NON-STRUCTURAL STRATEGY OF DEBRIS FLOW MITIGATION IN MOUNTAINOUS AREAS AFTER THE CHICHI EARTHQUAKE

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ABSTRACT

Since the Chichi Earthquake (M_L=7.3) in 1999, the occurrence of sediment-related disasters, such as landslides and debris flows, have become more frequent in Taiwan. Also, as controlling structures cannot be fully implemented promptly, the government has initiated non-structural disaster mitigation programs. First, the debris flow evacuation drills for local communities were promoted in 2000, advocating safety and securing lives by disaster prevention measures. Typhoon Toraji in July 2001 caused many debris flow events, but some communities performed the evacuation plan that rapidly reduced the casualties; thus, the government expanded evacuation drills to more communities. In addition, the early warning system created after the Chichi Earthquake enables residents to be capable of debris flow prevention. The rainfall threshold values of debris flow warnings for different areas are revised according to the onsite weather stations and geographic features. Real-time information is gradually integrated to form a basis for debris flow disaster warning system, which can announce warnings to people living in debris flow zones. The warning system is classified into yellow and red alarms, and is effective to evacuate the public before disasters happen. Overall, the fewer casualties from debris flow disasters during the decade after the Chichi Earthquake is not due to reduced sediment-related disasters, but to the gradually improved early warning and evacuation systems. However, the compound disasters caused by Typhoon Morakot in 2009 reminds us that the mitigation system needs to be continuously modified and responds timely to various catastrophic disasters.

Key words: Monitoring system, Evacuation and shelter, Rainfall threshold value, Debris flow, Preparedness guidelines.

INTRODUCTION

Taiwan is located on the collision boundary between the Philippine Sea plate and Eurasian plate. Mountainous terrain dominates the region, which is characterized by fragile rocks formations and frequent seismic activity. Additionally, torrential rains brought by typhoons cause numerous disasters. Debris flows after strong earthquakes are usually due to material from hillslope collapsing, mixed with groundwater or surface runoff. Hence, when the groundwater level arises or surface runoff occurs, hillslope collapses and debris flows can occur. After the Chichi Earthquake in 1999, numerous severe typhoons— Typhoon Xangsane in 2000, Typhoon Toraji, Nari and Lekima in 2001, Typhoon Mindulle and Aere in 2004, Typhoon Kalmaegi, Sinlaku, and Jangmi in 2008 —caused many serious disasters in central
Taiwan. Mitigating disasters by evacuating residents and improving the system for monitoring debris flows and landslides are essential (Fang, et al., 2008).

Since the Chichi Earthquake, Taiwan has frequently been hit by typhoons and heavy rainfalls that caused numerous landslides and debris flows, resulting in losses to life and property. Disaster management to reduce the impact is extremely important. To improve the disaster prevention and evacuation system and to strengthen the four-phase management process (mitigation, preparedness, response and recovery), Taiwan’s central government had announced the Disaster Prevention and Response Act in 2000. In 2002, the government drafted the Disaster Prevention and Response Basic Plan, and the Council of Agriculture, Executive Yuan, announced the Debris Flow Disaster Prevention and Response Operation Plan against debris flow. Because debris flows are impossible to predict, preparedness and response to emergency have become extremely important, and are considered as major tasks of Soil and Water Conservation Bureau (SWCB), in additional to usual engineering construction (Chen, 2004).

In accordance with the Debris Flow Disaster Prevention and Response Operation Plan, SWCB has started organizing debris flow evacuation practices, and constructed debris flow monitoring stations to improve preparedness since 2000. SWCB also established the rainfall threshold for debris flow warning. When the threshold is met, SWCB will issue debris flow alert and request local communities to evacuate from the dangerous area before debris flow occurs. The effectiveness of preparation in advance and quick response to emergency shows great influence on reducing hazard-related casualties since 2002.

**EVACUATION AFTER DEBRIS FLOWS**

Most slopelands in Taiwan have unstable geological situation with steep slopes, a fragile geomorphology, and rivers that flow rapidly. These natural conditions interact with other factors such as rainfall and the after-effects of Chichi Earthquake, resulting that the mountainous regions in central Taiwan have loose and collapsed soil. The possibility of sediment-related disasters has endangered property and life, and threatens economic development and traffic in mountainous areas. This situation has become worsen after rainfall give that debris flows and landslides become more common recently. After the Chichi Earthquake, typhoon or heavy rainfall can cause modest debris flows and landslides. For example, on July 29, 2001, Typhoon Toraji hit Taiwan and caused many debris flows in eastern and central Taiwan, resulting 55 fatalities, 33 people injured and 93 missing.

