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

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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.

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 debris flows are analyzed in detail.

Keywords: debris flows, debris flow monitoring system, mobile debris flow monitoring station
tems 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.

In the field, all the observation data detected by
the web-based display system—the debris flow disas -
ter 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 in -
quire 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 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 trans-
mit the monitoring data to the SWCB at the lower
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<table>
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<th>Length of main channel (m)</th>
<th>Average slope of main channel (deg)</th>
<th>Rocks geology</th>
<th>No. of debris flow events</th>
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Tab. 1 - Debris flow monitoring stations of SWCB
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,
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 Taka-Hashi (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.

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 Taka-Hashi (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 in three 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; Tengol & 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.

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. 6(b) - Abutment damage of Aiyuzih bridge due to debris flows](image1)

![Fig. 7 - Wire sensor and rainfall data during debris flow period on July 2, 2004, Shenmu station](image2)
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.

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