 Hz) can be observed from 06 : 16:40 to 06 : 16:55. The amplitude of the ground velocity in this time period is also higher than in other time periods.

The 5th intrinsic mode function (IMF) of the data at SGSB in Figure 2(a) is obtained by EMD, as shown in Figure 2(c); the Fourier transform for the 5th IMF at SGSB in Figure 2(c) is shown in Figure 2(d) (Feng, 2011). In Figure 2(c), signals induced by the Xiaolin landslide can be more clearly distinguished. The duration of the landslide-induced ground shaking is roughly 98 sec at SGSB in Jiaxian. The frequencies that are related to the impact of the Xiaolin landslide occur between 0·7 and 1·3 Hz, as observed in Figure 2(d).

Analysis of the stage records from the Shanlin gauge station

The water levels of the Qishan River recorded at the Shanlin gauge station and the estimated discharges at Jiaxian from 18 : 00 on 7 August, to 18 : 00 on 9 August, are presented in Figure 3 to show the dam-break flooding event during Typhoon Morakot. The water level started to decrease at 07 : 10 on Aug. 9 (A′ in Figure 3). The water level at Shanlin decreased at 07 : 10 because the dam blockage at Xiaolin occurred at 06 : 16 and the effect of the blockage took about 54 min to reach the Shanlin gauge. The water level reached its lowest stage at 07 : 50 (B′). This progressive drop lasted 40 min (B′ to A′) and is caused by the drainage of the water downstream after the river was blocked. The water level increased by 7·9 m after the dam-break flooding occurred; the water level

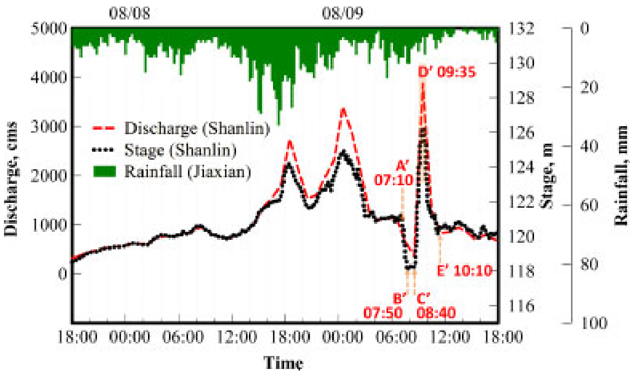

Figure 3. The measured stage and estimated discharge at the Shanlin gauge station (1730H058) from 18 : 00 7 August to 18 : 00 9 August 2009, and the rainfall at the Jiaxian rain gauge station C0V250 (Note: Data rate: 1. Stage: 10 min; 2. Discharge: hourly; 3. Rainfall: 15 min)

began at an elevation of 118·3 m and increased to its peak stage at an elevation of 126·2 m from 08 : 40 (C′) to 09 : 35 (D′). The flooding surge wave retreated at approximately 10 : 10 (E′). The prime symbol used here and in Figure 3 (A′ to E′) distinguishes water levels from the corresponding timings (A to E) estimated from the Jiaxian seismic signals in Figure 4.

The duration of the landslide dam blocking the Qishan River is estimated to be approximately 1 h 30 min from A′ (07 : 10) to C′ (08 : 40), as shown in Figure 3. However, this estimate uses stage data from the Shanlin gauge and may contain at least ±5-min error due to the low sample rate of one sample every 10 min. The duration of the dam-break surge wave was approximately 90 min at the Shanlin gauge station, as determined from the time difference between C′ (08 : 40) and E′ (10 : 10) in Figure 3.

Analysis of the data from the Jiaxian SGSB station

Observations of the phases and timings of the dam-break process. The data from SGSB in Jiaxian were used to discern the timing of the various phases of the landslide and flooding. The timing estimates should provide better results than using the stage data from the Shanlin station because the sampling rate at SGSB is much higher than the 10-min time intervals of the stage data. The time-series and time-frequency HHT spectra from 06 : 00 to 10 : 00, 9 August 2009, are shown in Figure 4(a) and (b); the lettered labels indicate the estimated times of various phases of the flooding. The phase times are difficult to recognize in the time-domain signals (Figure 4(a)), but they are easier to identify in the time-frequency spectra (Figure 4(b)).

