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ANALYSIS OF DEBRIS FLOW UNDERGROUND SOUND BY WAVELET TRANSFORM - A CASE STUDY OF EVENTS IN AIYUZIH RIVER

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ABSTRACT

Since 2002, the Soil and Water Conservation Bureau, which is responsible for the conservation and administrative management of hillside in Taiwan, has been cooperating with Feng Chia University. Together, they have successively carried out the establishment and maintenance of 17 debris flow monitoring stations over the Taiwan and 3 mobile debris flow monitoring stations. Geophone is one of the most important sensor to detect whether debris flow occur or not. The wavelet transform is employed in this study to analyze the underground sound of debris flows obtained from the geophones. Three debris flow events observed at Shenmu monitoring station (Nantou County) on July 2, 2004 and on August 8, 2009 are selected as examples. It is found that the wavelet transform not only can separate ambient noise effectively but also can be used to determine the beginning time of debris flow event. In order to estimate the magnitude of debris flow event, a so-called wavelet accumulated energy indicator is proposed. When debris flow occurs, the wavelet accumulated energy will increase. So the wavelet accumulated energy's threshold value is double of normal value. It can be used to determine the occurrence of debris flow and to estimate its magnitude.

KEY WORD: *geophone, debris flow underground sound, wavelet transform, wavelet energy accumulated indicator*

INTRODUCTION

Taiwan locates in the circum-Pacific seismic zone and frequent seismicity results in loose topsoil in the mountainous areas. When rainy season comes, typhoons accompanied by heavy rain usually cause severe disaster in Taiwan. Because of common existence of steep slopes, intensive precipitation, and piled-up sediment in the area, debris flow is not uncommon to occur. Debris flows have occurred more often after the Chi-Chi Earthquake in 1999 and Typhoon Toraji in 2001. The increase of debris flow has struck Taiwan badly in terms of economic and environmental loss. Debris flow has become a pronoun of landslide-related hazards in Taiwan. Because of the concerns of serious impacts, a debris flow monitoring system has been developed to capture debris flows before and after their occurrence. The monitoring system has not only provided data for debris flow researches, but also helped local agencies on disaster response with a real-time warning system. The Soil and Water Conservation Bureau (SWCB) of Council of Agriculture has established 17 permanent debris flow monitoring stations which has effectively enhanced government's capability of emergency response.

In order to obtain ground vibrations during a debris flow, two sets of geophones were installed in a serial manner at Aiyutze River. The downstream geophone was set at the right bank of river, close to Aiyutze Bridge. The midstream geophone was installed about 178 m away from the bridge. The two sets were

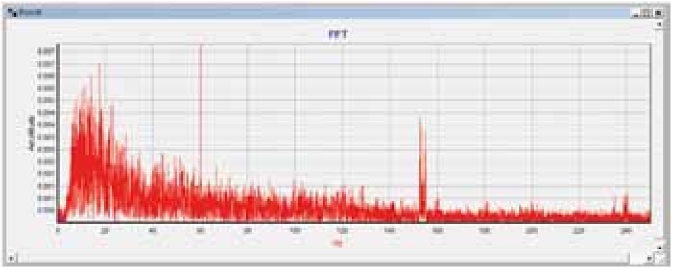

Fig.1 - The FFT analysis of x axis located at downstream from 16:41 to 16:42 on July 2, 2004

173 m apart. Triaxial geophones made by Geospace Co. were used and the measurable frequency ranges between 8 to1500 Hz.

The characteristic of frequency generated by collision and friction between sand and cobbles inside a debris flow should be at a low frequency range, which is distinctive from signals of water flowing, rain, wind, and voltage noises. However, high sampling rate should still be applied in measurement, because high frequency signals cannot be excluded. Accordingly, this study used sampling rate of 500 Hz, with maximum effective frequency of half 500 Hz, i.e., 250 Hz.

In this paper, current signal analysis methods for geophones have been explored to find an approach which can identify a debris flow quickly and effectively. The proposed approach can allow engineers to discover the variation of signals when a debris flow is about to happen, and determine the scale of hazard during an event. The signal analysis of geophones, as a result, can improve the public's response to debris flow disasters.

