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THE PRESENT DEVELOPMENT OF DEBRIS FLOW MONITORING TECHNOLOGY IN TAIWAN – A CASE STUDY PRESENTATION

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ABSTRACT

In order to document the on-site debris flow events, the Soil and Water Conservation Bureau (SWCB), Council of Agriculture, Taiwan, has devoted to develop the debris flow monitoring system since 2002. This paper introduces the technology of 17 on-site and 3 mobile debris flow monitoring stations established by SWCB in Taiwan. In each on-site monitoring station, several observation instruments including rain gauges, CCD cameras, wire sensors, geophones, and water level meters were installed to collect the dynamic debris flow information that can be used as the references for countermeasures of debris flow disaster mitigation. Besides, several meteorological sensors are also adopted recently in order to record the long-term climate change effects on the slopeland of Taiwan. The framework of the debris flow monitoring system consists of monitoring sensors, instrumental cabin (vehicle platform for mobile station), transmission system and web-based display system. During the typhoon Mindulle period in 2004, a debris flow event in Aiyuzih creek was observed by the Shenmu debris flow monitoring station on July 2, Nantou County, central Taiwan. On-site observation data including the rainfall patterns, video images, wire sensor ruptures and ground vibrations caused by debirs flows are analyzed in detail.

***Key word**: debris flows, debris flow monitoring system, mobile debris flow monitoring station*

INTRODUCTION

Taiwan's steep topographical features, young and weak geological formations, earthquakes, erodible soils and heavy rainfall cause landslides and debris flows on the island, which often result in extensive human lives and property losses. Although there were quite a few debris flow events in the past few years, little field observation data were obtained from actual debris flow hazards. The lack of field data might result in slow research progress of debris flows. To improve the capability of collecting field data, the Soil and Water Conservation Bureau (SWCB), Council of Agriculture has started the debris flow monitoring project since 2002. So far, 17 on-site and 3 mobile debris flow monitoring stations have been established around Taiwan.

Various studies have investigated the debris flow observation works. Wu *et alii* (1990) observed various characteristics and mechanism of debris flows at the Jiangjia Gully observation and research station, Yunnan Province, China. A lot of field debris flow data were recorded and several real-time warning systems were proposed using precipitation, ground vibrations and ultrasonic mud-level measurements. Berti *et alii* (2000) mentioned the field monitoring system installed in Acquabona Creek in the Dolomites (Eastern Italian Alps). A double threshold controlled by the geophone signals and rain intensity is adopted for the switch between two different operation modes. Lavigne *et alii* (2000) used rain gauges and various ground vibration sensing systems to monitor more than 50 volcanic debris flows or lahars generated around Mount Merapi in Indonesia. MARCHI *et alii* (2002) discussed the debris flow monitoring works in the Moscardo Torrent (Italian Apls). The monitoring system consists of different sensors was adopted to measure the rainfall, flow stage and ground vibrations caused by debris flows. HÜRLIMANN *et alii* (2003) discussed the field data of debris flows events occurred at the Swiss Alps. The real-time data of debris flows were gathered by debris-flow observation stations equipped with video cameras, ultrasonic devices, a radar device, geophones, and rain gauges. BADOUX *et alii* (2008) described debris-flow detection and alarm systems using a wide range of detection sensors for the Alpine Illgraben catchment, Switzerland. In Taiwan, LIU & CHEN (2003) developed an integrated debris flow monitoring system with various sensors. They classified the operation of the integrated debris flow monitoring system into three stages according to different criteria of the rain gauge, ground water level and ground vibrations. YIN *et alii* (2007a) introduced the establishment and various specifications related to the debris flow monitoring system in Taiwan. The main purpose of this paper is to introduce the framework and operation mechanism of the on-site and mobile debris flow monitoring stations established by the SWCB in Taiwan. In 2004, a debris flow event in Aiyuzih creek caused by typhoon Mindulle on July 2 was recorded by the Shenmu debris flow monitoring station. The field observation data are analyzed and discussed in detail herein.