In Figure 4(b), the occurrence of the Xiaolin landslide (LS) and the blockage of the Qishan River can be clearly observed. Among the surge wave timings labelled C, D and E (08 : 03, 08 : 43, 09 : 08, respectively), there exists a broad-frequency high-amplitude time period in the spectrogram that is indicated by the trapezoidal time-frequency signature zone. Particularly in interval around D, the high-amplitude spectra of the surge wave lasts for 15–20 min. The high-amplitude zone is distributed primarily from 1 to 8 Hz, which encompasses the frequency content of the vibrations from the dam-break surge wave. The spectral peaks at frequencies from

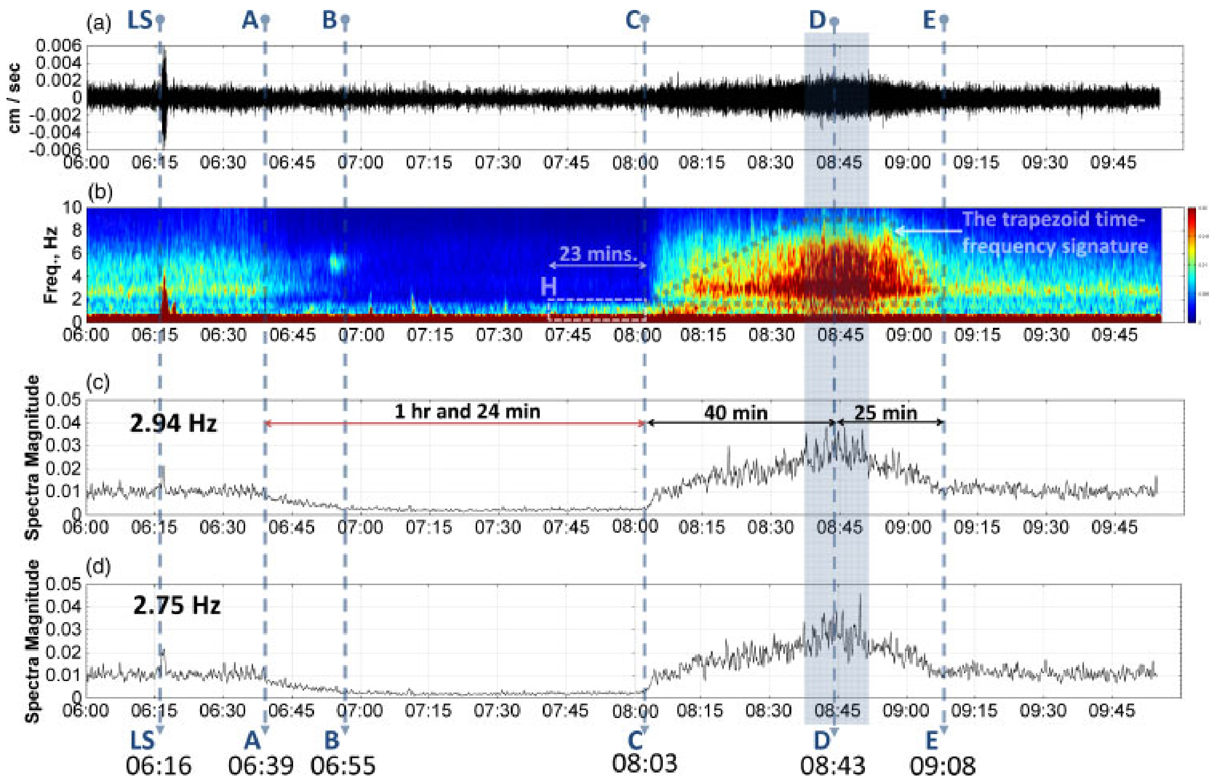

Figure 4. (a) Time-series signals; (b) HHT time-frequency spectra at SGSB from 06 : 00 to 10 : 00 on 9 August 2009; (c) Magnitude of the 2·94 Hz signal extracted from the time-frequency spectra; (d) Magnitude of the 2·75 Hz signal extracted from the time-frequency spectra

