J. Mt. Sci. (2010) 7: 291–300
DOI: 10.1007/s11629-010-2021-3

Non-Structural Mitigation Programs For Sediment-Related Disasters after the Chichi Earthquake in Taiwan

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Abstract: Following the Chichi Earthquake (M_L=7.3) in 1999, sediment-related disasters, such as landslides and debris flows, have become more frequent in Taiwan. Because engineering structures cannot be fully and rapidly emplaced, the government has initiated non-structural hazard mitigation programs. Initially, community debris flow evacuation drills were promoted in 2000. Typhoon Toraji caused numerous debris flow events in July 2001, and some communities evacuated according to the drills, significantly reducing the numbers of possible casualties. Based on that result, the government expanded the program for evacuation drills. Secondly, the early warning system created after the Chichi Earthquake will prevent many potential future casualties. Rainfall threshold values for debris flow warnings in different areas are determined from information received from local weather stations and modified for local geomorphologic situations. Real-time information is gradually being integrated to create a debris flow disaster warning system, the goal of which is to provide warnings to zones in which debris flows are likely. The warning system was launched in 2005 and has two levels of alarms: yellow and red. The final, red alarm triggers enforced evacuation. Overall, the decrease in casualties from debris flows during the decade after the Chichi Earthquake is not the result of a decrease in number or severity of sediment related disasters, but is more directly related to the gradually improved early warning and evacuation system. However, the compound hazards resulting from Typhoon Morakot in 2009 remind us of the ongoing need for improving the existing mitigation system.

Received: 12 January 2010
Accepted: 1 May 2010

Keywords: Warning system; evacuation and shelter; rainfall threshold value for debris flow; Chichi Earthquake

Introduction

Taiwan is located at the interface between the Philippine Sea Plate and the Eurasia Plate. It is in the Pacific Rim seismic zone and experiences almost 1,000 human-experienced shocks annually (Central Weather Bureau (CWB), 2008). Taiwan is noted for its youthful topography and fragile geology. Climate change increases the amount of bare land and numbers of landslides in Taiwan. Mountainous areas account for 72% of the total area of Taiwan (Soil and Water Conservation Bureau (SWCB), 2004a), and steep hills and torrent slopes are subject to the severe climatic conditions of a mean annual rainfall of 2,515 mm. Debris flows are mainly caused by steep channels, abundant sediment, and high and intense rainfall. Thus, Taiwan has natural conditions for sediment-related disasters in its mountains. Furthermore, the mountainous areas are frequently developed in agricultural areas, and residents live in probable hazardous zones. Therefore, the probability of sediment-related disasters in Taiwan's mountainous areas is high and many have occurred. On

21 September 1999, the Chichi Earthquake occurred in central Taiwan. Its magnitude was 7.3 on the Richter scale, and there were 3,228 aftershocks (CWB, 2008). Such strong shocks destabilized mountain slopes in central Taiwan, and that region is prone to slope failures and debris flows.

Before the Chichi Earthquake, Taiwan experienced 27 debris flow disaster events between 1981 and 1999. The landslides from the Chichi Earthquake in central Taiwan in 1999 encompassed 8,694 ha, a figure increased to 22,308 ha with Typhoon Toraji in 2001 (Wu and Chen, 2009; Lin, et al., 2002), resulting in an increase in landslides and debris flow hazard zones. Typhoon Toraji caused 16 debris flow disasters in 2001. There were 485 debris flow torrents in Taiwan before 1999, 722 after the Chichi Earthquake in 1999, 1,420 torrents after Typhoon Toraji in 2001 (SWCB, 2004b), and 1,503 torrents after Typhoon Morakot in 2009 (SWCB, 2009). These substantial increases show how the disaster areas threatened by debris flow after earthquakes rapidly increase. Construction of engineering structures is an effective method for reducing debris flow disasters (Cui et al., 2007); however, considering limited budgets in Taiwan, it is impossible to construct disaster prevention engineering structures in all debris flow areas in a short period. Therefore, the government aims to gradually develop non-structural methods, such as an early warning and evacuation system to mitigate disasters and secure the safety of public life. The Disaster Prevention and Response Act (DPRA) was implemented in 2000. The Debris Flow Disaster Prevention and Response Operation Plan for Debris Flow Disasters Act was then issued in 2002 based on DPRA. Non-structural mitigation programs were legalized, and, thus, the preparedness and response operations of various debris flow hazard zones improved over time, with increasing successful results. This paper presents the specific achievements in Taiwan in terms of non-structural disaster prevention programs over the last decade.