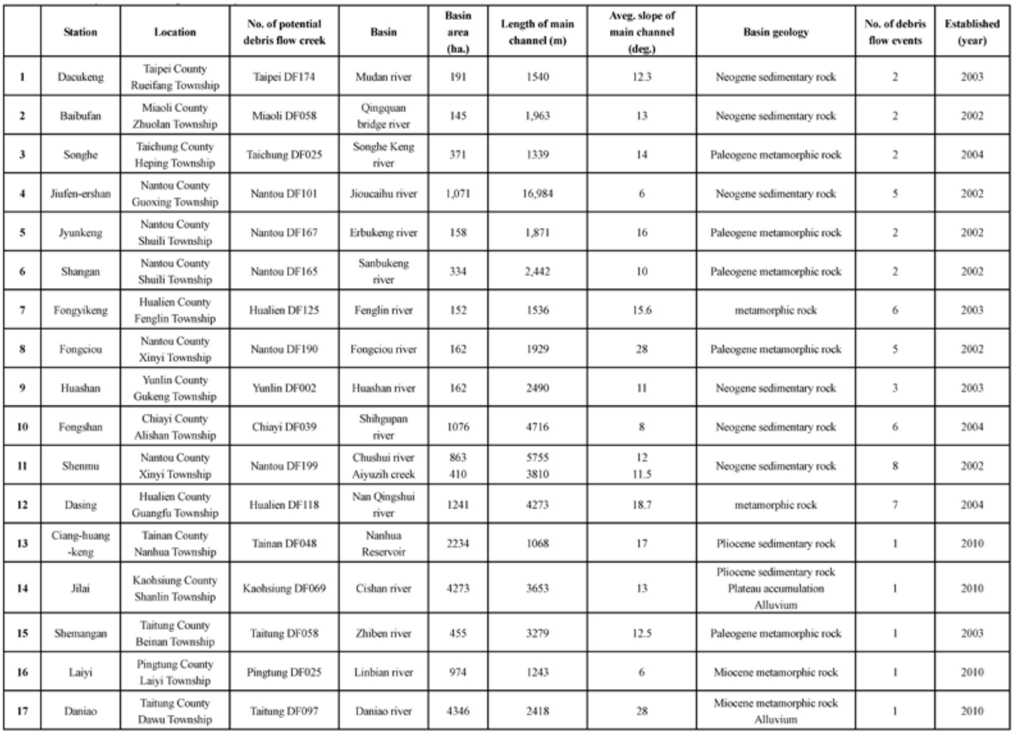
ON-SITE DEBRIS FLOW MONITORING STATION

The framework of the on-site debris flow monitoring station mainly consists of monitoring sensors, the instrumental cabin, the transmission system and the web-based display system. In Taiwan, the current 17 on-site debris flow monitoring stations are located at the vicinity of potential debris flow torrents which are prone to debris flows as shown in Fig. 1 and Table 1. According to the survey of SWCB, there are 1552 potential debris flow torrents around Taiwan island. The investigation of these torrents is primarily based on the features of the hydrology, geography, geology and protected objects (population and/or infrastructure) in the field. Originally, in each monitoring station, five primary observation sensors including rain gauges, infrared CCD (charge-coupled device) cameras, wire sensors, geophones and an ultrasonic water level meter are adopted to detect debris flows. Recently, several meteorological sensors such as light meters, thermo-hydrometers, anemometers, wind direction vanes, soil moisture probes and barometers are put to use in order to record the long-term effects of climate change on the slopeland of Taiwan.

Fig. 1 - Distribution of 17 on-site debris flow monitoring stations in Taiwan

Fig. 2 - Instrumental cabin of Jiufen-ershan station in Nantou County.