Table I. Approximate timings of the various phases of the Xiaolin landslide and dam-break flooding

Phases of the landslide and flooding	Approximate timing (hh : mm on 9 Aug. 2009, Taiwan time)	Approximate duration after the dam-break (hh : mm)
L: Xiaolin landslide	06 : 16	
Estimated timing of the rapid erosion and outburst of the dammed water	07 : 40	00 : 00
SGSB (Jiaxian broadband station):		
A: Spectral magnitude began to drop due to blockage	06 : 39	
B: Low-spectral magnitude due to blockage	06 : 55	
C: Spectral magnitude began to increase	08 : 03	00 : 23
D: High-spectral magnitude zone	08 : 43	01 : 03
E: Dam-break surge wave retreated	09 : 08	01 : 28
1730H058 (Shanlin stream station):		
A′: Water level began to drop due to blockage	07 : 10	
B′: Lowest water level due to blockage	07 : 50	
C′: Water level began to increase	08 : 40	01 : 00
D′: High water-level zone	09 : 35[a]	01 : 55
E′: Dam-break surge wave retreated	10 : 10	02 : 40

[a] The time 09 : 35 is estimated to account for possible sample rate errors.

2·6 to 3 Hz were mainly induced by the dam-break surge wave. From 07 : 40 to 08 : 03, the 23-min-long zone H displays some brighter spectra in the lower frequencies than the spectra during 06 : 55 and 07 : 40.

The spectral magnitudes of the 2·94 Hz and 2·75 Hz frequencies were extracted from the time-frequency spectra to help identify the timing of the landslide and flooding phases (Figure 4(c) and (d)). The spectral magnitudes of the time series in Figure 4(c) and (d) clearly show the timing of LS and A to E; the timing and changes in magnitude are very similar at the two frequencies. The approximate timing of the phases obtained from the data of SGSB station and Shanlin gauge station (Figures 3 and 4) are listed in Table I.

The amplitudes of the 2·75 and 2·94 Hz signals at SGSB as compared to the Shanlin station are presented in Figure 5. The Qishan River stages recorded at the Shanlin station are shifted back in time by 37 min to align C′ with C. The timing and duration of the shaded D and D′ intervals represent the stronger wave duration of 15–20 min. The spectral magnitudes at Jiaxian and the time-shifted water levels at Shanlin are well correlated. These results also explain the lengthening and 'smearing' of the surge wave as it travelled down the stream, as will be described later.

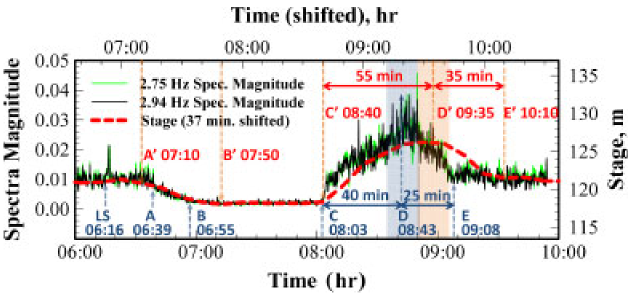

Figure 5. The spectra magnitude of the 2·75 and 2·94 Hz frequencies at Jiaxian SGSB station *versus* the Shanlin stage; the Qishan River stage recorded at Shanlin is shifted back by 37 min to align C′ with C.

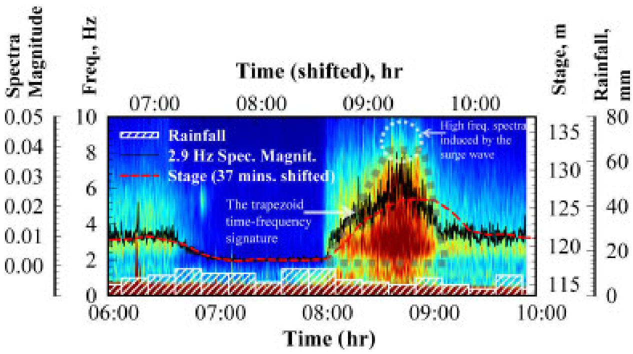

Figure 6. A composite plot of the HHT spectra, the magnitude of the 2·94 Hz signal, C0V250 rainfall data at Jiaxian and the 37-min-shifted stage at Shanlin

A composite plot of the spectrogram of the 2·94 Hz spectral magnitude, C0V250 rainfall data at Jiaxian and the shifted stage data at Shanlin is shown in Figure 6. A high-frequency spectral zone is indicated by a dashed circle, and the zone of the trapezoid time-frequency signature from Figure 4(b) is also shown.