1 Debris Flow Evacuation

Although few debris flow disasters before the Chichi Earthquake were recorded in Taiwan, there were heavy casualties because of the lack of preventive education. For example, Typhoon Herb in 1996 caused many debris flows in central Taiwan, resulting in 106 deaths. After the Chichi Earthquake, the number of debris flow hazard zones rapidly increased, and primary evacuation drills were performed in some communities threatened by debris flow after 2000. To ensure safety in a future earthquake and during secondary disasters, the people of Taiwan were given evacuation routes, shelters, and maps, and they practiced a real evacuation. The organization that was related to disaster prevention and relief oversaw the disaster response drills. The organization announces warnings, instructs evacuations, and organizes disaster relief. The drills and response measures allowed the people to be prepared before and after the disasters.

The attack of Typhoon Toraji caused debris flows in central Taiwan and resulted in 181 deaths. Most mountain communities suffered high casualty rates because they did not practice evacuation drills. However, 12 communities, including Shenmu and Jyunkeng, performed drills in 2001. These communities evacuated to a safety shelter and suffered only one casualty. These results made people realize the importance of crisis awareness and of residential evacuation for their personal safety. The number of communities that performed debris flow evacuation drills increased between 2000 and 2008. A total of 453 drills were performed as a result of government promotion (Figure 1). However, disaster prevention is not only the duty of government, but it is also the responsibility of local residents. The “bottom-up” program was promoted in 2004, based on the original evacuation drills. This program is similar to the Education for Self- Warning and Evacuation (ESWEV) campaign used in the United States that prepares residents in flow pathways near volcanoes to seek high ground after a seismic shock or prolonged rumbling noises (Scott et al., 2001). Disaster resistant communities were successively promoted under the community-based disaster prevention planning by residents themselves. Once residents are aware of disaster prevention, they readily participate in the disaster field studies and help plan evacuation routes and shelters. They organize disaster prevention forces and seek to

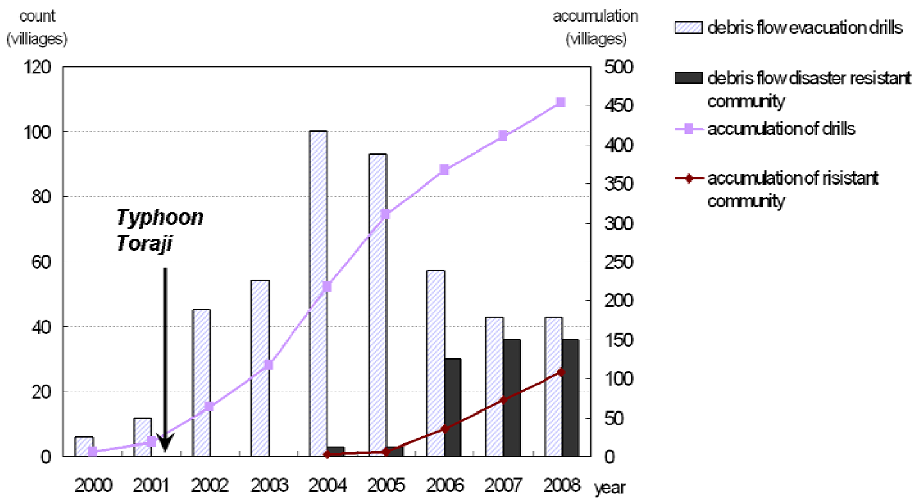


Figure 1 Statistics of debris flow evacuation drills and resistant communities

organize self-aid and mutual assistance with others to expedite evacuations in response to both warnings of debris flow probability and to actual flows (SWCB, 2007).

2 Early Warning System

2.1 Period of monitoring station system (before 2003)

Taiwan had no successful warning system for debris flows before Typhoon Toraji in 2001. Even when the concept of evacuation was gradually promoted in 2000, the government had no debris flow warning system, and residents had to judge the time for evacuation by themselves. Debris flow monitoring stations were constructed in 1996. Real-time observation data are transmitted to the emergency center of the SWCB through satellite communications. Because of high maintenance costs and consequent abandonment of many monitoring stations, only 13 have continually been in use to the present (Figure 2).