GEOPHONE SIGNAL ANALYSIS

FAST FOURIER TRANSFORM (FFT) ANALYSIS

Geophone measures the signals of ground vibration caused by large cobbles rolling on, friction against and colliding with channel bed in a debris flow. Such signal of vibration, also known as underground sound of debris flow, propagates through soil or on the ground surface. Wu *et alii* (1990), who obtained data from 18 debris flows using piezo-electric ceramic geophones, indicated that the soil composition and particle size can affect the characteristics of frequency of debris flow. After FFT, their analyses show that the frequency ranges mostly between 25 to 80 Hz.

Arattano (2003) analyzed the signals of four debris flows at Moscardo, Eastern Italian Alps. He found that the amplitude reached a maximum when the debris flow surged over the geophone, showing a peak on the graph. Also found in his study was that the average velocity of debris flow can be estimated when using two adjacent measuring geophones with known distance. Itakura *et alii* (1997) measured the signals of debris flows at Nojiri River and found that the predominant frequency of debris flow ranged in 20-60 Hz. Liu (1999) revealed that, from lab and field experiments, particle size was not a factor and the frequency recorded ranged mostly between 20-80 Hz, particularly 40-60 Hz. Richard (1996) at U.S. Geological Survey (USGS) also found that the frequency of a debris flow ranges between 10-300 Hz, with evident frequency of 30-80 Hz.

SWCB successfully collected the first representative data of debris flow, since the establishment of monitoring stations, at Shenmu Village in Nantou County during Typhoon Mindulle in 2004. The geophone signals obtained from Aiyutze River were analyzed by FFT, as shown in Fig. 1. The figure shows that the predominant frequency is between 10-60 Hz with peak of amplitude at 20 Hz. Fang *et alii* (2008) analyzed same debris flow and found that the frequency of geophone was in a relatively lower range of 5-60 Hz.

Most of the documents mentioned above utilized FFT to transform signals from time domain into frequency domain, and determined the occurrence of debris flow by evaluating characteristics of low frequency range. However, using FFT to analyze non-stationary, instantaneous signals may cause frequency distortion as a result. The vibration signals of a debris flow are transient, non-periodical, and non-stationary. To improve frequency distortion, Huang (2005) and Hsieh (2004) used the Gabor Transform to perform signal analysis. Gabor Transform has capability of describing the characteristics of instantaneous signals in terms of frequency and time domains. Yet both FFT and Gabor Transform require more computation time that makes the system unable to evaluate debris flow signals in a real-time manner. At current, most signal analyses are conducted after debris flow events. Therefore, it is necessary to develop an analysis procedure for geophone signals which could allow real-time indication of debris flow for decision makers.

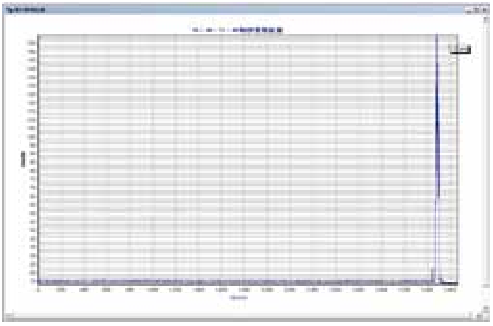

Fig.2 - The accumulated energy of geophone located at downstream from 16:00 to 17:00 on Aug 8, 2008

ACCUMULATED ENERGY

Conventional FFT analyses take large amount of computations and cannot perform real-time evaluation of geophones for debris flows. Lin & Liu (2005) used the method of energy integration to analyze characteristics of debris flow and found that there exists a notable spike in accumulated energy of known debris flow incidents. An accumulated energy, thus, is defined as the integration of 500 records per second over the time history of velocity. The accumulated energy represents the work (in Joule), product of force and displacement, from a debris flow. The estimated accumulated energy will be immediately transmitted back to the monitoring center and used for debris flow prediction. Figure 2 shows the accumulated energy per second from the downstream geophone of Aiyutze River during the debris flow on July 2, 2004.

As monitoring equipments have to continuously monitor potential debris flow torrents 24 hours a day, noises can occur in geophone recordings whenever the spot light is turned on at night or a generator starts in case of power failure. These noises are analyzed, by FFT, to be multiples of 60 Hz, which is at higher frequency range. Because the accumulated energy per second uses time history of geophone data, the power generator and spotlight switch can affect the energy estimated, influencing the determination of debris flow incident.