Hydrologic interpretation of the dam-breach flood behaviour. Flow stage evolution analogized by the spectral magnitude and lifespan of the dam: Although there is no stage record at Jiaxian, the spectrogram and spectral magnitudes in Figure 4 were used as a proxy for stage data at Jiaxian. The Xiaolin landslide caused a spike at 06 : 16 in Figure 4 (LS) when the Qishan River was blocked. This blockage also caused the abrupt drop in water level at Jiaxian 23 min later at 6 : 39 (A). The spectral magnitudes at 2·94 and 2·75 Hz reached their lowest levels at about 06 : 55 (B). This gradual drop occurred over about 16 min (B to A) and is a shorter time interval than the 40 min (B′ to A′) previously observed at Shanlin because the stream length from Xiaolin to Jiaxian (12 km) is shorter than the stream length from Xiaolin to Shanlin (30·5 km); thus, there was much less water to drain, allowing the Xiaolin-Jiaxian segment to drain in a shorter amount of time. The spectral magnitude suddenly rose at 08 : 03 (C) when the surge wave began to arrive. The duration of the landslide dam is approximated at 1 h 24 min by calculating the difference in time between A (06 : 39) and C (08 : 03) in Figure 4; this is also the length of time that the landslide dam blocked the Qishan River. This duration should be closer to the actual lifespan of the dam than the 1 h 30 min estimated from the Shanlin stage records. The abrupt drop and rise in the water level at Jiaxian due to the landslide dam blockage and surge wave evolved downstream and was later observed at Shanlin, as described in the previous section

Mean speed of the surge wave: A way to calculate the mean velocity of the flooding surge wave is to use the arrival times of the surge wave at SGSB and the Shanlin station. The difference in time between the surge wave arrival at SGSB and at Shanlin station is 37 min, which was calculated using the C and C′ times at the stations (08 : 03 and 08 : 40) from Figure 5. Therefore, the velocity of the flooding surge wave can be approximated as $8{\cdot}3 \pm 0{\cdot}3$ m/sec for the 18·5 km length of the stream between these two stations and a time difference of 37 min. The timing of the dam-break at Xiaolin was then estimated to be at 07 : 40; this time was determined by calculating the time required for the surge to arrive at Jiaxian by dividing the stream distance between Xiaolin and Jiaxian (12 km) by 8·3 m/sec. This time is 23 min earlier than that indicated by C at SGSB. The flood water took approximately 25 min to retreat from Jiaxian (D to E, Figures 4 and 5, Table I).

Surge wave attenuation: The surge wave lengthened as it progressed down the channel, so the length of the wave when it passed the Jiaxian seismometer is longer than when it left the dam, and the wave at the Shanlin gauge is even longer. The amplitude of the spectral magnitude at Jiaxian is compared with the Shanlin stage amplitude in Figure 5; the stage amplitude at Shanlin is smaller, indicating that the surge wave height decreased as it travelled downstream. The dam-break surge wave caused an increase in the water level for approximately 40 min, followed by a decrease that lasted 25 min at Jiaxian (65 min total duration), as obtained from the time differences among points C, D and E of the SGSB data (Figure 4). The surge wave at Shanlin increased the water level for 55 min followed by a 35-min decrease, for a total of 90 min, obtained using the stage data at Shanlin in Figure 5.

Erosion time required for breaching of the landslide dam: The time needed for the dam-break flood to increase water levels from the lowest stage (C in Figure 4) to the highest stage (D in Figure 4) was approximately 40 min. The corresponding duration at the Shanlin gauge station is 55 min from C′ to D′ in Figure 5. These two duration intervals can be used to estimate the amount of time necessary for overtopping water to erode the landslide dam and cause its failure. As stated previously, the duration of the surge wave increased as it travelled down the channel. Therefore, the time needed for the impounded water to pass through the breached dam should be shorter as about 20 to 30 min are required for overtopping water to acutely erode the dam and cause it to complete the breach.