In the field, all the observation data detected by



	Station	Location	No. of potential debris flow creek	Basin	Basin area (ha.)	Length of main channel (m)	Aveg. slope of main channel (deg.)	Basin geology	No. of debris flow events	Established (year)
1	Dacukeng	Taipei County Rueifang Township	Taipei DF174	Mudan river	191	1540	12.3	Neogene sedimentary rock	2	2003
2	Baibufan	Miaoli County Zhuolan Township	Miaoli DF058	Qingquan bridge river	145	1,963	13	Neogene sedimentary rock	2	2002
3	Songhe	Taichung County Heping Township	Taichung DF025	Songhe Keng river	371	1339	14	Paleogene metamorphic rock	2	2004
4	Jiufen-ershan	Nantou County Guoxing Township	Nantou DF101	Jioucaihu river	1,071	16,984	6	Neogene sedimentary rock	5	2002
5	Jyunkeng	Nantou County Shuili Township	Nantou DF167	Erbukeng river	158	1,871	16	Paleogene metamorphic rock	2	2002
6	Shangan	Nantou County Shuili Township	Nantou DF165	Sanbukeng river	334	2,442	10	Paleogene metamorphic rock	2	2002
7	Fongyikeng	Hualien County Fenglin Township	Hualien DF125	Fenglin river	152	1536	15.6	metamorphic rock	6	2003
8	Fongciou	Nantou County Xinyi Township	Nantou DF190	Fongciou river	162	1929	28	Paleogene metamorphic rock	5	2002
9	Huashan	Yunlin County Gukeng Township	Yunlin DF002	Huashan river	162	2490	11	Neogene sedimentary rock	3	2003
10	Fongshan	Chiayi County Alishan Township	Chiayi DF039	Shihgupan river	1076	4716	8	Neogene sedimentary rock	6	2004
11	Shenmu	Nantou County Xinyi Township	Nantou DF199	Chushui river Aiyuzih creek	863 410	5755 3810	12 11.5	Neogene sedimentary rock	8	2002
12	Dasing	Hualien County Guangfu Township	Hualien DF118	Nan Qingshui river	1241	4273	18.7	metamorphic rock	7	2004
13	Ciang-huang-keng	Tainan County Nanhua Township	Tainan DF048	Nanhua Reservoir	2234	1068	17	Pliocene sedimentary rock	1	2010
14	Jilai	Kaohsiung County Shanlin Township	Kaohsiung DF069	Cishan river	4273	3653	13	Pliocene sedimentary rock Plateau accumulation Alluvium	1	2010
15	Shemangan	Taitung County Beinan Township	Taitung DF058	Zhiben river	455	3279	12.5	Paleogene metamorphic rock	1	2003
16	Laiyi	Pingtung County Laiyi Township	Pingtung DF025	Linbian river	974	1243	6	Miocene metamorphic rock	1	2010
17	Daniao	Taitung County Dawu Township	Taitung DF097	Daniao river	4346	2418	28	Miocene metamorphic rock Alluvium	1	2010

Tab. 1 - Debris flow monitoring stations of SWCB

the monitoring sensors will be transmitted to the on-site instrumental cabin through wire or wireless ways for preliminary data processing. Usually the instrumental cabin, as shown in Fig. 2, is situated at a relatively safer place near the objective potential debris flow torrent. The cabin made of concrete has two rooms for the information instruments and power supply circuit. The primary (domestic power 110 voltages) and back-up (battery sets and diesel-electric generator) power modules keep the monitoring station operating constantly especially during the typhoon period. After preliminary process and storage, the observation data in the instrumental cabin are transmitted through the satellite (primary transmission, 256 Kb/s) to the SWCB. In case the satellite communication failure occurs, several back-up transmission modules including the asymmetric digital subscriber line (ADSL), the domestic and the mobile telecommunication can be utilized to transmit the monitoring data to the SWCB at the lower transmission speed. All the real-time information transmitted from the on-site and/or mobile debris flow monitoring stations to SWCB is illustrated on the web-based display system-the debris flow disaster prevention information system (http://246.swcb.gov.tw) which is a decision-making support system providing disaster information for commanders and operators to make decisions during the emergency response stages. It also allows the public to inquire different slopeland information for precaution against landslide and debris flow disasters.

