Characteristics of debris flow vibration signals in Shenmu, Taiwan

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ABSTRACT

Influenced by the climate change and the extreme weather, debris flow has become a common disaster in Taiwan in recent years. To protect people from the impacts of debris flows, monitoring and warning system were established in Taiwan since 2002. Most of the warning systems or models are based on the analysis of rainfall, the major cause of debris flow (Jan et al., 2003; Jan and Lee, 2004; Lee 2006). The measurement of rainfall, however, is an indirect option of debris flow monitoring (Huang et al., 2013), resulting in "false alarms" most of the time. One direct measure is to use geophone and broadband seismograph (Chu et al., 2014; Huang et al., 2012) to record the vibration signals of debris flows. This study analyzed the vibration signals of a site in Shenmu, Taiwan, where debris flows frequently occurred (Lee et al., 2014), and discussed the performance of using vibration signals for debris flow warning. The results of using vibration signals were practically promising for debris flow monitoring.

KEYWORDS

debris flow; geophone; seismograph; ground vibration; monitoring

INTRODUCTION

Influenced by the climate change and the extreme weather, debris flow has become a common disaster in Taiwan in recent years. To protect people from the impacts of debris flows, monitoring and warning system were established by the Soil and Water Conservation Bureau (SWCB) in Taiwan since 2002. Currently there are 19 debris flow monitoring stations in Taiwan (Fig. 1). Most of the stations are located at the central part of Taiwan.

Most of the warning systems or models are based on the analysis of rainfall, the major cause of debris flow (Jan et al., 2003; Jan and Lee, 2004; Lee 2006). The warnings based on the rainfall thresholds for debris flows were useful from the past experience. The measurement of rainfall, however, is an indirect option of debris flow monitoring (Huang et al., 2013), which is useful for disaster response but usually results in "false alarms". In contrast to the rainfall

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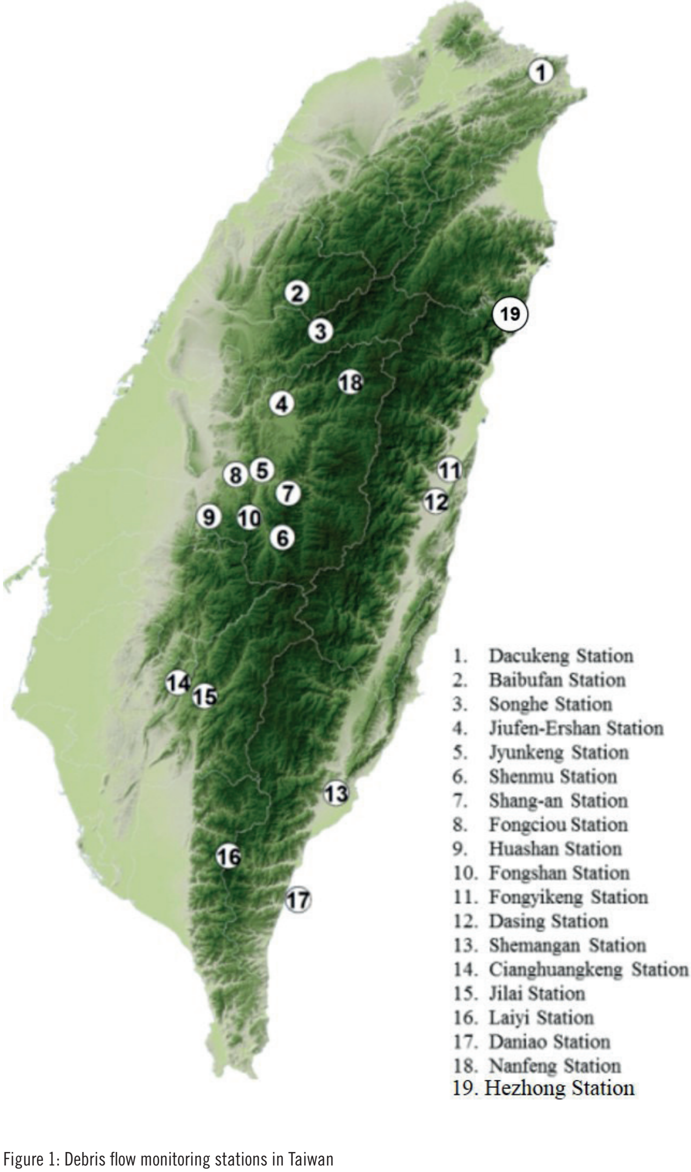