Approximate timing of the dam breach: The erosion of the landslide dam is estimated to start at 07 : 40, and the complete breach occurred within 20 to 30 min. Rainfall could have caused the dammed lake to overtop the dam for a period of time, but rainfall could not have caused serious erosion prior to 07 : 40. The duration of this non-erosive water overflow should depend on the resistance of the damming debriss to erosion.

Interestingly, some low-frequency spectra from 0·4 to 1 Hz are found in the H zone from 7 : 40 to 8 : 03 (23 min in length), as indicated in Figure 4(b). The 'H zone' spectra may be related to long-period flooding waves originating from the surge wave as it left the dam. The beginning of the H zone is close to the deduced dam-breach timing at approximately 07 : 40. The signals of the long-period flooding waves could travel farther than short-period waves because they are less damped than high-frequency signals. Therefore, the lower-frequency H zone is also another piece of qualitative evidence that the dammed water started to rapidly erode the landslide dam at 07 : 40.

Discharge and bedload transport: The discharge at the Shanlin gauge is estimated by the Water Resources Agency (WRA) of Taiwan and is plotted with the stage information in Figure 3. One year prior to Typhoon Morakot, the WRA (2008) obtained a rating curve of suspension load for the Shanlin station. The formula for the sediment rating curve (suspension load) at Shanlin Bridge generated by the WRA (2008) is: $Q_S = 0{\cdot}9481 \times Q^{1{\cdot}8235}$, where Q_S is sediment transport (ton/day) and Q is discharge (cms). There are no field survey data for bedloads, which are generally estimated as 10% of the total sediment load for rivers in Taiwan. The rate of suspension loads during the strong flooding waves is extrapolated using the above formula and the estimated maximum discharge of 3870 cms as 3 304 000 ton/day. Therefore, the bedloads are approximated as one-ninth of the suspension load, or 367 000 ton/day. For a 30-min duration of the strong flooding waves, the bedload estimate is 15 300 tons; this bedload transport during the surge wave could cause some large shaking recorded at SGSB in Jiaxian as well as showing some strong spectra magnitudes in the time-frequency spectrum. However, its actual contribution is difficult to quantify.

The new, continuous seismic records from the broadband station combined with the stage data help us to understand more of the observed flood behaviour, including the abrupt stage changes that evolved downstream, the mean surge wave speed and the attenuation effect of the surge wave.

Seismic source, source distance, frequency characteristics and noise: The main source of the seismic signals is most likely the turbulence of the stream flow. There were spectral magnitudes of about 0·01 for the

2·94 and 2·75 Hz signals (Figure 4(c) and (d)) before time A, prior to when the effects of the damming were experienced downstream. When the stage gradually decreased, the spectral magnitude also decreased.

Large grain-size bedloads carried by the surge wave front were mostly mudstone/shale and sandstone from the landslide damming debris, and they may contribute some additional low-frequency seismic vibrations by impacting the riverbed when the surge wave front left the dam. The riverbed near Xiaolin and Jiaxian consists of both bedrock and thin alluvial debris. The contribution of the bedload/bed impacts to the observed vibrations is difficult to quantify as previously mentioned because the low-frequency signals recorded at Jiaxian may be combined with the signal from the low-frequency surge wave, as indicated by the 0·4–1 Hz spectra in the H zone (Figure 4(b)).

The low-frequency signals were recorded at the more distant SGSB, due to their smaller extent of attenuation than that observed for higher-frequency signals. However, the spectra in the H zone from 07 : 40 to 07 : 50 are not as distinguishable; therefore, the bedload evidence for the 07 : 40 time is only qualitative. Conversely, after 07 : 50, the higher-magnitude spectral portion (brighter and red color in Figure 4(b)) can more confidently be considered the low-frequency spectra caused by the flood and distant bedload impacts. The bedloads should break down into smaller grain sizes as they travel downstream; therefore, the vibrations caused by the bedload should gradually decrease downstream, and the impacts between the bedload and riverbed should become weaker and of higher frequency and will attenuate more rapidly.