In the past, the public was not familiar with disaster prevention tasks and lacked of training such that panic was typical response to a disaster. The public had no understanding of how to response to a disaster, and just waited for rescue teams from official departments. Disasters are often accompanied with broken roads and bridges, which usually causes difficulty on timely response from government agencies and rescue teams. Electricity outage also interrupts the communication and delays rescue. Furthermore, damage to lifelines also affects resident’ basic living needs. When such a situation occurs, most people rely on the government or civilian agencies for rescue; thus, the scale of a disaster and number of casualties increase when the central or local government cannot response timely to a disaster or when traffic and communication are adversely affected. In recent years, residents are still unable to perform disaster prevention and rescue tasks. Developing such abilities should be the first priority in community disaster prevention.
Since the Disaster Prevention and Response Act was introduced in 2000, SWCB, the agency governing debris flow disasters, has developed debris flow evacuation plans, evacuation drills, and disaster prevention strategies (Fig. 1). Evacuation plans include on-site investigations of dangerous debris flows, communication of information, planning evacuation routes and shelters, drawing evacuation maps for debris flows in villages, and holding meetings for resident. In addition to holding a practice for resident evacuation, government agencies participate in drills following procedures of issuing disaster alerts, determining evacuation routes, evaluating disaster status, and sharing information. After these plans and drills are implemented, residents typically understand and are aware of disaster plans and actively participate in training. Residents can help on evacuation and rescue operations before alerts are issued. When a disaster occurs, residents can utilize needed resources and provide assistance. After a disaster, residents can restore living environment and try to keep the goal of becoming a disaster-resistant community. Currently, debris flow evacuation plans have been deployed in 652 villages in Taiwan. In total, 552 evacuation drills have been held and 164 villages have met the standards for disaster-resistant communities (Fig. 2).

![Debris flow evacuation planning](image1.png)

![Debris flow evacuation drills](image2.png)

![Discussion of disaster-resistant community](image3.png)

![Disaster-resistant community map](image4.png)

**Fig. 1** Debris flow evacuation planning and drills, (SWCB, 2007, 2008)
DEBRIS FLOW MONITORING SYSTEM

SWCB, which is responsible for conserving and managing mountainous areas in Taiwan, cooperated with several universities since 2002. Together they have established and maintained 13 on-site debris flow monitoring stations. Furthermore, two mobile debris flow monitoring stations have been constructed. The locations of on-site debris flow monitoring stations were selected from 1552 potential debris flow torrents by SWCB after Typhoon Toraji and Nari (Fig. 3). Figure 4 shows the setup of these monitoring stations. These monitoring stations integrate real-time information about debris flow torrents and use satellite and wireless transmission technologies to transmit data obtained by various monitoring sensors back to the debris flow response system. Such real-time data transmission to SWCB serves as a reference for mitigating natural disasters (Fang et al., 2007).
Each monitoring station has a data-acquisition center that collects and stores observed data from each sensor. The primary communication network is mainly through the Zhongxin No. 1 satellite. Unlike cell phones that cannot work in mountainous and remote areas, the satellite offers wider bandwidth and full coverage. Thus, transmission quality is enhanced. To maintain the transmission of information to the Debris Flow Emergency Response Center when the satellite communication is down, ADSL, GSM, GPRS or PSTN networks are used as a backup transmission system (Fang et al., 2007).

The debris flow disaster information system (http://246.swcb.gov.tw) collects and displays real-time debris-flow information and integrates observational and forecast information from the Central Weather Bureau (CWB). Figure 5 shows the integrated hardware structure of the system (Fang et al., 2007).

![Integrated hardware structure of the debris flow disaster response system](image)

Because of limited resources and work force, the 13 debris flow monitoring stations cannot cover all 1552 dangerous debris flow torrents in Taiwan. Therefore, mobile debris flow
monitoring stations were established. These mobile stations extend the range of monitoring system. These mobile debris flow monitoring stations are only used during an event if necessary. Therefore, periodical maintaining time and cost are minimized, and are significantly lower than that of on-site debris flow monitoring stations. The mobile stations also avoid reduction in equipment lifetime caused by long-term outdoor exposure, and increase the usability of monitoring system when the debris flows occurs. Since 2003, SWCB has been co-operating with academia to establish the mobile debris flow monitoring station (Fang, et al., 2007). Two mobile debris flow monitoring stations have been completed (Figs. 6 and 7).