Figure 1: Debris flow monitoring stations in Taiwan

measurement, using geophone (short period seismograph) and broadband seismograph (Chu et al., 2014; Huang et al., 2012) are direct options of debris flow monitoring, and they were used to record the vibration signals generated by debris flows. The vibration signals of cases in Shenmu, Taiwan, were analyzed to understand the characteristics of debris flow, and the possibility of applying geophones and broadband seismographs to debris flow warnings was discussed.

STUDY AREA AND VIBRATION DETECTION OF DEBRIS FLOW

The Shenmu area is located in the central Taiwan, where debris flows frequently occurred (Lee et al., 2014). A debris flow monitoring station was built in 2002. The local village is adjacent to the confluence of three streams: Aiyuzi Stream (DF226), Huosa Stream (DF227) and Chushuei Stream (DF199). These streams are classified as high-potential debris flow torrents. Table 1 summarized the environment of Shenmu, Table 2 and Fig. 2 indicate the area and locations of landslides along these three streams after 2009, and Table 3 lists the debris flow events in this area. It should be noted that the debris flows usually occurred at the Aiyuzi Stream in the past 5 years, due to its shorter length and large landslide area in its upstream (Huang, et al., 2013).

Table 1: Environment of Shenmu Station (Huang, et al., 2013).

Location	Shenmu Village, Nantou County	**Debris Flow No.**	DF199, DF227, DF226
Catchment	Zhuoshui River	**Streams**	Chusuei, Huosa, Aiyuzi
Debris Flow Warning Threshold	250 mm	**Hazard Type**	Channelized debris flow
Monitored Length	5.518 km	**Catchment Area**	7,216.45 ha (Shenmu)
Geology	neogene sedimentary rock	**Slope at Source**	30~50°
Landslide area	Large, 1%≦ landslide ratio ≦5%	**Sediment**	Average debris material size: 3”-12”
Vegetation	Natural woods, medium sparse	**Damaged by**	debris, overflow
Engineering Practice	None	**Priority of Mitigation**	High
Station Elevation	1,187 m	**Coordinate (TWD97)**	X: 235367 Y: 2602749
Protected Targets	**Residents**	**Facility**	**Transportation**
	> 5 households	school	roads, bridges

Table 2: The landslide area in Shenmu after 2009 (Huang, et al., 2013).

Debris Flow No.	Stream	Length (km)	Catchment Area (ha)	Landslide Area (ha)
DF199	Chusuei Stream	7.16	861.56	33.29
DF227	Huosa Stream	17.66	2,620	149.32
DF226	Aiyuzi Stream	3.30	400.64	99.85

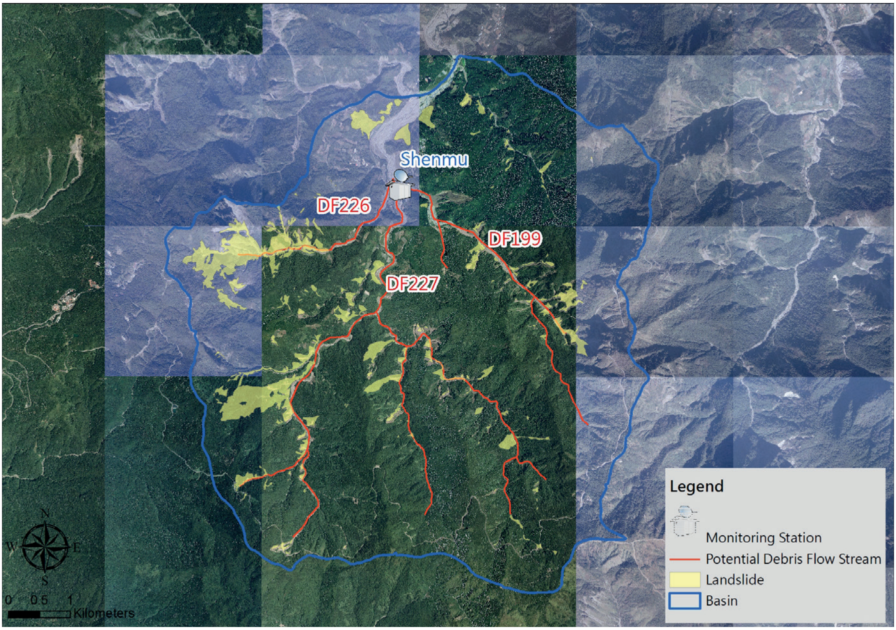

Figure 2: The landslide areas of Shenmu site (image taken in 2009 after Typhoon Morakot).