The timing of the higher-magnitude spectra (07 : 50–08 : 03) can be useful in alerting the public to flood surge waves and for emergency evacuation because the seismic waves at Jiaxian were identified 13 min before the surge wave arrived in Jiaxian at 08 : 03.

Although estimating signal attenuation with distance using only one seismic station is difficult, the time (07 : 50, Figure 4(b)) can be used to estimate the source distance of the low-frequency seismic waves. The source distance of the long-period surge wave and the large bedload impacts (0·4–1 Hz) is approximately 6·5 km (13 min × 8·3 m/sec). The source distance of the high-frequency (8–10 Hz) signals from the surge wave (Figure 4(b), time D) can be approximated as 500–600 m because the distance from SGSB station to the Qishan River is about 500–600 m.

Thus, the above source-distance estimate and the frequency dependence of the attenuation indicate that the frequency is dependent upon the source region (high frequencies are proximal, long periods are distal). The source area is effectively a line load; when the surge wave front is 500–600 m from SGSB at its closest, the spectral magnitude becomes larger, and the recorded frequencies will increase (white circle in Figure 6). This can be used to estimate when the surge-wave front arrived and passed, corresponding to the shaded zone in Figure 4 around time D. Again, a trapezoidal shape in the time-frequency spectrogram is shown in Figures 4(b) and 6, as the signature for surge wave front passing the seismometer. The strong flooding waves lasted about 15–20 min, causing it to have a trapezoidal shape as opposed to the triangular shape suggested by Suriñach *et al.* (2005).

The signals below 0·4 Hz are considered noise in this study. From B to C in Figure 4(b) as well as in Figure 7(a), there are always high spectral magnitudes for frequencies below 0·4 Hz even with a very low stream stage before the typhoon, and these signals are difficult to relate to stage or discharge. These signals may be related to some kind of long-period Earth noise or oscillation from the Earth's rotation. Some of the low-frequency energy may belong to long-period flooding waves, but

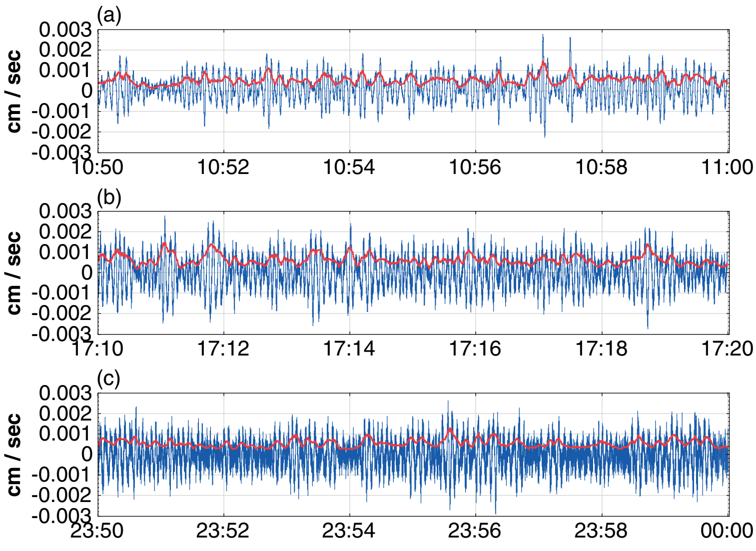

Figure 7. Signals recorded at SGSB during the three time periods (corresponding to the spectra in Figure 8). The thicker red solid lines are the moving average of the amplitudes with a 5-s moving window