Two operation modes -“normal mode” and “event mode” were originally designed in the monitoring system according to the rainfall condition in the field. During the “normal mode” in usual times, the sampling rate of the monitoring devices is at low frequency. When the rain gages pick up rainfall data exceeding the proposed thresholds (rainfall intensity exceeds 10 mm/hr or accumulated rainfall exceeds 100 mm within 24 hours), the “event mode” is triggered. All sensors are upgraded to higher sampling rate to detect field observation data. At the same time, the system automatically sends a triggering signal to crew of the debris flow emergency response task force of SWCB by mobile telecommunication system for further necessary emergency response actions.

DEBRIS FLOW OBSERVATION DATA - DEBRIS FLOW EVENT ON JULY 2, 2004

SHENMU DEBRIS FLOW MONITORING STATION

At the end of June, 2004, typhoon Mindulle attacked Taiwan and was accompanied by strong southwest air current with heavy precipitation and caused severe floods and landslides in mountain areas especially in central Taiwan. From the statistics of central emergency operation center, typhoon Mindulle resulted in 41 casualties and 89 billion NT dollars agricultural loss in the whole country. On July 2, a debris flow detected by the Shenmu debris flow monitoring station was bursting in Aiyuzih creek. In this paper, the observations and preliminary interpretations of monitoring data from a representative debris flow event detected by Shenmu station are discussed in detail. Shenmu station is located at the upstream area of Hoshe creek, a branch of Chenyoulan river in Shenmu Village, Nantou County. Due to the presence of two faults passing through this area, the down-cutting of the riverbed is severe, the bedrock is weak and unstable, and active landslides as well as debris avalanches scatter among the watershed. Three branches including Chushuei creek, Housa creek, and Aiyuzih creek merge at Shenmu Bridge and flow into the Hoshe creek as shown in Fig. 3. Among them, Chushuei and Aiyuzih creeks are monitored at the same time. The debris flow event described in this paper occurred in Aiyuzih creek which is characterized by severe landslides, a high degree of sediment transport and debris flow activities. The landslide rate in Aiyuzih creek catchment is 2.57% as shown in Fig. 4. The length of the main Aiyuzih creek is 3810 m with an average slope of 11.5 degrees. The catchment area is 410 ha. Among the catchment, 93.4% of the area is characterised by a slope angle over 30%. The elevation of the catchment ranges from 2100 m a.s.l. to 1150 m a.s.l.. The layout of the monitoring instruments of Shenmu station is shown in Fig. 3.

RAIN GAUGE AND WIRE SENSORS

From July 2 to 5, the accumulated rainfall measured by Shenmu station reached 1254 mm compared with the average annual rainfall of Taiwan-2450 mm. From the CCD camera, the largest debris flow event was observed at 4:41 pm on July 2 in Aiyuzih creek. The preceding rainfall was 14 mm within 15 hours (from July 1, 3:00 pm to July 2, 6:00 am). The monitoring data of wire sensors and the rain gauge during the debris flow occurrence are shown in Fig. 7. The 10-minute rainfall intensity before the debris flow surge (4:41 pm) was 5.5 mm (also the peak 10-minute rainfall intensity), and the accumulated rainfall reached 182 mm at the moment of the debris flow occurrence. Wu *et alii* (1990) concluded that water is not only the major ingredient of debris flows but also a determinant of debris flow occurrence. They use the 10-minute rainfall intensity and the preceding rainfall as the indices to develop the debris flow forecasting model in Jingjia Gully, Yunnan Province, China. Berti *et alii* (2000) analyzed the field observation data and proposed that high intensity rainfall in a short period of time is the major cause of debris flow occurrence. They also mentioned the probable correlation between debris flows and peak 10-minute rainfall intensity. In Aiyuzih creek, two sets of wire sensors were installed at the same cross-section near the pier of Aiyuzih bridge. The lower one (2 m above the riverbed) broke at 09:16 am on July 2 because of the raised water level in the channel (hyper-concentrated flood observed from the images of CCD camera). The upper one (3 m above the riverbed) broke at 4:41 pm, July 2, under the impact of the front surge of debris flows (also observed from the images of CCD camera). Comparison between the timing of wire sensor rupture and the image data indicates that the break of wire sensor cannot precisely represent debris flows (sometimes the hyper-concentrated floods or drift wood). Thus, wire sensors result limited in detecting the occurrence of debris flows. It is also found that when the wire sensor was broken (9:16 am by the floods and 4:41 pm by the debris flows on July 2), the 10-minute rainfall also reached the peak intensity (5.5 mm). Therefore,