The sensors and instrument of rain gauges, geophones, broadband seismographs, wire sensors, and CCD camera were installed in the Shenmu Monitoring Station. The rain gauge is classified as the indirect option in the monitoring system to measure rainfall data. Most of researches about debris flow had been contributed in developing the relationship between the debris flow occurrence and rainfall. Rainfall is easy to measure and if a reasonable prediction model is using rainfall as a variable, it can provide a time window that can greatly improve the disaster warning and evacuation. The comparison of rainfall-based debris flow monitoring models can be made by model's rainfall indices: accumulative rainfall (R), rainfall intensity (I), and the duration (T) (Lee, 2006). Each rainfall index has its characteristics in modeling debris flow. Therefore, Jan and Lee (2004) promoted a model considering the influence of all rainfall indices (R, T, and I), and used debris flow cases to determine the rainfall thresholds of a given location. This method was adopted by SWCB and works for debris flow warning in Taiwan.

The direct option in debris flow monitoring system refers to the instruments and sensors that response when a debris flow actually occurs. Wire sensors, geophones and broadband seismographs are classified as this type. Wire sensors are simply steel wires crossing the river with signal transducers at ends. When a debris flow occurs, the flowing mass of debris will break the wire and results in a signal being sent out. Geophones and broadband seismographs are sensors installed along the river banks to detect ground surface vibration which comes

Table 3: Debris flow hazard history of Shenmu (after Huang, et al., 2013).

Date	Event	Location (stream)	Occurrence	Geophone Warning*	Hazard Type
2004/5/20	-	Aiyuzi	14:53	NA	debris flow
2004/5/21	-	Aiyuzi	16:08	NA	debris flow
2004/5/29	-	Aiyuzi	16:19	NA	debris flow
2004/6/11	-	Aiyuzi	16:42	NA	debris flow
2004/7/2	Typhoon Mindulle	Aiyuzi	16:41	NA	debris flow
2005/7/19	Typhoon Haitang	Chusuei, Aiyuzi	-	NA	flood
2005/8/4	Typhoon Matsa	Chusuei, Aiyuzi	-	NA	flood
2005/9/1	Typhoon Talim	Chusuei, Aiyuzi	-	NA	flood
2006/6/9	0609 Rainfall	Chusuei, Aiyuzi	about 08:00	NA	debris flow
2007/8/13	0809 Rainfall	Chusuei	-	NA	flood
2007/8/18	Typhoon Sepat	Chusuei	-	NA	flood
2007/10/6	Typhoon Krosa	Chusuei	-	NA	flood
2008/7/17	Typhoon Kalmaegi	Chusuei	-	NA	flood
2008/7/18	Typhoon Kalmaegi	Aiyuzi	-	NA	flood
2009/8/8	Typhoon Morakot	Chusuei,Aiyuzi, Huosa	08:00 (landslide) 16:57 (debris flow)	NA	landslide, debris flow
2010/9/19	Typhoon Fanapi	Huosa	-	NA	flood
2011/7/13	-	Aiyuzi	14:33	No	debris flow
2011/7/19	0719 Rainfall	Aiyuzi	3:19	No	debris flow
2011/11/10	-	Aiyuzi	13:17	Yes 13:18 (Nov 10)	debris flow
2012/5/4	-	Aiyuzi	15:56 16:09	No	debris flow
2012/5/20	-	Aiyuzi	8:15	No	flood
2012/6/10	0610 Rainfall	Aiyuzi	10:34 15:14	No (unstable communication)	debris flow
2012/6/11	0610 Rainfall	Chusuei	17:08	No	flood
2013	0517 Rainfall	Aiyuzi	7:02 (May 19)	No	flood
2013	Typhoon Saulik	Aiyuzi	6:54 (July 13)	Yes 6:47 (July 13)	debris flow
2013	Typhoon Trami	Aiyuzi	22:41 (Aug. 21)	NA (under repair)	flood
2014	0520 Rainfall	Aiyuzi	12:53 (May 20)	NA (unstable communication)	debris flow