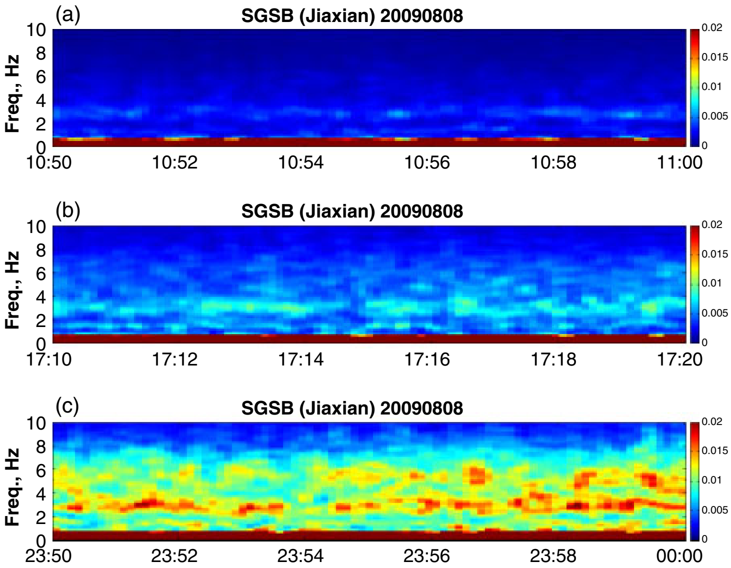

Figure 8. Time-frequency spectra at SGSB for the three time periods with differing water levels

this specific signal is hard to distinguish from the overall signal.

Relationship of the frequency spectra to the stream discharge

To investigate the frequency content of the data from SGSB station during different stages of discharge or at different water levels, signals from different time intervals were taken for (a) an intermediate discharge (10 : 50–11 : 00 on 8 August), (b) the peak hourly precipitation (17 : 10–17 : 20 on 8 August 8), and (c) a relatively large discharge (23 : 50 on 8 August 8 to 00 : 00 on 9 August 9). The discharge amount was determined by referring to the water level records from the Shanlin stream station. After accounting for the roughly 40 min delay of water flow from Jiaxian to Shanlin, the corresponding water levels and estimated discharges of the Shanlin gauge station for the three respective periods are (a) 120 m and 750 cms, (b) 123 m and 1800 cms, and (c) 125 m and 3400 cms. The peak rainfall for a 15-min time interval was 33 mm, which occurred from 17 : 00 to 17 : 15 on 8 August 8 at the Jiaxian rain gauge station (C0V250).

The seismic data for the three periods, with a moving average applied, are shown in Figure 7. Figure 8 shows the time-frequency spectra at SGSB for these periods. Although increases in the amplitudes and the moving average amplitudes in the time domain are observed, the time-frequency spectra reveal more characteristics of the frequency content and the spectral magnitudes for the analysed three periods (Figure 8).

Frequencies below 0·4 Hz still contain mainly noise. A bandpass filter centred at 3 Hz was applied to the three selected periods. After filtering, the frequencies of signals during the three periods are between 2·5 and 3·5 Hz, as shown in Figure 9, which clearly shows the amplitude shifts for the different discharges.

The spectral magnitudes (Figure 8) and seismic amplitudes (Figure 9) increase with increasing discharge, and the vibration frequencies also increase as discharge increases. For low stream levels or low discharges, the spectral magnitudes are not clearly defined (Figure 8(a)). Larger discharges generate more high-frequency signals (Figure 8(c)). The spectra of the higher discharges show that strong spectra magnitudes appear in the frequency range from 2·6 to 3 Hz (Figure 8(c)), close to the frequency range of the spectra peaks from the dam-break flooding (Figure 4(b)). In addition, there is also strong magnitude with frequencies from 4·5 to 5 Hz, beside 2·6 to 3 Hz. At certain times, this higher frequency becomes prominent because its spectral magnitude is larger than that of the lower vibration frequency (2·6–3 Hz). Therefore, high-frequency energy should be present when the discharge is large or the water level is high.

The spectral magnitude at SGSB is not directly relevant to the amount of precipitation recorded at the Jiaxian rain gauge station (C0V250). The spectral magnitude of the time period with the highest precipitation rate during Typhoon Morakot (Figure 8(b)) is not as high as the spectral magnitude of the time period with relatively high discharge (Figure 8(c)). This result confirms that the seismic signals at SGSB are not caused by rainfall at Jiaxian; they are directly related to the discharge or water level in the Qishan River.

If additional discharge, stage and flow velocity data can be collected, correlation of the data to the spectral magnitude and frequency will be possible, which may be useful for the study of channel hydraulics in the future.