Therefore, a new method utilizing wavelet transform proposed by the authors provides a solution to resolve the drawbacks of FFT and energy estimation for geophone signal analysis.

METHOD OF ANALYSIS WITH WAVELET TRANSFORM

In order to effectively capture the vibration signals, wavelet analysis is employed to separate signals into various bands of frequency, from which the characteristic frequency range can be selected to further signal process. The wavelet transform shows the advantage of processing non-stationary signals and the capability of indicating signals of unbalanced vibration.

Yang (2006) mentioned that one feature of wavelet analysis is that the resulting transform differs with the selection of mother wavelet. Thus, a mother wavelet with specific characteristics can be chosen according to different requirements. Wavelet transform can reach better screening results when using short-time and long-time windows for higher and lower frequencies, respectively. Hence, wavelet analysis is suitable for non-stationary and instantaneous signals of geophones. The method of Haar mother wavelet was applied and studied in this paper.

Kristian (2000) study shows that the orthogonal set of Haar wavelets is composed of a group of square waves with amplitude of ±1 in certain intervals and 0 in others:

Definition 1 (The Haar Scaling Function)

Let *Φ* a scaling function and can be defined as

$$\phi(t) = \begin{cases} 1 & t \in [0,1) \\ 0 & t \in [0,1) \end{cases} \tag{1}$$

Eq. (1) is a lowpass function as shown in Fig. 3(a). The general form can be expressed as

$$\phi_i^j(t) = \sqrt{2^j}\,\phi(2^j t - i) \quad \text{and } j=0,1,\ldots \text{ and } i=0,1,\ldots,2^j-1.$$

where $\Phi_0^0(t)=\Phi(t)$ implies the special case. The general expression forms a vector space, Wj, as follow.

$$V^j = sp\{\phi_i^j\}_{i=0,\ldots,2^j-1}$$

where *sp* denotes the linear space, *j* is related with function expansion, and i is related with function shift. The normalization constant $\sqrt{2^J}$ is chosen such that $<\phi_i^j, \phi_i^j> = \int_0^1 \phi_i^j(t)^2 dt = 1$.

If one considers the wavelet function on other intervals rather than [0,1], the normalization constant will change.

Definition 2 (The Haar Scaling Function)

Let *ψ* the mother wavelet function and can be defined by

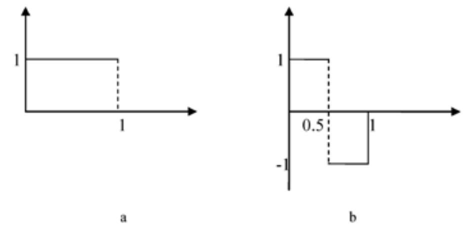

Fig. 3 - The define function of Haar wavelet transform; 3a Lowpass function, 3b Highpass function

$$\psi(t)=\begin{cases}1 & t\in[0,\frac{1}{2})\\ -1 & t\in[\frac{1}{2},1)\\ 0 & t\notin[0,1)\end{cases} \tag{2}$$

Eq. (2) is a highpass function as shown in Fig. 3(b). The general form can be expressed as

$$\phi_i^j(t)=\sqrt{2^j}\,\phi(2^j t-i) \text{ and } j=0,1,\ldots \text{ and } i=0,1,\ldots,2^j-1.$$

where $\Phi_0^0(t)=\Phi(t)$ implies the special case. The general expression forms a vector space, W^j, as follow.

$$V^j=sp\{\phi_i^j\}_{i=0,\ldots,2^j-1}$$

where *sp* denotes the linear space, *j* is related with function expansion, and i is related with function shift. The normalization constant √2 is chosen such that $<\phi_i^j,\phi_i^j>=\int_0^1 \phi_i^j(t)^2dt=1$.