The channels from which debris flows in originate Taiwan are mostly 500~2000 m long. When a debris flow occurs, the time for residents' response after acquiring the warning from the monitoring station is less than 10 minutes (Chen, 2002). Therefore, the warning times from instruments detecting actual flows in the field is too short to be effective as an early warning system to trigger organized evacuations (Chen, 2002). In addition, limited budgets restrict the building of additional monitoring stations. Thus, the main task of the monitoring stations is not to provide real-time warnings, but the gathering of debris flow observation data for academic research and structure design, such as the transport mechanisms and dynamics of debris flow and optimal designs for check-dam systems and their locations.

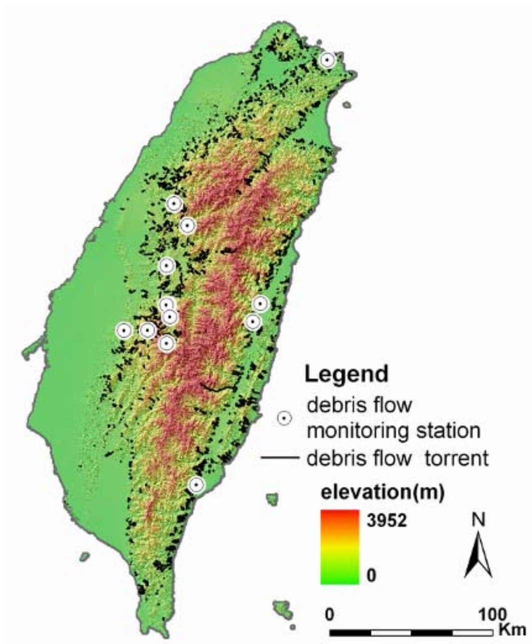


Figure 2 Debris flow torrents (source channels) and 13 debris flow monitoring stations in Taiwan

2.2 Initial stage of the early warning system (2003~2005)

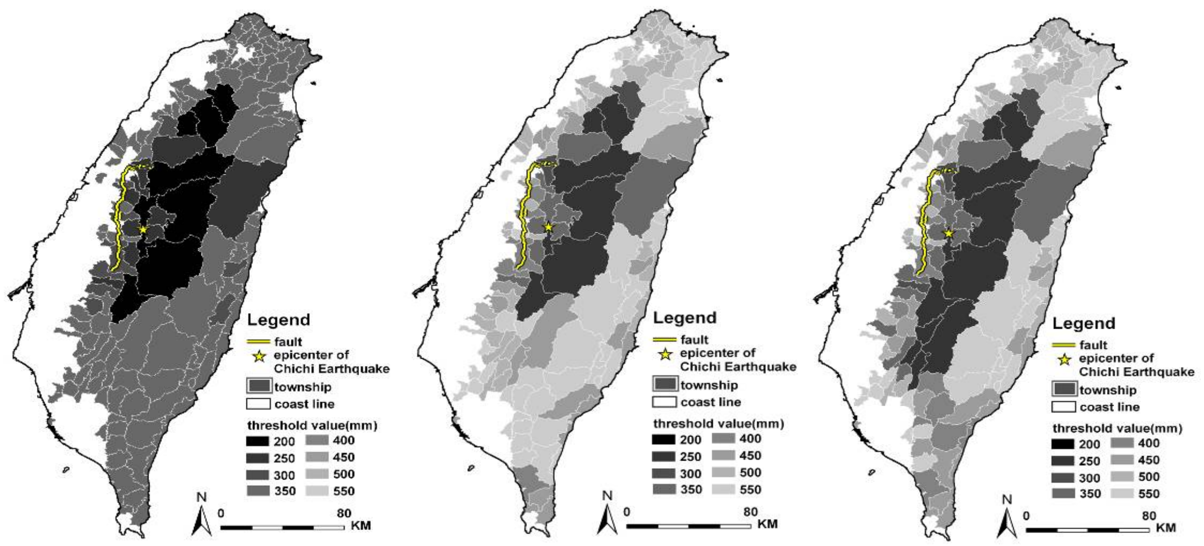
To predict debris flows during periods of heavy typhoon rainfall, the emergency center of SWCB was established to plan various data analyses and warning techniques. The Debris Flow Disaster Response System, as officially implemented in 2002, integrates all real-time observation data in an online system, including typhoon information, rainfall accumulation, live video, and information about debris flows. It can be synchronously used by the emergency center of SWCB to release all debris flow warnings during the heavy rainfall of typhoons (SWCB, 2008b).