SUMMARY AND CONCLUSIONS

The seismic signals caused by the Xiaolin landslide and the subsequent dam-break flood in Taiwan were recorded continuously at the Jiaxian broadband seismic station. The new data improves our understanding of dam-break

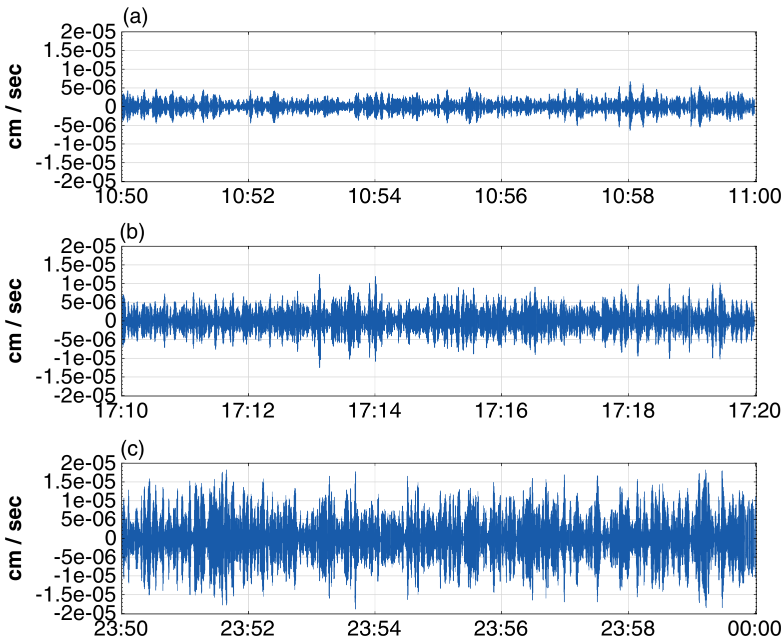

Figure 9. Signals at SGSB bandpass-filtered from 2·5 to 3·5 Hz for the three time periods in Figure 7

flood behaviour, including abrupt stage changes as they evolve downstream, the mean surge wave-speed and the smearing effect of the surge wave as well as the seismic characteristics induced by these waves.

The approximate timing of the events of the Xiaolin landslide were obtained. The Xiaolin landslide formed a landslide dam at 06:16 on 9 August 2009. The dam survived for approximately 1 h 24 min and breached at 07:40. The time needed to erode the Xiaolin landslide dam was estimated to be 20–30 min. After the breach, the dam-break surge wave arrived at Jiaxian (12 km downstream of Xiaolin) 23 min later, and at Shanlin (30·5 km downstream) 60 min later. The surge wave lasted approximately 65 and 90 min at Jiaxian and Shanlin stations, respectively. The average flooding velocity was about 8·3 ± 0·3 m/s from Jiaxian to Shanlin.

The energy of the surge wave front approached the seismic station; it produced a unique trapezoidal time-frequency signature. This signature is caused by the shorter source-receiver distance, which causes the higher-frequency vibrations to be less attenuated and large enough to be recorded. The surge wave was effectively a line load.

The discharge is estimated to be as high as 3870 cms, and the bedload transported for the half-hour duration of the strong flooding waves is estimated to be 15 300 tons. The strong bedload/riverbed impacts should contribute some spectral traces in the spectrogram.

The H zone in the spectrogram, which exhibited higher magnitudes and lower frequency spectra, is considered to be the result of the long-period flooding waves leaving the dam. This zone was used to determine the source distance of low-frequency (0·4–1 Hz) signals, which is estimated to be 6·5 km. The source distance based on higher-frequency (8–10 Hz) signals is estimated to be 500–600 m, which is the distance from the seismic station to the Qishan River.

Stream discharge and water level are directly related to the seismic frequency. Floods with greater amounts of energy have higher-frequency seismic signals. The frequency range of the seismic response to the average flood was approximately 2·6–3 Hz. Large stream discharges or high stream stages generate higher-frequency spectra (4·5–5 Hz).

These dam-break flooding interpretations are useful for calibrating numerical models of flood behaviour, studies of erosion of natural dams, hydraulic design and dam-break hazard prevention programs. This novel method of using seismic signals to probe channel flow may become an important new source of empirical constraints on river dynamics.

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