We consider a signal, *f*, with 8 samples. The procedure to be described can be applied to any finite signals. The analysis can be simplified if the length (dimension) of the signal is *2K*, where *K* is positive integer. Let *f* expand to space of $V^0\oplus W^0\oplus W^1\oplus W^2$ where $\oplus$ denotes addition of spatial vectors. Then, according to Definition 1 and 2, we can get the following expression.

$$\begin{aligned}&=<f,\phi_0^0>\phi_0^0+<f,\psi_0^0>\psi_0^0+<f,\psi_0^1>\psi_0^1+<f,\psi_1^1>\psi_1^1+\\&<f,\psi_0^2>\psi_0^2+<f,\psi_1^2>\psi_1^2+<f,\psi_2^2>\psi_2^2+\\&<f,\psi_3^2>\psi_3^2\end{aligned} \tag{3}$$

where $<f,\Phi_i^j>$ and $<f,\psi_i^j>$ are the inner products of spatial vectors, Φ_i^j and ψ_i^j represents averaging and differencing values. The number of computations should be 2 to the power of n. The expressions above can also be used as filter for signals. The averaging value corresponds to a lowpass filter and it can filter out high frequency signals. Since the partial signals of significant change correspond to high frequency parts, the averaging procedure tends to smooth the data. For Harr wavelets, the lowpass filter can be expressed as the average of two consecutive signals. The differencing values correspond to highpass filter, which can filter out low frequency signals. Since the noises usually occur at high frequency ranges, the Harr wavelets can detect the noises and reflect the signals.

Let f(Hz) represent the effective frequency of signal, f, and the frequency range can be divided into the portions of Low and High frequencies, after n times of wavelet transform. The low frequency is represented by L1 and H1~Hn, represent the high frequency range. Equations are expressed as follows.

$$f(Hz)=L_1(Hz)+H_1(Hz)+H_2(Hz)+\cdots H_n(Hz)$$

where

$$L_1(Hz)=0\sim f(Hz)/2^n$$

$$H_1(Hz)=f(Hz)/2^n\sim f(Hz)/2^{n-1}$$

$$H_2(Hz)=f(Hz)/2^{n-1}\sim f(Hz)/2^{n-2}$$

$$\ldots$$

$$H_n(Hz)=f(Hz)/2^1\sim f(Hz)/2^0$$

As the equations define, in the interval [0,1), every Haar wavelet comprises exactly one wavelet at certain intervals and 0 at others. Therefore, the Haar set forms a partial base, and the zeros of an interval make Haar wavelet transform easier and faster than any other transform methods. Because wavelet transform divides signals into low and high frequencies, it is similar to Fourier transform. Since the characteristics of different signals (background noise) correspond to different frequencies, the signal process using wavelet transform is an important method for geophone data analysis.

The Haar wavelet transform can divide the geophone signals into two portions of high and low frequency zones. This study used sampling rate of 500 Hz with effective frequency of 250 Hz. The authors found that in analyzing the geophone signals at Aiyutze River, the characteristic frequency of spike was at about 20 Hz. After three times of wavelet transform, the low frequency range of 0-31.25 Hz was considerably suitable to represent the signals of debris flow in Aiyutze River. In comparison to this finding, four times of wavelet transform which resulted in frequency range of 0-15.63 Hz, implying overlook of the spike, and two times transform which had frequency of 0-62.5 Hz, including the equipment voltage frequency

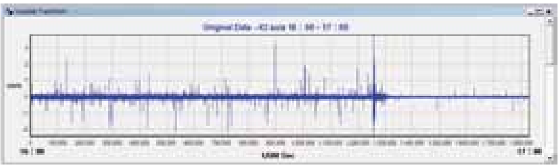

Fig. 4 - The original data located at downstream from 16:00 to 17:00 on July 2, 2004

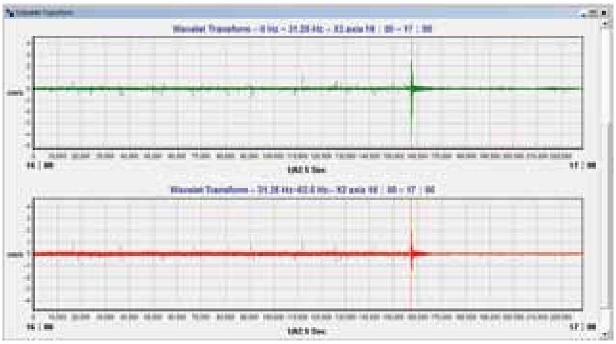

Fig. 5 - The wavelet transform result of lower frequency located at downstream from 16:00 to 17:00 on July 2, 2004

of 60 Hz, were both not appropriate. Therefore, the application of three times of wavelet transform had been conducted as standard procedure in this study.