**DEBRIS FLOW WARNING MODES IN TAIWAN**

Debris flows can occur depending on the geological conditions and hydrological features of a given area. One can use a rainfall event and corresponding accumulated rainfall, combined with the concept of cumulative probability, to determine rainfall thresholds for debris flow warning. Currently, the threshold value is 70%, which is the rainfall amount needed for a probable debris flow. This threshold value is divided into seven amounts of accumulated rainfall 200, 250, 300, 350, 400, 450, 500, 550 and 600 mm.

The threshold value must consider the factors that cause loose soil on slopeland and should be adjusted yearly. To make an early waning timely and proper, the threshold value of an area affected by earthquake should be reduced from 70% to 50% and monitored closely (SWCB, 2008).

To measure rainfall, SWCB and CWB have developed a Quantitative Precipitation Estimation and Segregation Using Multiple Sensors (QPESUMS) system (Chiou et al., 2007). Radar data of QPESUMS are measurements of Mosaic Hybrid Scan Reflectivity, which is measured close to the ground at the smallest elevation angle (Zhang et al., 2005). The estimate rainfall is based on the reflectivity \( R \) of radar (Xin et al., 1997). This estimate is verified by rainfall stations to determine the predicted rainfall after 1 and 3 hours in debris flow areas (Fig. 8). The predicted rainfall serves as standards for issuing alerts.

Debris flow warning has two levels, which are yellow and red alarms. When the estimated rainfall amount exceeds the threshold, SWCB will issue a yellow alarm for a dangerous area and the local government should initiate evacuation strategies. When actual rainfall reaches
the debris flow warning threshold, status is changed to red alarm, and the local government should instruct and force residents to evacuate from the area (Fig. 9).

CASE HISTORY - SHENMU VILLAGE

Evacuation: Typhoon Toraji in July 2001 and Typhoon Mindulle in July 2004

Shenmu Village, which is located in Hsinyi Township, Nantou County, has 12 neighborhoods, 70 households with 630 residents. The village has 7 dangerous potential debris flow torrents. The village experienced debris flows during Typhoon Herb in 1996. Many houses were damaged and the traffic network was broken. The Chushuei torrent had several debris flows in May 1998, and May and July in 1999. These debris flow destroyed bridges and left residents isolated. When Typhoon Toraji hit central Taiwan in July 2001, debris flow occurred in Aiyuzi torrent and washed away the Aiyuzi Bridge.

In 1999, SWCB, Council of Agriculture, held a debris flow drill in Shenmu Village. During the drill, the Debris Flow Prevention Squadron of Hsinyi Township demonstrated various prevention measures and trained residents by rescue strategies. In June 2001, SWCB held a large debris flow evacuation drill that taught residents and local agencies about the evacuation
process (Fig. 10). Drill results were satisfying. In July 2001, Typhoon Toraji caused 55 deaths and Typhoon Mindulle in 2004 caused 6 deaths in Taiwan; however, because of proper preparation and evacuation, the debris flow in Shenmu Village did not cause casualties.

Debris flow event observed in Aiyuzi River

Due to many debris flows in Shenmu Village in recent years, SWCB set up monitoring stations in 2002 to acquire instantaneous data for debris flow warning and research. Figure 12 shows the equipment and location of the monitoring station in Shenmu Village.

Debris flow during Typhoon Mindulle

Due to the strong southwest current brought by Typhoon Mindulle, strong torrential rains...
began in the Shenmu area at 8 a.m. on July 2, 2004. During July 2 to 5, the Shenmu monitoring station recorded 1254 mm of rainfall. Figure 13 shows the intensity and accumulated rainfall.

The intensity and accumulation of rainfall measured by the Shenmu monitoring station was used to verify the warning for debris flows issued by the SWCB. On July 2 at 9:40 a.m., the warning index was red alarm (Point A in Fig. 14). At 9:16 a.m., the wire sensor signaled that the steel wire was broken (Point B in Fig. 14). Before the debris flow broke the wire (16:41:52) (Point D in Fig. 14), geophone No. 1 located upstream detected strong ground vibrations at 16:36:28 (Point C in Fig. 14); that is, it detected the debris flow 5 minutes ahead of wire sensor’s signal.

The front wave of debris flows along the Aiyuzi torrent was recorded by a video camera. Comparing the images taken at 16:41:41 and 16:41:51, it indicates that the front wave of the debris flows advanced 130 m in 10 seconds (Fig. 15). The average velocity of the front wave
of debris flows was about 13m/sec.