Initially, the rainfall intensity and accumulated rainfall were defined as a debris flow rainfall triggering index (RTI) (Jan and Lee, 2004). The debris flow warning model is a plot with the RTI-data on the ordinate and the time of rainfall on the abscissa, in order to effectively evaluate the temporal variations in debris flow occurrence probability during a rainstorm. However, because the concept of rainfall intensity is difficult for some people to accept, we use only accumulated rainfall as the rainfall threshold value (RTV) for the debris flow warning system. RTVs depend on geologic features and rainfall characteristics that are identified by historical data on debris flow occurrence. The regression analysis determines the lower critical warning line ($RTV=RTV_{10}$) with the upper critical warning line ($RTV=RTV_{90}$) based on historical rainfalls. For the application, RTV_{70} is determined as the critical value for an early warning system because it has a 70% occurrence probability, one that can be accepted by residents. The RTV is between 200~550 mm, and is divided into eight levels (Figure 3a). After the Chichi Earthquake, the RTV for warnings in the primary susceptible areas was set at a relatively low level, because hillslopes had been destabilized by the earthquake and were more likely to become sources for debris flows; however, the level was increased following geological recovery (Figure 3b); but the level was decreased again because attacked by Typhoon Morakot (Figure 3c). Beginning in 2002, the real-time observation data from 153 automatic rainfall stations of CWB were synchronously obtained online and integrated into the Debris Flow Disaster Response System.

Once the rainfall condition of an area reaches the RTV for a warning, the emergency center of SWCB will broadcast a warning message to the hazard-prone areas by fax and text messaging through the Debris Flow Disaster Response System (SWCB, 2008b). At this stage, the release of a debris flow warning can only advise residents to evacuate. However, the residents can choose to evacuate. There is no executively forced, mandatory evacuation.

2.3 Recent developments in the early warning system (2005~2008)

Since 2005, the release of debris flow warnings required the communities to work together. Because some areas have no rainfall station,



(a) 2003~2005 (b) 2005~2008 (c) 2009

Figure 3 Rainfall threshold values for debris flow during different periods after the Chichi Earthquake residents of communities near debris flow torrents are recruited as professional volunteers to observe the local real-time rainfall by using simple rain gauges and communication equipment. In addition to providing rainfall data in areas lacking formal rainfall stations, they announce the onset of dangerous conditions and advise the residents to evacuate. The system of Quantitative Precipitation Estimation and Segregation Using Multiple Sensors (QPESUMS) was initiated in 2006 for calculating and analyzing the predicted rainfall within 1~3 hours in order to provide information for future rainfall trends for the emergency center of SWCB and to strengthen the accuracy of debris flow warning analyses (SWCB, 2008b).

In 2005, the debris flow warning system in Taiwan was classified into two alarm levels: yellow and red (Figure 4). When the predicted rainfall is greater than the RTV for a debris flow warning, a yellow alarm is released to the affected community, and the local government advises residents to evacuate. In contrast, a red alarm is released when the actual accumulated rainfall reaches the RTV for a debris flow warning. The local government will then enforce public evacuation. Therefore, rapid notification is required. Local police and fire-fighting units are asked for assistance when a red alarm is announced or when the rainfall accumulation observed by the community reaches the RTV of debris flow. Those who refuse to evacuate will be forced to evacuate to safe shelters. Thus, as the procurement of rainfall information and warning release methods have improved since 2005, the early warning system for debris flows in Taiwan has entered a relatively optimal stage.

3 Case Study

3.1 Shenmu Community

Shenmu Community is located in Shinyi Township, Nantou County. It has 969 residents living in 338 houses, and 13 debris flow torrents. In 1996, Typhoon Herb caused many debris flow disasters, damaging several houses and destroying roads. Many debris flows occurred in May 1998 as well as in May and July 1999, which destroyed bridges and besieged residents. Shenmu Community performed a debris flow evacuation drill in June 2001 to familiarize the residents with the evacuation process. It became one of the first debris flow resistant communities to practice evacuation drills in Taiwan (Chen et al., 2009). Typhoon Toraji in July 2001 and Typhoon Mindulle in July 2004 caused high rates of casualties in Taiwan; however, there were no deaths in the Shenmu Community, despite numerous debris flow torrents and occurrences, because the residents evacuated in advance.