CASE STUDIES OF GEOPHONE SIGNAL ANALYSIS

TYPHOON MINDULLE

In 2004, Taiwan was stricken by Typhoon Mindulle during June 28 to July 3. The monitoring station at Aiyutze River captured the debris flow first time after the establishment of monitoring system. The accumulated precipitation was high up to 1,254 mm in three days (July 2 to 4), and the heavy rain had triggered landslides in the upstream area, resulting in debris flows and caused serious damage to downstream facilities.

The debris flow incident, occurred at 4:41 p.m. on July 2, was observed by two sets of geophones deployed along the Aiyutze River. The signal of downstream geophone (in Fig. 4) was analyzed by wavelet transform and separated into low and high frequency parts, as shown in Fig. 5. It is clear from the figure to view the spike indicating the occurrence of debris flow when in the frequency range of 0-31 Hz. Similar result can be found for frequency of 31-62 Hz. These results show the success of wavelet transform and support the low-frequency.

TYPHOON MORAKOT

During Typhoon Morakot in August, 2009, the monitoring station at Aiyutze River captured two incidents of debris flow. The accumulated precipitation was measured as high as 1,596.5 mm during the five-day period (Aug. 6 to 10) of heavy rain. The rainfall had caused massive collapse in the upstream of Aiyutze River, and the triggered debris flow had seriously damaged the Aiyutze Bridge.

The first event of debris flow on August 8 caused the wire broken in the upstream of Aiyutze River. Figure 6 shows the time history of rainfall and the timing of wire rupture.

The signal analysis of geophones for the debris flows at 4:38 and 16:57 on August 8 reveals obvious signal vibration in either time history or wavelet transform, as shown in Fig. 6and 7. The evidences from wire ruptures, character frequencies in the wavelet transform, and CCD images confirm that a debris flow did occur at Aiyutze River during Typhoon Morakot. Based on the records of geophones in the midstream and downstream of Aiyutze River, the flowing velocity of debris flow events is 17 m/sec, respectively, as shown in Fig. 8.

WAVELET ACCUMULATED ENERGY INDICATOR

We compared the total precipitation of two typhoons on July 2, 2004 and Aug. 08, 2009 and found that on July 2, 2004, the accumulated 3-day precipitation was 1,254 mm (418 mm/day in average), and 1,596.5 mm over four days (399 mm/day in average) on Aug. 08, 2009. The maximum 10-minute rainfall intensities were of 70 and 80 mm, respectively. The two incidents were thus similar in both accumulated rainfall and rainfall intensity. From the analysis results in previous sections, the debris flow of Aug. 08 was greater in scale than that of July 2.

As the wavelet transform has been verified that it is possible to filter out the high frequency portion from

Fig. 6 - The original data located at downstream from 16:00 to 17:00 on August 8, 2009

Fig. 7 - The wavelet transform result of lower frequency located at downstream from 16:00 to 17:00 on August 8, 2009

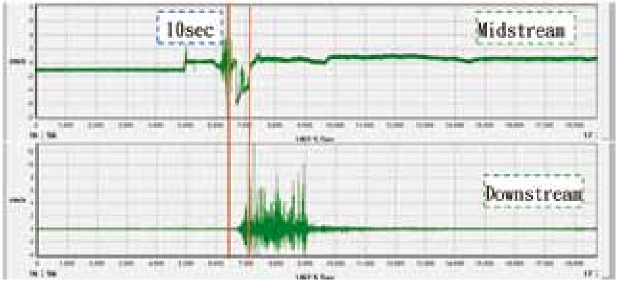

Fig.8 - The wavelet transform result at upstream and downstream from 16:56 to 17:00 on August 8, 2009

the original ground vibration time history, only the low frequency portions were considered from events of 2004/07/02 and 2009/08/08, and the resulting accumulated energy are shown in Fig. 9 and 10. It can be seen from the figures that when debris flow arrives, the wavelet energy accumulation increases significantly. Compared to accumulated energy per second, as previously mentioned, the energy after wavelet transform accumulates only over the low frequency portion of the ground vibration history and the results are not affected by interference of environmental signals and can better serve in the determination of debris flow triggering. Therefore, the energy accumulation after wavelet transform can be used as an indicator, Wavelet Energy Indicator, for debris flow evaluation.