*: the warning was issued when the max. accumulated wavelet energy was 5 times the background wavelet energy.

from the movement of debris in the channel. The warning level for debris flow by geophone signals was predefined based on its accumulated wavelet energy (Lee et. al., 2012), and is still under testing. When the warning was issued by the geophone, it was checked with the status of nearby wire sensors (broken or not) and the CCD image (in-situ conditions). As shown in Table 3, the warnings were not issued every time when a debris flow occurred in the past 5 years. This may because of the scale of debris flows and the geophone warning criteria. More study is needed on geophone warning criteria, and this paper will focus on the characteristics of debris flow vibration signals.

The layout of monitoring sensors is shown in Fig. 3. One geophone and two seismographs are installed at the Aiyuzi Stream. The geophone of GS-20 DX made by Geospace Tech. was used, which has clean band pass of 250 Hz and intrinsic sensitivity of 0.7 V/in/sec. The broadband of Yardbird DF-2 was first installed at the site in 2013, made by Institute of Earth Science, Academia Sinica Taiwan, with frequency measurement of 0.13~200 Hz, intrinsic sensitivity of 150 V/m/s, and 24 bit digital resolution. The signal data of z-direction (vertical) recorded by the geophone at the upstream and the broadband seismograph at the downstream of Aiyuzi Stream were used for analysis in this study.

Figure 3: The monitoring layout of Shenmu Station.

METHODS AND STUDY CASES

To analyze the vibration signals of debris flows, the signal was processed to convert the data into a time sequence of velocity. Fast Fourier Transform (FFT) was first applied to obtain the distribution of vibration frequencies. The filter method of Haar wavelet transform (Fang et al., 2008) was used in the signal analysis for geophone data, as well as to estimate the wavelet energy. The spectrograms of signal were plotted to illustrate the frequency characteristics from the broadband seismograph, and used to compare the signals of geophone and broadband seismograph.

Four cases in the past 5 years were used for analysis and comparison (Table 4). All of them were debris flow events. The scale of debris flow, small, medium, and large, was determined

Table 4: Wavelet energy change and time widow of warning of 4 events.

Year	Event	Max. hourly rainfall (mm)	Flow speed (m/s)	Warning announced*	DF[a] arrived**	Max. accumulated wavelet energy (J_{max})	Background wavelet energy (J_b)	DF?	DF mass	DF Scale	Used for analysis (G or BS)****
2011	1110 Rainfall	17	1.77	13:18	13:29	242.5	19.7	Y	mainly sediment (Ø <50 cm)	medium	G
2013	0530 Heavy Rainfall	15	~1.0	NA	~15:24	NA	31.45	Y	mainly sediment (Ø <20 cm)	small	BS
2013	Typhoon Saulik	51.5	8.52	6:47	6:54	7243.78	31.45	Y	mixed sediment (Ø >50cm)	large	G & BS
2014	0520 Heavy Rainfall	39.5	4.87	NA***	12:53	180.10	30.27	Y	mixed sediment (Ø >50cm)	medium to large	G & BS

*, **: the time recorded based on the geophone at the upper stream of Aiyuzi River.
***: communication unstable, no record.
****: G for geophone (GS-20 DX) and BS for broadband seismograph (Yardbird DF-2)
a: DF = Debris Flow

based on the maximum hourly rainfall, average flow speed, and the maximum accumulated wavelet energy.