During Typhoon Toraji in 2001, houses, roads, and bridges were destroyed by debris flows in Shenmu Community. However, there were no casualties because the residents evacuated before the debris flow. As for the Mujiliao Community, six people were buried in their homes by the debris

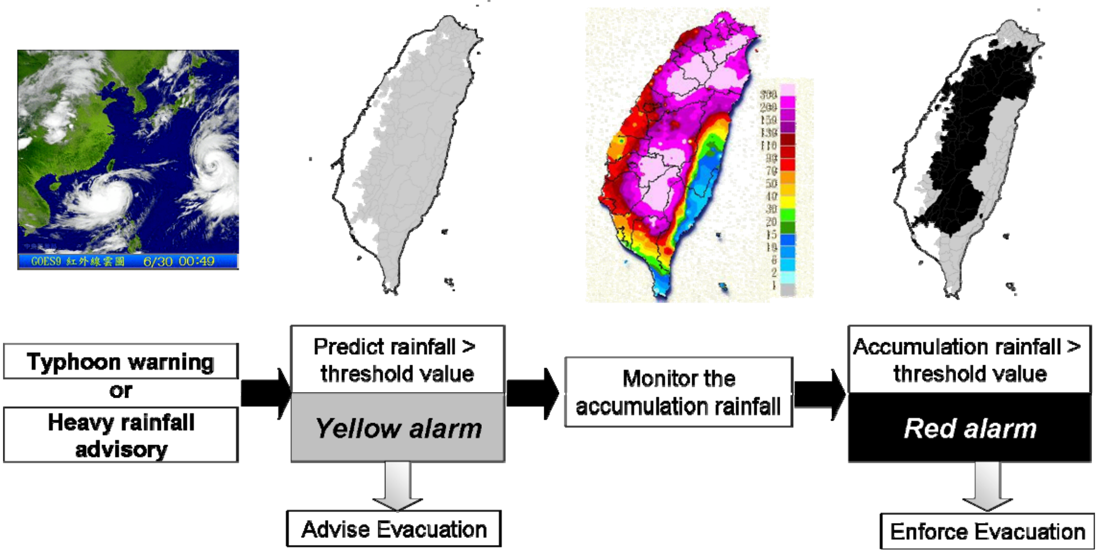


Figure 4 Current debris flow early warning system in Taiwan

flow because they refused to evacuate.

In the same situation, Typhoon Mindulle in July 2004 triggered debris flow disasters in Shenmu Community and damaged houses and bridges. All residents evacuated to shelters before the debris flows occurred. There were no casualties because of the successful early warning system (Figure 5).

3.2 Minduyou Community

Minduyou Community is located in Wufong Township, Hsinchu County. On 25 August 2004, Typhoon Aere caused debris flow disasters. Two houses were buried, and six deaths occurred, because this community had not implemented the debris flow evacuation drill. The residents suffered a high casualty rate because they had no warning and did not evacuate.

The hourly rainfall in Minduyou Community during 23~25 August 2004 is shown in Figure 6. The threshold value was estimated on 24 August, at 7:00 a.m. according to the rainfall threshold value for a debris flow warning. However, the actual time of the occurrence of debris flow was 9:55 a.m. on 25 August. Although the timing was sufficient for residents to evacuate, they did not completely evacuate on that day. The government reviewed whether previous promotions of community evacuation planning and drills led by the government and followed by residents could effectively have improved the residents' awareness of disaster prevention. After analysis of the review, the disaster prevention planning and "bottom-up" program led by residents and assisted by the government was started in 2004 for disaster resistant community operations (as summarized in Figure 1).

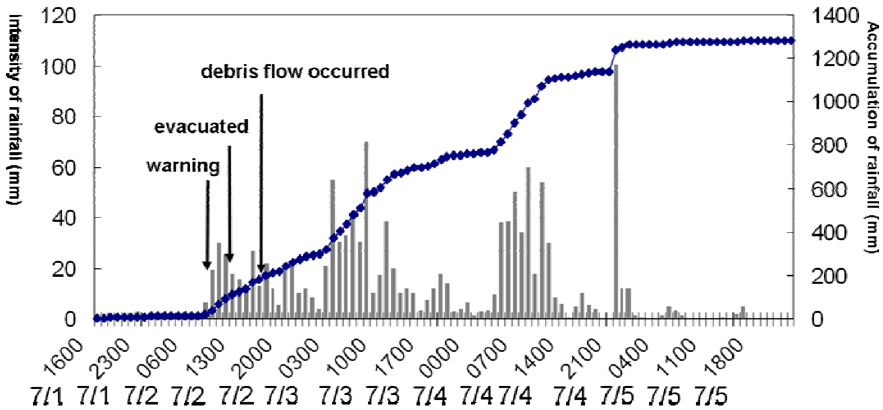


Figure 5 Intensity and accumulation of rainfall at Shenmu Community during Typhoon Mindulle, 2004