The Wavelet Energy Indicator was applied to debris flows of July 02, 2004, and Aug. 08, 2009, in the Aiyutze River area. After applying wavelet transform and estimating accumulated energy, energy indicators of background and three scales were set for reference, as shown in Table 1. A debris flow is determined to occur when the estimated wavelet energy is twice or greater than the background value. This energy indicator will be sent with other data back to the monitoring station and served as a factor to determine the scale and occurrence of debris flows.

CONCLUSIONS

1. Wavelet transform can isolate different ranges of frequency from a whole time domain, and can indicate directly the characteristic lower frequency range of debris flow, as well as filtering out the higher frequency range.

2. Superposing a number of sequences of wavelet-transformed lower and higher frequency ranges can obtain the original signal sequence. The Haar transform is the original and simplest transform function.

3. It is useful to obtain high and low frequency ranges by applying wavelet transform three times to the original geophone data. The energy indicator estimated over the low frequency range can be used to determine the occurrence and scale of a debris flow.

4. The energy indicators for downstream area of Aiyutze River was estimated and determined based on the incidents of July 02, 2004, and Aug. 08, 2009. More debris flow data will be gathered in the near fu-

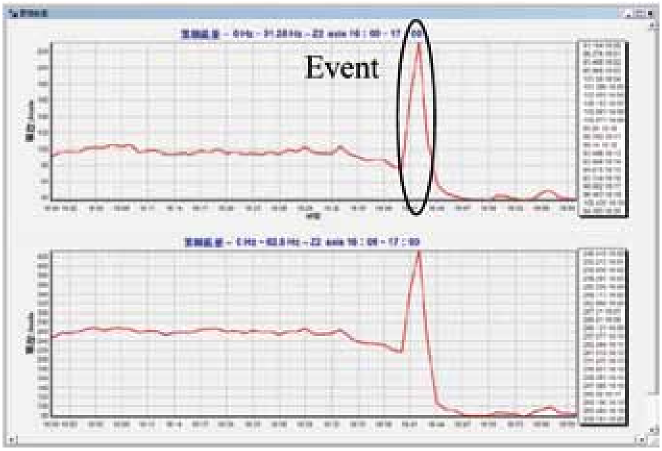

Fig. 9 - The accumulated energy of geophone using wavelet transform located at downstream from on July 2, 2004

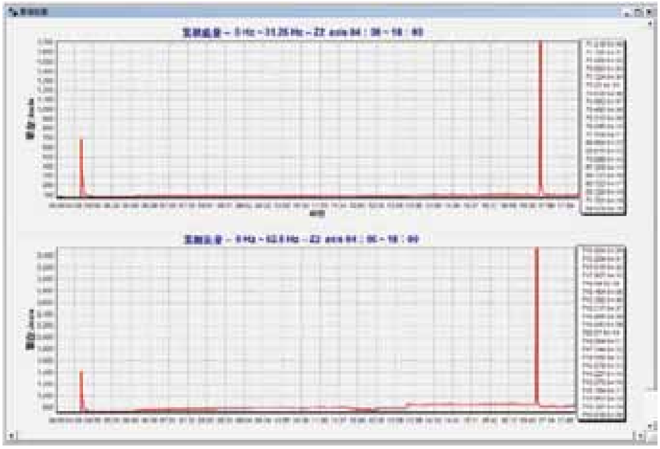

Fig. 10 - The accumulated energy of geophone using wavelet transform located at downstream from on July 2, 2004

Scale of events	background	2004/07/02 16:41	2009/08/08 4:38	2009/08/08 16:57
Value	100	230	691	1712
multiple	--	double	sextuple	octuple

Tab. 2 - The Indicator value of geophone located at downstream (unit: Joule)

ture to update the indicators and to establish the debris flow database.

5. Featuring fast and effective analysis for geophone signals, the method proposed in this study can be installed directly on the computers at a monitoring station. When a debris flow is about to occur, the on-site computer can conduct wavelet transform and send back the results for further analysis.

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