RESULTS

The observation of three cases by the upstream geophone in the Aiyuzi Stream is shown in Fig. 4. It was noted that there peaks occurred in the signal before the arrive of debris flows. Fig. 5 shows the results of FFT, and it indicates that the significant frequency range of debris flow was less than 30 Hz in all three cases. The finding was in agreement with other researches (Fang et al., 2008). In order to understand the signature frequency, the Haar wavelet transform was applied to extract the signals of 0~31.25 Hz, as shown in Fig. 6. The signals of 0~31.25 Hz from the figure had more clear on peaks than those in Fig. 4. Therefore, the characteristic frequency of debris flow in Shenmu was about 0~31.25 Hz. In order to further analyze the relationship of signature frequency and the scale of debris flow, the spectrograms was used to find out the initial major frequency of debris flow front end.
The spectrograms are shown in Fig. 7. Although the noise appeared in the figure, the energy distribution with time was still recognizable. In this figure, the frequency at which the energy propagated by the debris flow started to increase (the color changed from blue to red) was about 10 Hz or less in the cases, except the case of 1110 Rainfall in 2011. When considered with the arrival time of debris flow (Table 4), it was noted that the energy of frequency about 5 Hz or less started to increase about 5 minutes (6:49) and 1 minutes (12:52) before the debris flow arrived at the location of geophone in the case of Typhoon Saulik 2013 and 0520 Heavy Rainfall 2014, respectively. However, due the sensitivity of the geophone, the signals at low frequencies (<10 Hz) were usually not easy to identify in the spectrograms. Nevertheless, the characteristic frequency of debris flow was implied to be 0~31.25 Hz and the front-end major frequency was less than 5 Hz.
Similar results were found in the broadband seismograph signals (Fig. 8). It is more significant to find the front-end major frequency (the white arrow in the figure) of about 2 Hz in the Typhoon Saulik 2013 case and about 5 Hz in the 0520 Heavy Rainfall 2014 case, which were

debris flows of large and medium to large scales, respectively. In contrast, the small debris flow of 0530 Rainfall 2013 had front-end major frequency of about 10 Hz (Table 5). Thus, the scale of a debris flow may be related to its front-end major frequency.

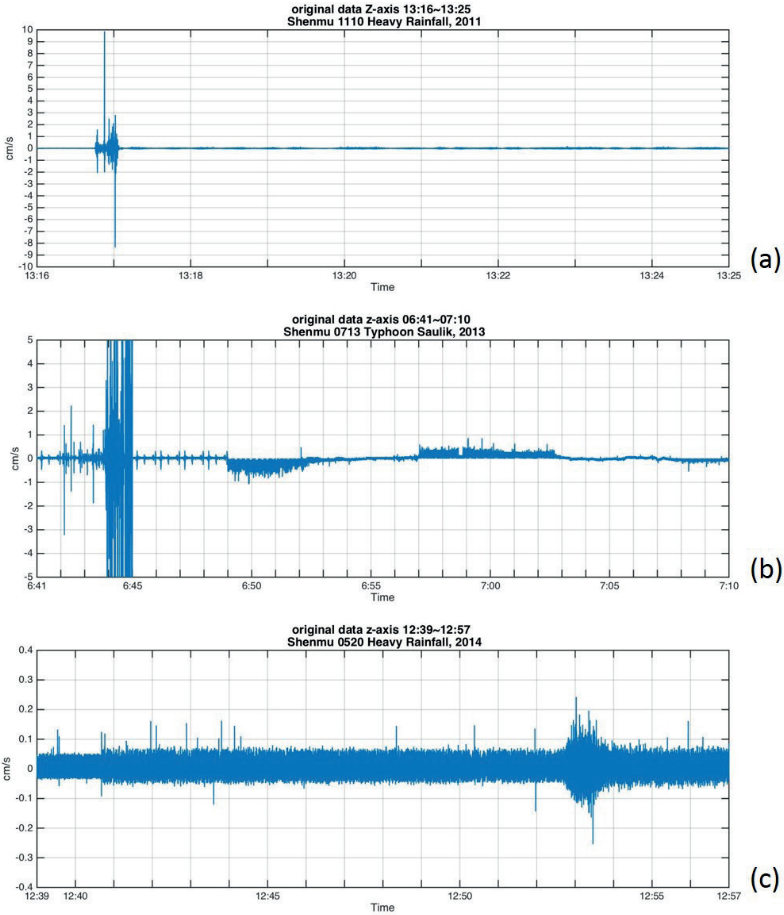

Figure 4: The vibration signals of the upstream geophone. (a) 1110 Rainfall (Nov. 10, 2011) (b) Typhoon Saulik (July 13, 2013) (c) 0520 Heavy Rainfall (May 20, 2014)

