The Effectiveness of Risk Avoidance through Land-Use Planning in Debris Flow Area - A case study in southern Taiwan -

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Reducing natural hazard risk at the early stage of land-use planning had become an important issue after Typhoon Morakot event (of 2009) and the announcement of Geological Act (2010) and National Land Use Planning Act (in preparation) in Taiwan. Through the periodically overall review of urban planning the chance to re-adjust the exposures from possible hazards is provided, and was among the most effective measures to avoid natural hazard risk in landslide or debris flow prone area. This paper compares the difference of exposures before and after the 3rd and 4th overall reviews of urban planning in a landslide, debris flow prone scenic area in southern Taiwan. We also conduct debris flow quantitative risk analysis based on Risk=Hazard*Exposure*Vulnerability concept to calculate the changes in debris flow risk. The result shows that the changes of exposure due to land-use planning plays a key-role in reducing natural hazard risk in mountainous area.

Key words: land-use planning, urban planning overall review, debris flow, risk analysis

1. INTRODUCTION

Taiwan is located in the region with frequent earthquakes, together with hill slopes and high precipitation provides good conditions for landslides and debris flows. In the past decade, with the combination effect of extreme weather, the number and frequency of sediment related hazard were higher than previous century.

According to UN statistics, Taiwan is among the highest absolute GDP (Gross Domestic Product) (140 billion USD), as well as the highest relative GDP (33%) exposure due to precipitation or earthquake triggered landslides [*UNISDR*, 2009]. Especially during Typhoon Morakot in 2009, landslides and debris flows had resulted in tremendous economic losses and casualties for the society. Thus reducing natural hazard losses had become an important issue in Taiwan.

From the perspective view of risk avoidance, avoid hazard zone in the early stage of land-use planning is among the most effective option to reduce natural hazard risk. In the past few decades the idea of risk management had been implanted in land-use planning and building restrictions worldwide to reduce natural hazard losses.

Brody and Highfield [2013] had concluded from the case studies of 450 local communities in USA that avoiding flood through open space protection is the best strategy to reduce damage cause by floods; in New Zealand land-use planning had the potential to reduce natural hazard risks and build community resilience [*Glavovic et al.*, 2010]; in California, USA, areas with earthquake, flood, wildfire were mapped out to provide information for avoiding hazards in land-use planning decision making [*Real*, 2010]; for flood risk management in Europe, through appropriate land-use practice and avoiding construction of houses and industries in flood prone areas would prevent flood damages [*Santato et al.*, 2013]; in South-east Asia the Regional Consultative Committee (RCC) also believes that incorporate disaster risk information in land-use planning could lead to the modification of vulnerability parameters and further reduce risk, thus land-use planning has become an effective tool for disaster risk reduction [*RCC*, 2011].

In Taiwan the legislation related to hazard mitigation land-use planning includes Urban Planning Law (Article 27), Regulations for the

Periodical Overall Review of Urban Planning (Article 5, 6), Disaster Prevention and Response Act (Article 20). However how to incorporate spatial planning with mitigation planning was not specified thus resulted in the procedure of overall review of the hazard information becoming a mere formality.

Besides, from the content of most periodical overall review reports, the hazard susceptibility and hazard history were usually appeared as qualitative descriptions in Urban Hazard Mitigation Planning and Project Effectiveness Review chapters, without providing quantitative calculation or spatial distribution. In comparison with population estimation and public facility review, which provides quantitative analysis, the current hazard information could still be improved. This study proposes using quantitative risk analysis (QRA) to highlight the importance of proper land-use planning, and providing an example about how land-use planning would affect the natural hazard risk within a debris flow prone area. Through the comparison of buildings (the exposure, or the element at risk) in two periodical overall reviews planning (3rd and 4th periodical overall reviews), the difference and effectiveness of land-use planning for reducing debris flow risk are also discussed.

2. DEBRIS FLOW RISK ASSESSMENT AND MANAGEMENT

For natural hazard risk this study follows the definition, which is shown in Eq.(1), of UNDRO (Office of the UN Disaster Relief Co-Ordinator) [*UNDRO*, 1979]:

$$Risk = Hazard * Exposure * Vulnerability \quad (1)$$

The definition has been applied for natural hazard risk management and analysis in various fields worldwide, particularly in areas with respect to flood, tsunami, landslide and debris flow hazards [*Varnes*, 1984; *Crichton*, 1999; *Glade*, 2003; *Bell and Glade*, 2004; *Hufschmidt et al.*, 2005; *Papathoma-Köhle et al.*, 2007; *Fedeski and Gwilliam*, 2007; *Huttenlau and Stötter*, 2011; *UNISDR*, 2011; *Kaźmierczak and Cavan*, 2011; *Velasquez et al.*, 2012; *Shepard et al.*, 2012].