Fig. 3 - Layout of monitoring instruments in Shenmu station

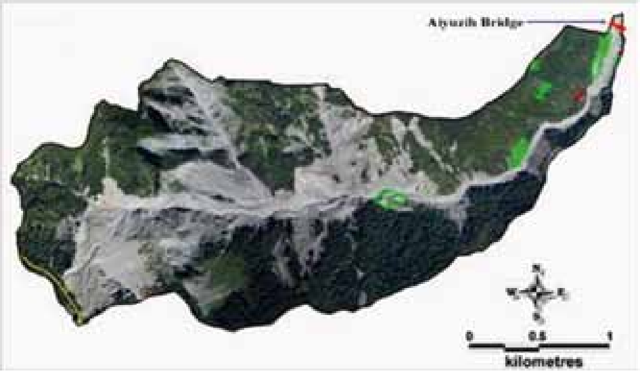


Fig. 4 - Aerial photo of Aiyuzih creek catchment

Fig. 5 - Debris flow image in Aiyuzih creek, Shenmu station

Fig. 6 - (a) River bank erosion by debris flows in Aiyuzih creek

we speculate that high intensity rainfall during a short period of time is the major cause of flash floods or debris flows.

CCD CAMERAS

Fig. 5 shows the image of debris flow surge in Aiyuzih creek. From the image data we noticed that shortly before the occurrence of the debris flow, however, the flow discharge in the channel was drastically reduced. It may be assumed that somewhere in the upstream area, the landslide probably occurred, blocking the channel temporarily. Meanwhile, the upstream water level was still rising, saturating the temporary dam. Unable to resist the water pressure, the dam composed of loose soil and rocks finally collapsed and turned into debris flows flushing downstream. The debris flows in the Aiyuzih creek not only incised the riverbed but also destroyed, with powerful lateral erosive forces, almost all the dry masonry bank revetments (about 5 m in height) and the abutment of Aiyuzih bridge as shown in Fig. 6. The channel width was widened from 36 m to 80m, the riverbed was scoured 2 to 3 m in depth. From the video images of Aiyuzih creek, several typical debris flow characteristics were identified such as a very low discharge just before the first surge, the accumulation of large boulders at the debris flow front, the obvious wavy surface of the surges, and a rapid decrease of the flow depth behind the front. Those findings accord with the debris flow characteristics presented by Takahashi (1991) including: (1) the forefront looks like a bore and the depth of the flow increases abruptly at the front; (2) the biggest stones accumulate at the forefront; (3) behind the front of the flow, the flow appears like a mud flow of gradually decreasing discharge. Besides, some specific parameters of debris flows in Aiyuzih creek are derived from those video images. The average velocity of debris flow front surge was about 13 m/s. The maximum particle size of the debris was about 4 to 5 m. The flowing depth of the front surge was between 5.5 to 6 m while the average depth of the debris flow was 2 m. The debris flows continued for about 5 minutes depositing approximately 77,400 m^3 of sediments.