In addition to the rainfall, the warning to a debris flow in Shenmu was also considered by applying geophone data. The test warnings were announced based on the accumulated wavelet energy estimated by the signals of the upstream geophone in Aiyuzi Stream. When the accumulated wavelet energy is 5 times the background value (Table 4), the warnings will be sent. From the past events, the testing warning rule of 5 times the background wavelet energy was considerably applicable. The time window between the warning and the arrival of debris flows at the upstream geophone was about 9 minutes in average at the Aiyuzi Steam. The 9-minute time window may not useful for evacuation during disaster response, but the direct measure of vibration signals provided distinct evidence of debris flow occurrence. Compared with the geophone data, the time window between the detected front-end signal and the arrival at the downstream of Aiyuzi Stream was about 4 minutes in average by the signals of broadband seismograph (Table 6). Both geophones and broadband seismographs were practically useful.

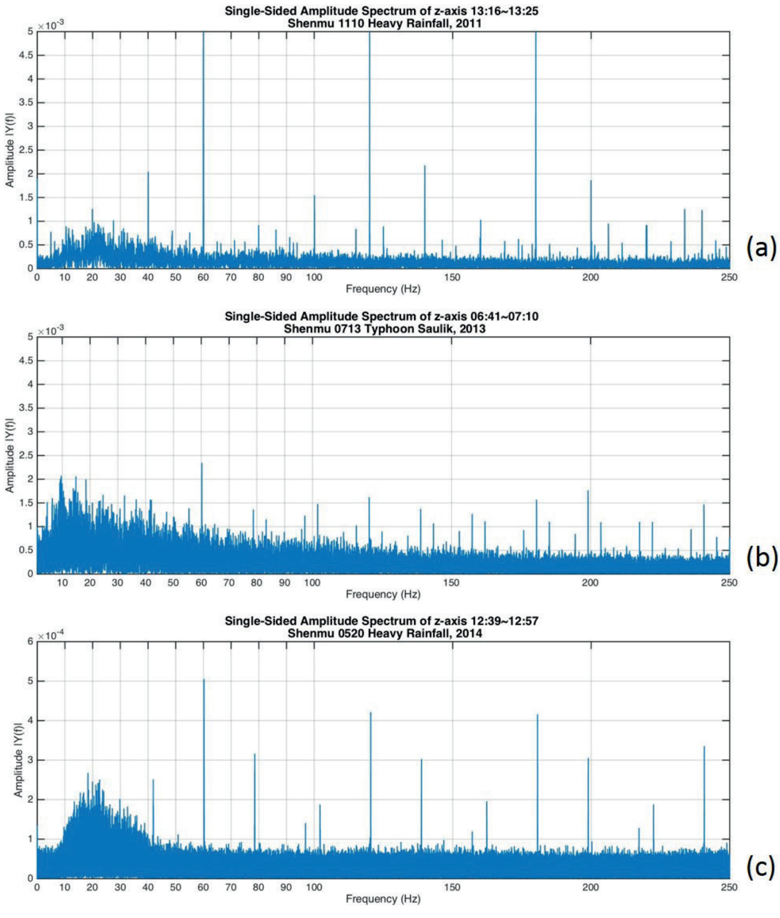

Figure 5: The FFT results of the geophone signals. (a) 1110 Rainfall (Nov. 10, 2011) (b) Typhoon Saulik (July 13, 2013) (c) 0520 Heavy Rainfall (May 20, 2014)