For debris flow risk in Taiwan, *Tsao et al.* [2012] had defined the components in Eq. (1) as follows:

Risk: The possible consequences when debris flow hazard occurred.

Hazard: Matters discussing triggering factors, return period, inundation area, depth, velocity, boulder size and impact force of debris flow.

Exposure: Elements at risk, for example crops and other valuable infrastructures or utilities within the possible inundation area, types and numbers of buildings and their residents.

Vulnerability: The damage ratio under specific magnitude, inundation height, velocity of debris flow to different types of elements at risk.

Risk management framework has been introduced in several nations or regions worldwide [*AGS*, 2000; *Fell et al.*, 2005; *Hufschmidt et al.*, 2005] for better management of natural hazard.

In Taiwan, a debris flow risk management framework (**Fig. 1**) was proposed in 2008 [*Tsao et al.*, 2010; *Tsao et al.*, 2012], and has been applied to 148 potential debris flow torrents in Taiwan [*Tsao et al.*, 2012]. From **Fig. 1**, different risk treatments should be carry out after risk assessment, and land-use planning falls into "risk avoidance" category in the corresponding risk treatments.

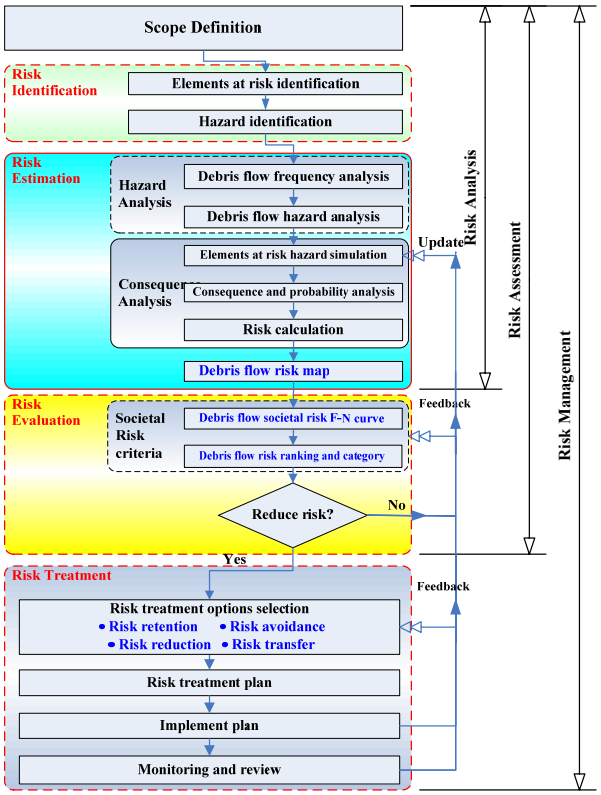

Fig. 1 Debris flow risk management framework (after *AGS*, 2000; *Tsao et al.*, 2010, 2012)

3. METHODOLOGY AND STUDY AREA

3.1 Quantitative risk analysis

Quantitative risk analysis (QRA) may be expressed as "a numerical scale concerning hazard probability, values of elements at risk, degree of loss and economic consequences" [*Blahut et al.*, 2014].

QRA is important for landslide and debris flow hazard because the result can be quantified and compared with each other, and provides the prioritization of management and mitigation actions to limited resources [*Corominas et al.*, 2014], and is vital information for decision makers in disaster mitigation. Recommended methodologies for landslide or debris flow quantitative risk analysis has been proposed since 1990's [*Dai et al.*, 2002; *Bell and Glade*, 2004; *Fuchs et al.*, 2007; *Friele et al.*, 2008; *Jaiswal et al.*, 2011; *Jakob et al.*, 2012; *Corominas et al.*, 2014], in this study we followed Eq.(2) proposed by *Tsao et al.* (2012) for quantitative debris flow risk analysis of building damages and fatalities.

$$Risk = P_{H|T_M} \times P_{S|H} \times P_{T|S} \times V_{prop|S} \times E_{prop} \qquad (2)$$

Where $P_{H|TM}$: Probability of different magnitude debris flow to occur, including the geological, meteorological conditions.