Geophones

Iverson (1997) described that debris flows are rapid, gravity-induced flows of mixtures of rocks, mud and water. Materials composing the debris flows rolled over, scrubbed and hit the riverbed as they flowed down the creek, causing significant ground vibrations. Takahashi (1991) pointed out that debris flows are accompanied by loud noises and the ground vibrates violently. These ground vibrations are also known as underground sounds, or geosounds, and are speculated to be generated by the collision of large boulders with the channel bed, especially near the front of debris flows. Along the Aiyuzih creek, three geophones were installed along the riverbank. However, the upstream one was buried by sediments earlier. During the debris flow event on July 2, 2004, only the midstream and downstream geophones ranging at a distance of 173 meters were usable as shown in Fig. 3. The sampling rate of each geophone is 500 Hz nthree directions simultaneously. The ground vibrations are three-dimensional with velocity amplitudes that roughly the same along three directions. For brevity, only ground vibrations in one direction are presented in this paper. The time-domain signals of the ground vibrations generated by debris flows were converted into the frequency domain by the Fast Fourier Transform (FFT) and into the time-frequency domain using the Gabor Transform after Huang *et alii* (2007) and Yin *et alii* (2007b). Fig. 8 displays the ground vibration analysis of the debris flow measured by the midstream geophone at 4:41 pm on July 2 in Aiyuzih creek. As can be seen from Fig. 8(a), the time domain signals reveal that at 4:41:38 pm the midstream geophone first detected the significant ground vibration, and at 16:41:44, the velocity amplitude reached its maximum. Subsequently, the midstream geophone installed inside the dry masonry bank revetment was washed away under the impact of the debris flow and then caused some false signals. From Fig. 8(b) and 8(c), frequencies of debris flow ground vibrations measured in the Aiyuzih creek are within 250 Hz and mainly in the range of 5 to 100 Hz. In particular, it is obvious at around 60 Hz, where the spectra have multiple peak values. This is corroborated by the literatures (Okuda *et alii,* 1980; Wu *et alii,* 1990; Tungol & Regalado (1997); Itakura *et alii,* 1997; Lavigne *et alii*, 2000); Huang *et alii,*2007 and Yin *et alii,* 2007b) stating that the frequency of ground vibrations generated by debris flows is relatively low-mainly between 10 and 100 Hz and occasionally exceeds 100 Hz.

fig 6(b) - Abutment damage of Aiyuzih bridge due to debris flows

Besides the image analysis, Arratano (2003) presented another effective way to figure out the mean velocity of debris flow front surge using the serial deployment of geophones along the torrent. In the time domain, the peak velocity of the ground vibration signals indicates that the front surge of the debris flow is at the nearest location to the geophone (also that the debris flow has reached this site). The time lag between the peak amplitude of the two consecutive geophones signals allows the mean velocity of the debris flow front surge to be estimated. The distance between the

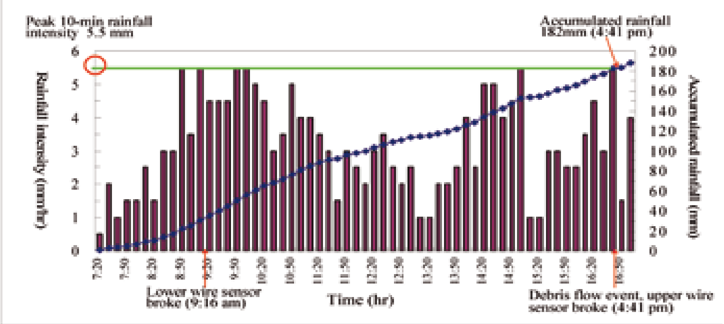


Fig. 7 - Wire sensor and rainfall data during debris flow period on July 2, 2004, Shenmu station

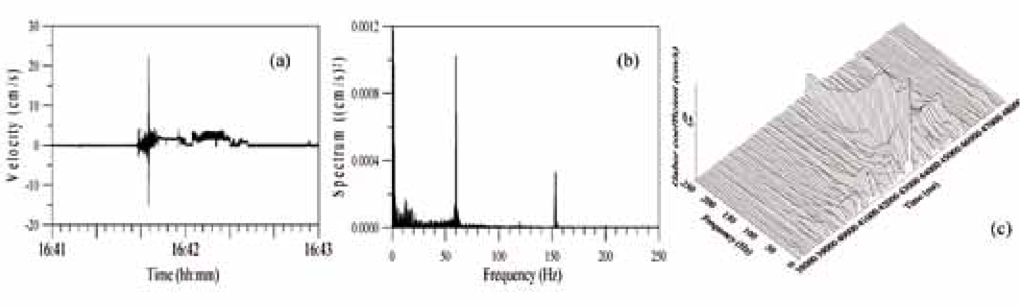


Fig. 8 - Ground vibration signals of debris flow monitored by the midstream geophone on July 2, 2004 in Aiyuzih creek; (a) time domain siganls, (b) spectrum of FFT, and (c) spectrum of Gabor transform