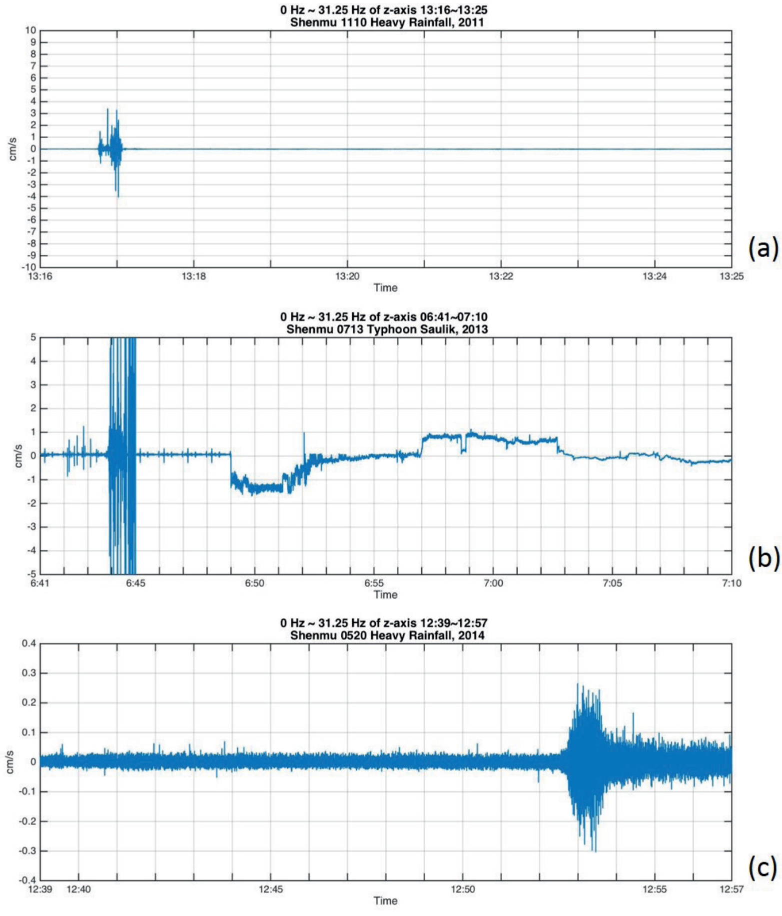

Figure 6: The signals of frequency 0~31.25 Hz of the upstream geophone. (a) 1110 Rainfall (Nov. 10, 2011) (b) Typhoon Saulik (July 13, 2013) (c) 0520 Heavy Rainfall (May 20, 2014)

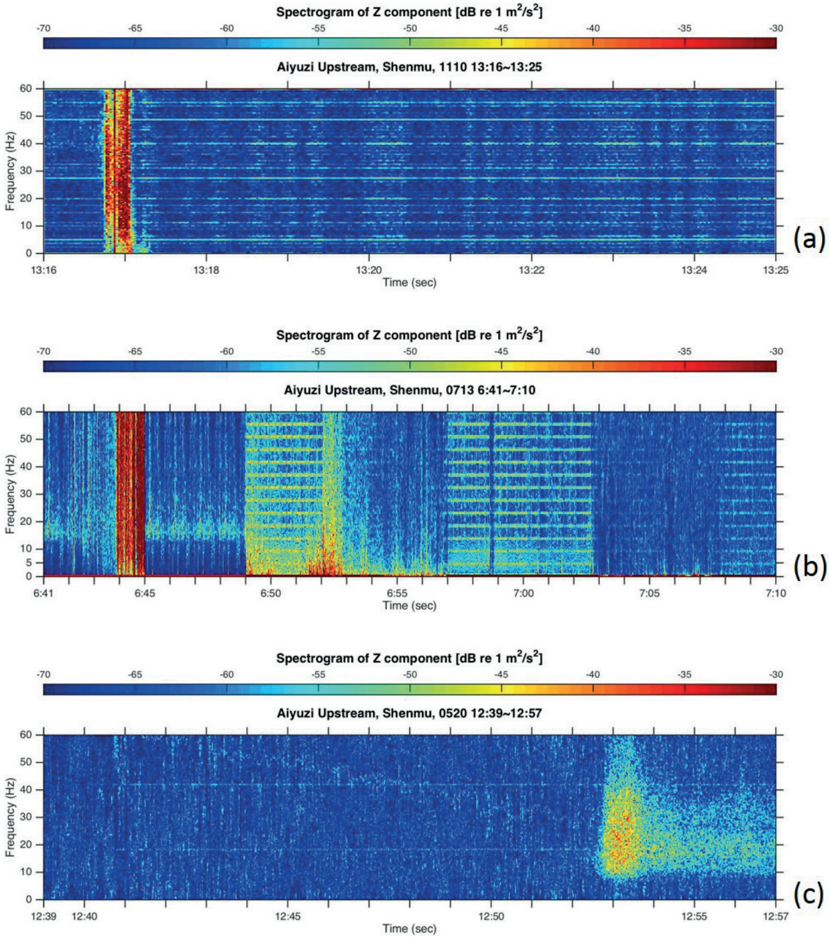

Figure 7: The spectrograms of signals at the upstream geophone. (a) 1110 Rainfall (Nov. 10, 2011) (b) Typhoon Saulik (July 13, 2013) (c) 0520 Heavy Rainfall (May 20, 2014)

Table 5: Broadband major frequency and the scale of debris flows.