$P_{S|H}$: Probability of spatial impact of each element at risk, topographic data (DEM, Digital Elevation Model) is included. Within the debris flow inundation area, the value is 1, otherwise the value is 0.

$P_{T|S}$: Probability of temporal impact of each element at risk. For elements at risk which does not move, as building, the value is 1. For residence house occupants, the value is 0.75 (18 hours per day), for school students and faculties the value is 0.375 (9 hours per day).

$V_{prop|S}$: Vulnerability of each type of elements at risk, ranging from 0 to 1.

E_{prop}: The value of each element at risk in NT dollars (TWD) or fatalities.

This study follows the concept of Eq.(2) and the 10 steps of risk analysis in **Fig. 2** [*Tsao et al.*, 2012] for quantitative debris flow risk analysis.

Fig. 2 includes the following procedures:

1. Scope definition (steps 1 to 2)

Identify the study area and types of losses to be analyzed, in this study we focus on building damages and fatalities within the building.

2. Risk identification (steps 3 to 5)

Field investigation has been conducted to gather elements at risk information (including types and values), debris flow hazard history, and triggering factors of debris flow. The information gathered from field is stored in GIS format.

3. Hazard analysis (steps 6 to 7)

In this study the two-dimensional commercial model FLO-2D [*O'Brien et al.*, 1993; *O'Brien*, 2006], which has been adopted in Taiwan for debris flow simulation [*Hsu et al.*, 2010; *Lin et al.*, 2011; *Peng and Lu*, 2013], is chosen for numerical simulation, with 5m*5m DEM topographic model. Rainfall data (meteorological information) is gathered for input, several return periods of simulation has been conducted (5, 10, 25, 50, 100, 200 years) to understand the flow velocity, inundation height and inundation area of the torrent.

4. Consequence analysis (steps 8 to 10)

The vulnerability curve for each type of elements at risk (building, human) is selected. This study applies the vulnerability curves in previous studies for damage calculation [*Tsao et al.*, 2010; *Lo et al.*, 2012]. Overlaying the simulation result with elements at risk GIS layer and calculate with vulnerability curves to determine the damage value, both economic losses of the buildings and fatalities are generated to annual average loss.

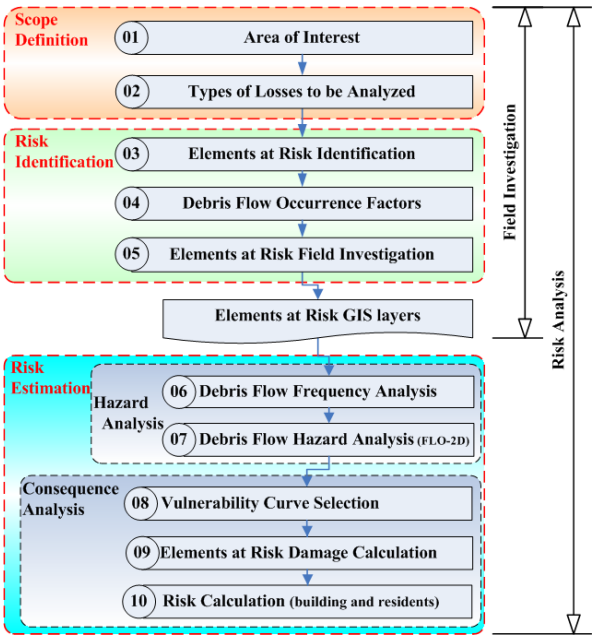

Fig. 2 Debris flow risk analysis procedure (modified from *Tsao et al.*, 2012)

3.2 Study area

Jhonglun Scenic Area locates in Chiayi County and is famous for its hot spring (**Fig. 3**), it is located at 302K of Provincial Highway No.3, about 30 minutes driving distance from downtown Chiayi City. After the discovery and excavation of hot spring wells in the region during 1980s, local government announced the planning of 'Jhonglun Scenic Area' in 1985, and the aftermath periodical overall reviews of the plan in 1990, 2000, 2009, and 2012 [*Chiayi County Government*, 2009, 2012]. The scenic area was incorporated into Siraya National Scenic Area in June, 2012. The list of urban planning and time track are shown in **Table 1** and **Fig. 4**. The total area of the scenic area is 107.82 Ha, which includes nearly the entire watershed of

Chiayi DF051 potential debris flow torrent. The outlays of the scenic area (3rd and 4th periodical overall review) are shown in **Fig. 5**.