midstream and downstream geophones is 173 m. Determined from the foregoing technique, the mean velocity of the debris flow front was 13.3 m/s according with the result of the dynamic image analysis obtained from CCD cameras (13 m/s). Another finding during the debris flow process is that the intensity of the ground vibration signals recorded by the midstream geophone (installed in the dry masonry bank revetment) is about 10 times higher than that of the downstream geophone (located in the concrete bank revetment). It seems that the geophone in the dry masonry bank revetment is more sensitive to pick up the ground vibrations. We speculate that the location of the geophone has considerable influence on the signal intensity of the ground vibrations generated by debris flows.

MOBILE DEBRIS FLOW MONITORING STATION AND MODULE SENSORS

Usually, the debris flow events in Taiwan are induced by typhoons accompanying heavy precipitation during the flood season (May to November). Since the typhoon routes are variable, debris flows events do not always occur at the sites where the debris flow monitoring stations locate. In order to enhance the probability of detecting the debris flow events, the SWCB has devoted to the research of mobile debris flow monitoring station since 2004. The mobile debris flow monitoring station, as implied by the name, is the mobility evolution from the original fixed on-site debris flow monitoring station. When the Central Weather Bureau issues the forecast of incoming typhoon, the mobile debris flow monitoring stations are sent to the site of highest probability of debris flow occurrence on the basis of a prediction model founded on typhoon routes and rainfall distribution prediction. Up to now, 3 mobile debris flow monitoring stations have been accomplished as shown in Fig. 9. Basically, the framework of mobile debris flow monitoring station is similar to the on-site station except for the specially designed lightweight instruments and the vehicle platform replacing the instrumental cabin. In order to extend the observation scope, the SWCB recently has developed the module sensors composed of wireless transmission, battery sets and portable devices for debris flow monitoring. So far, several modules sensors were manufactured including the rain gauge, wire sensors and CCD cameras as shown in Fig. 10. The module sensors can be equipped with either the on-site or the mobile debris flow monitoring stations through the wireless transmission techniques especially for the upstream areas monitoring where the landslides and debris flows usually initiate.

CONCLUSIONS

The 17 on-site and 3 mobile debris flow monitoring stations established by SWCB have opened a new approach of debris flow observation in Taiwan. From the developing experiences and field observation data analysis, the following conclusions are presented herein:

The main purpose of the debris flow monitoring system is to collect field debris flow data as much as possible. The precious monitoring information can be utilized not only for helping us to understand the physical mechanism of debris flows, but also to improve the accuracy of the current debris flow warning system based on rainfall thresholds.

The rupture of wire sensors cannot precisely represent debris flows (sometimes the hyper-concentrated floods or drift wood). In other words, wire sensors have limits in detecting the occurrence of debris flows.

From the analysis of 10-minute rainfall pattern, wire sensors rupture time and debris flow occurrence time, we speculate that high intensity rainfall during a short period of time is probably the major cause of flash floods and debris flows.

From the video images of debris flows in Aiyuzih creek, several debris flow characteristics were apparent such as a very low discharge just before the first surge, the accumulation of large boulders at the debris flow front, the obvious wavy surface of the surges, and a rapid decrease of the flow depth behind the front.

Frequencies of debris flow ground vibrations measured in Aiyuzih creek are within 250 Hz and mainly in the range of 5 to 100 Hz. In particular, it is obvious at around 60 Hz, where the spectra have multiple peak values. This is corroborated by other literatures stating that the frequency of ground vibrations generated by debris flows is relatively low.

The average velocity of debris flow front surge from dynamic image measurement (13 m/s) accords with the result from ground vibration signal analysis using the serial deployment of geophones (13.3 m/s) along the Aiyuzih creek. It is implied that both CCD cameras and geophones can be used as the estimation of mean velocity of debris flow front surges.

Fig. 9 - Mobile debris flow monitoring station

Fig. 10 - Modules of the rain gauge and CCD camera

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