![Debris flow images of the Aiyuzi torrent (Fang et al., 2007)](image)

**Fig. 15** Debris flow images of the Aiyuzi torrent (Fang et al., 2007)
(a)16:41:41, (b)16:41:51

**Evaluation**

The effectiveness of the evacuation and monitoring system can be determined based on the significant decrease of casualties during debris flows caused by typhoons and heavy rainfall. One can also evaluate the preparedness index of village using simple preparedness guidelines for debris flow disaster prevention (Chen, 2008). The preparedness index primarily divides debris flow disaster prevention into system preparedness and environmental preparedness. These two items are weighted, and a village’s preparedness index is the total of weighted scores. The system preparedness is mainly evaluated by the completeness of rescue equipment, monitoring station and evacuation system. The environment preparedness aims at the completeness of natural environment restoration and disaster-preventing engineering construction.

After the evaluation is performed for each village, the village preparedness indices can be drawn on the distribution graph based on the weighted scores from the system preparedness and environment preparedness. This distribution graph is separated into three zones indicating the level of preparedness, which are Green Zone (good preparedness), Yellow Zone (medium preparedness), and Red Zone (poor preparedness). The index can be used to assess village disaster preparedness and evaluate differences before and after preparedness measures are implemented. For Shenmu Village, the score before preparedness measures was close to zero in 1999. However, according to the evaluation made after 2008, it is evident that although the score in environment preparedness is not high, the total preparedness is improved as the system preparedness is improved (Fig. 16) (Chen, 2008). The capacity of system preparedness is much improved than environment preparedness.
Fig. 16 Distribution graph of village preparedness (Chen, 2008) a. Before preparation b. Current status

From the 10 villages in Fig. 16, one can see that the effect of preparedness improvements is substantial. Since Typhoon Toraji in 2001 and Typhoon Mindulle in 2004, the debris flows that have occurred during 2004-2008 have not caused any deaths or injuries. This can be attributed to the disaster evacuation and monitoring system.

REFLECTIONS ON TYPHOON MORAKOT

Typhoon Morakot brought extraordinarily intense torrential rains when it struck southern Taiwan on August 8, 2009. The cumulative rainfall measured at many rainfall stations set historical records. The accumulative rainfall in southern Taiwan for the two days of Aug. 8-9 reached 2200 mm, which was significantly higher than the previous record of 1986.5 mm during Typhoon Herb in 1996. The continuous torrential rain during Typhoon Morakot caused many landslides and debris flow in southern Taiwan. The most severe of these incidents was the landslide that buried the Shiaolin community at 6:09 a.m. on Aug. 9, causing more than 400 deaths. This was also the deadliest single sediment-related disaster in Taiwan's history.

This disaster occurred after the torrential rains caused a massive landslide on Mt. Shiandu, which is located immediately behind the site of the community, nearly instantly burying most of the community in heavy sediment (Fig. 17). Afterwards, a landslide dam blocked the Chishan River, submerging the site of the community in hyperconcentrated discharge. Since transportation out of the community had been cut off during the previous night, most residents were trapped in their homes which explains the high death toll. Therefore, disaster mitigation and risk management of compound disasters need great attention in the future.
CONCLUSIONS

The Chichi Earthquake in 1999 caused many casualties due to debris flows and landslides. Since the Disaster Prevention and Response Act was announced in 2000, SWCB has completed evacuation plans for 522 villages. Additionally, 453 evacuation drills have been conducted and 13 monitoring stations have been set up, planning to establish four stations in southern Taiwan after typhoon Morakot, which have remarkably increased local residents’ knowledge of debris flow and evacuation plan. Furthermore, the 9 levels of rainfall threshold warning system for debris flow are now completed. Residents living in the impacted areas can be evacuated before a disaster occurs, thereby achieving the goal of disaster prevention.

In 1999, Shenmu Village had many debris flows during Typhoon Herb. In response, the government held debris flow drills in 1999 and 2001. Although debris flows occurred during Typhoon Toraji in 2001 and Typhoon Mindulle in 2004, no casualties were reported due to well developed residential evacuation plan. Changes to the village preparedness index indicate that the village has improved its disaster prevention and preparedness status.

Although various engineering regulations can improve conditions for controlling landslides and debris flows, the evacuation and shelter measures and other hazard prevention strategies are still on the top priority for authorities. We conclude that these methods are effective as no casualties from debris flow incidents since 2004. Evacuation planning and setting up a monitoring and warning system are the best ways to reduce disaster severity and the loss of life. However, the compound disasters caused by Typhoon Morakot in 2009 reminds us that the mitigation system needs to be continuously modified and responds timely to various catastrophic disasters.

REFERENCE