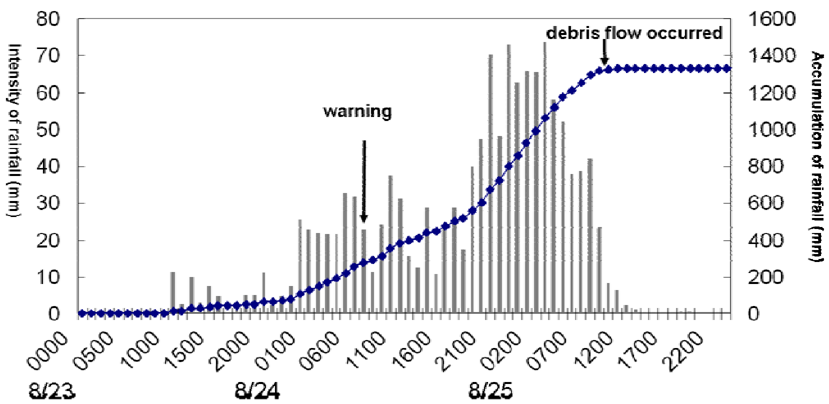


Figure 6 Intensity and accumulation of rainfall at Minduyou Community during Typhoon Aere, 2004

4 Achievement of Disaster Mitigation

The debris flow early warning system in Taiwan improved gradually during the past decade. As the evacuation drills were promoted, the casualties from debris flows disasters fell correspondingly year by year. Based on the mean numbers of casualties in debris flow disasters in Taiwan, each debris flow disaster caused 8.26 casualties before the Chichi Earthquake, which is clearly higher than the corresponding value of 2.36 after the Chichi Earthquake (Figure 7). The key factors for the decreased casualty rate were the debris flow evacuation drills promoted in Taiwan since 2000 and the progressive improvements in the debris flow early warning system, developed and enacted after Typhoon Toraji in 2001. The concept of preparedness and response in disaster management is now in effect, thus reducing the number of casualties.

The Chichi Earthquake occurred 10 years ago. According to surveys of the amount of sediment deposited in the main reservoirs in central Taiwan, the past seven years have had universally higher rates of sedimentation than the historical mean value, by a factor of 1.4~3.6 times higher (Figure 8), showing that sediment-related disasters are still occurring. In addition, typhoons attacked Taiwan 7.11 times annually between 2000~2008, which is clearly higher than the 4.84 occurrences before 2000 (Figure 9). The number of rain days with a rainfall intensity of 10~50 mm/hr during a typhoon increased almost 100% compared to the average of the past 45 years (Chen, 2009 and Liu et al., 2008). Although the natural environment had not changed, there were 10.22 debris flow events per year between 2000~2008, an increase of 1.42

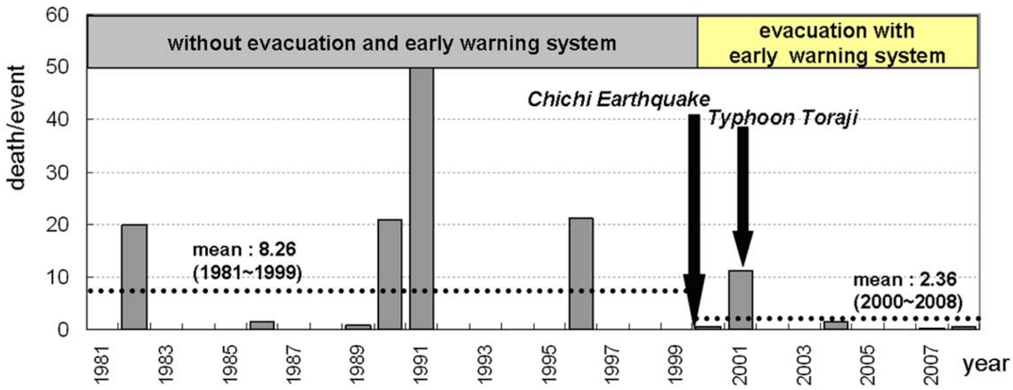


Figure 7 Statistics of historical debris flow disasters and the mean numbers of casualties