Event	Date	Scale	Flow speed	Major frequency
1	2013/5/30	small	~ 1 m/s	11 Hz
2	2013/7/13	large	~ 10 m/s	2 Hz
3	2014/5/20	median	~ 5 m/s	5 Hz

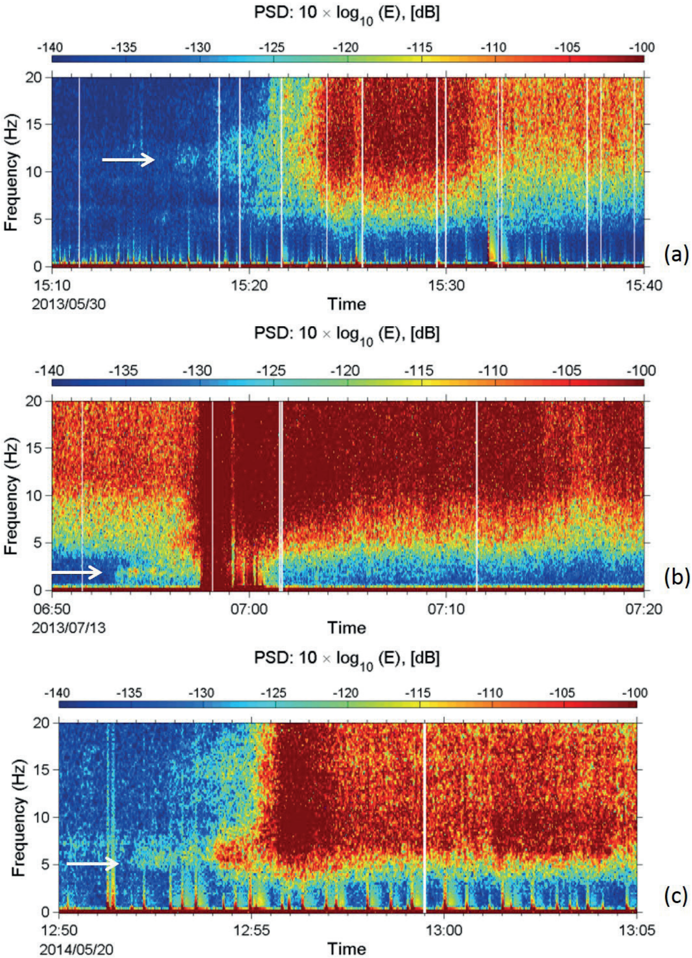

Figure 8: The spectrograms of broadband seismograph in Aiyuzi River during (a) 0530 Rainfall 2013 (b) Typhoon Saulik in 2013 (c) 0520 Heavy Rainfall in 2014.

Table 6: Time earlier of observed frequency by the broadband seismograph at downstream to the occurrence of debris flow (6:57:39) during Typhoon Saulik 2013.

Observed Frequency	Recorded Time	Time earlier
2 Hz	6:53:25	4 m 14 s
8 Hz	6:57:02	37 s
20 Hz	6:57:25	14 s
Peak wave	6:57:39	0

CONCLUSION

The data of broadband seismographs and geophones along the Aiyuzi River in Shenmu was used in this study, as well as 4 debris flow events. The frequency range of 0~10 Hz (broadband seismograph) and 0~31.25 Hz (short period seismograph) were practically suitable for debris flow warning in terms of vibration characteristics. It was noted that large debris flows had signature frequency less than 10 Hz, and the small to median debris flows usually had signature frequency greater than 10 Hz. The time window of response to the debris flow was about 4 minutes for broadband seismographs and 9 minutes in average for geophone from the cases in Shenmu. Warning levels of geophone signal were suggested to be 5 times the background energy (in joule) for debris flow warning. Overall, the study showed that the direct method of geophones and broadband seismograph was practically promising for debris flow monitoring.

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