Table 1 Achievements of debris flow disaster mitigation funds

Year	Investments for debris flow hazard mitigation (million TW$)			events/yr	deaths/event (person)
	structure	non-structure	total		
2002	4669.40	50.00	4719.40	0	0.00
2003	7100.60	90.00	7190.60	2	0.00
2004	3874.50	70.00	3944.50	13	1.54
2005	3783.80	143.00	3926.80	18	0.00
2006	6378.70	116.40	6495.10	3	0.00
2007	6786.70	91.90	6878.60	6	0.17
2008	6674.50	142.50	6817.00	22	0.55
total	39268.20	703.80	39972.00	-	-

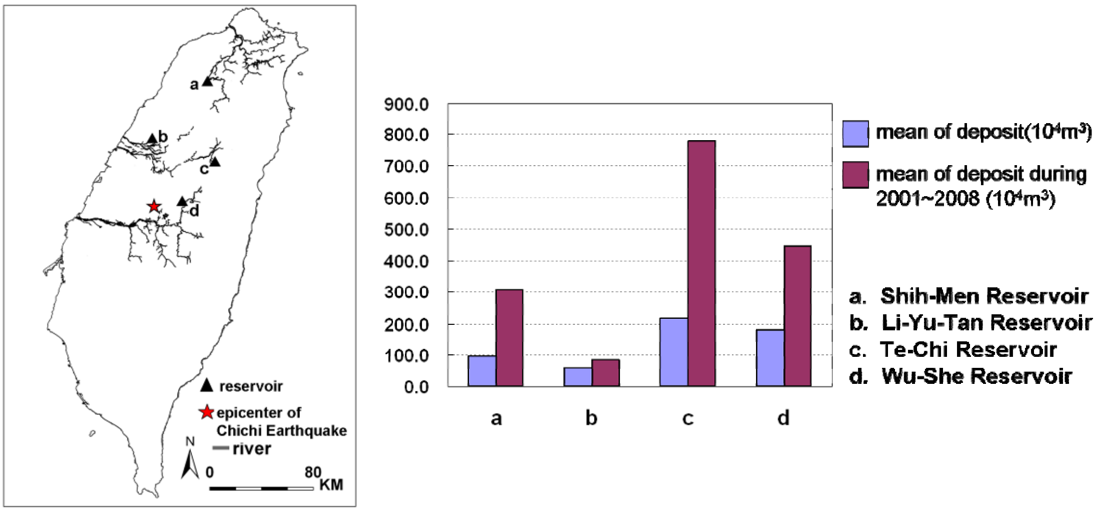


Figure 8 The mean annual sediment yields in the past seven years compared to historical values of reservoir sedimentation rates in central Taiwan

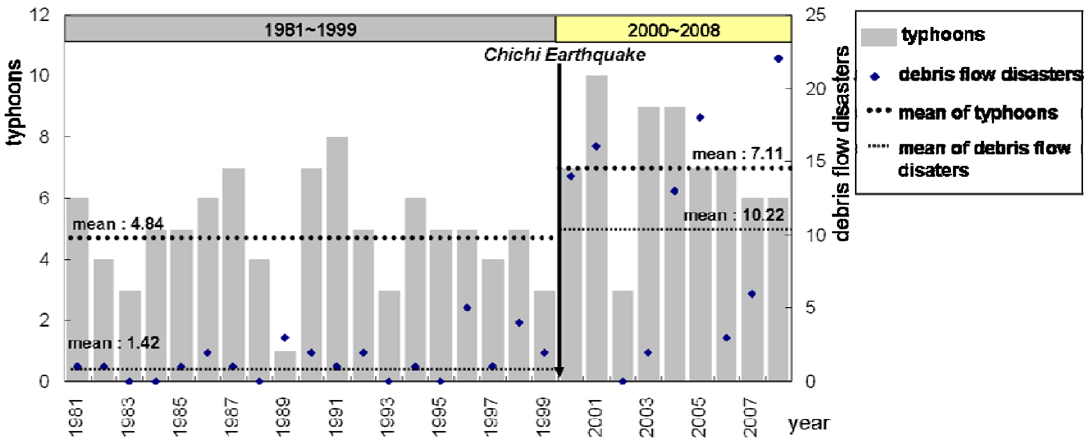


Figure 9 Historical typhoons and debris flow disasters in Taiwan

times compared to the frequency before the Chichi Earthquake (Figure 9). These environmental conditions indicate that the decreased number of casualties in debris flow disasters since 2000 is due neither to a decrease in the number of disasters nor to improvements of the natural environment but to the gradually improved early warning system, which allows residents to evacuate in advance.

According to the statistics for investment in debris flow disaster mitigation between 2002~2008 (Table 1), the investment for non-structural disaster prevention programs, such as evacuation and the early warning system, is far less than the investment for structural works, and the ratio for non-structural disaster prevention is only 1.06%~3.64% of the annual total investment. The frequency of debris flow disasters in the past seven years has obviously increased. It indicates that the aforesaid natural environment has not been improved; in addition, it shows that existing disaster mitigation programs cannot fully reduce the occurrence of debris flow disasters.

Although the ratio of investment for non-structural disaster prevention is low, the mean number of casualties in each debris flow disaster is far below the 8.26 who died before the Chichi Earthquake. This means that the funds invested in evacuation and the early warning system have produced notable and significant benefits.

5 Reflections on Typhoon Morakot in 2009

Typhoon Morakot brought extraordinarily

torrential rainfall when it struck central and southern Taiwan on August 8, 2009. The cumulative rainfall measured at many rainfall stations set historical records. The accumulation of rainfall in southern Taiwan on August 8-10 reached 2800 mm, which was significantly higher than the previous record of 1986.5 mm during Typhoon Herb in 1996. The continuous torrential rainfall during Typhoon Morakot caused many landslides and debris flow events. The most severe of these incidents was the landslide that buried the Shiaolin Community at 6:09 a.m. on August 9, causing more than 400 deaths. This was also the deadliest sediment-related disaster event in Taiwan's history.

This disaster occurred after the torrential rainfall caused a massive landslide on Mt. Shiandu, which is located behind the Shiaolin Community. The disaster buried most of the community in a heavy landslide (Figure 10). Afterwards, a landslide dam blocked the Chishan River (Chen and Hsu, 2009). One hour later, the landslide dam collapsed and buried other parts of the community in debris flow. The local residents could not evacuate from this compound disaster. Although the Shiaolin Community had conducted debris flow evacuation drills and professional volunteers had been recruited, the debris flow warning system could not prevent loss of life after either the landslide or the landslide dam collapse, in the latter case because of the short time between emplacement and failure. Shelters in the community were buried and washed away as well. The landslide dam failure and other secondary disasters have been gradually increasing due to climate change (Cui, et al. 2009), and we have limited knowledge and experience about these hazards. Therefore, disaster mitigation and risk management of compound disasters needs increased focus in future research and planning.

6 Conclusions

Sediment-related disasters, such as landslides and debris flows, have become frequent after the Chichi Earthquake in 1999. We have initiated non-structural disaster mitigation programs: debris flow evacuation drills in 2000, “bottom-up” disaster resistant communities in 2004, and the RTV early warning system in 2005. Overall, the decreased number of casualties from debris flows in the decade after the Chichi Earthquake is not due to a decrease of sediment related disasters, but to the gradual improvements in the early warning and evacuation systems.

The non-structural disaster prevention programs promoted and cooperatively managed by the government and local residents gradually reduced deaths from debris flows. However, the catastrophic disasters caused by Typhoon Morakot in 2009 remind us that the mitigation system needs to be continuously and rapidly improved and promoted for compound hazards, such as a landslide running out to dam a river. As a consequence, disaster prevention and evacuation systems for mountainous communities should be reviewed. Furthermore, because of the gradual increase in the frequency of extreme weather events, a major campaign should be undertaken to survey susceptible areas and improve community safety and evacuation systems in order to reduce future damage and fatalities.

(a) Before Typhoon Morakot (Google Earth, 2009) (b) After Typhoon Morakot (Chuo, 2009)

Figure 10 Disaster at Shiaolin community during Typhoon Morakot in 2009

Acknowledgements

This work was supported by the Soil and Water Conservation Bureau, Council of Agriculture, and National Basic Research Program of China (2008CB425802).

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