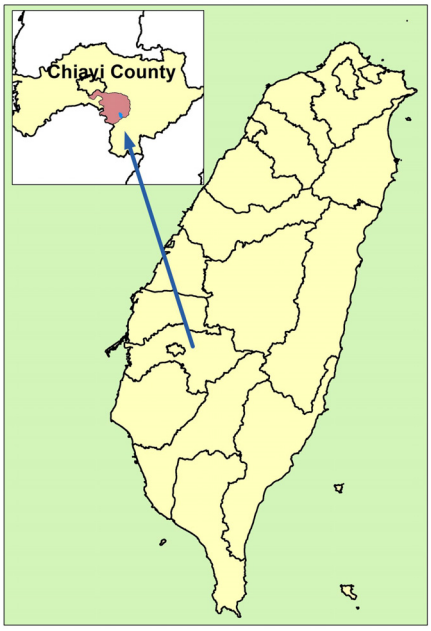

Fig. 3 Location of Jhonglun Scenic Area

Table 1 Basic information of Jhonglun Scenic Area Plans

Name of plan	Effective date	Corresponding law	Plan target year	Remark
Jhonglun Scenic Area Plan	Jan., 1985	Urban Planning Law (Article 12, 16)	1996	-
1st periodical overall review	Jun., 1990	Urban Planning Law (Article 26)	1996	Chi-Chi earthquake, 1999
2nd periodical overall review	Oct., 2001	Urban Planning Law (Article 26)	2011	Typhoon Nari, 2001
3rd periodical overall review	Nov., 2009	Urban Planning Law (Article 26)	2011	0612 Heavy rainfall, 2005
4th periodical overall review	(under public review)	Urban Planning Law (Article 26)	2036	Typhoon Morakot, 2009

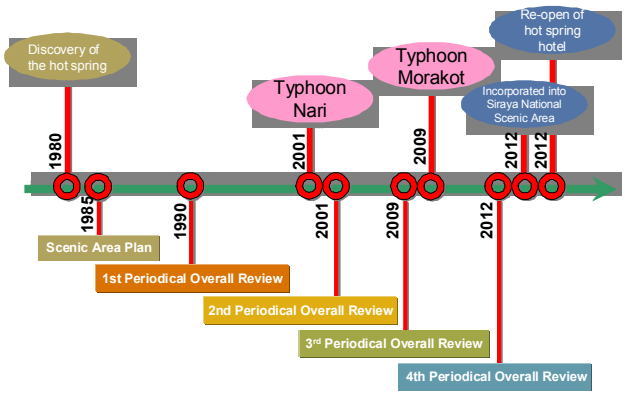

Fig. 4 Event time-line of Jhonglun Scenic Area

Table 2 Main modification items of the 3rd and 4th Periodical Overall Review of Jhonglun Scenic Area Plan

Name of plan	Plan target year	Plan annual visitors	Main changes
3rd periodical overall review	2011	248,480	1. School district modified to hot spring resort. 2. Modification of hazard mitigation plan.
4th periodical overall review	2036	126,000	1. Public land (include commercial district) modified to park area with low intensity use. 2. Hotel district and road area modified to recreation area. 3. Protected area modified to administration district (police station). 4. Parking area modified to hot spring well area. 5. Gas station area modified to agriculture district.

The elevation in the study area is between 300 and 600 meters, 76.8% of the total area contains slopes greater than 30%. According to the Soil and Water Conservation Law, development on these slopes is forbidden. The geology formation within the region is mainly consisted with mudstone or shale, both are relatively weak in strength. The eastern and southern part of the region is penetrated by Chukou fault.

The hot spring in the region is capable of providing 180 tons daily to fulfill the estimated 2 hotel districts and 2 public bathing zones. The estimated tourists for the scenic area was set at 248,480 visitors annually in the 3rd periodical overall review, however in the 4th overall review the number was reduced to 126,000 visitors annually, because the scenic area was redefined as "easy slow life style", according to post-Morakot regional reconstruction guideline. The planned investment of more than 140 million TWD (approximately 4.6 million USD) in 5 years (as in 3rd review) for public facility and infrastructures was also reduced to 47 million TWD in 25 years (as in 4th review).

From the definition of natural hazard risk (Eq.(1)) one could understand that the change of exposure (elements at risk) would lead to the change of risk. Three sets of exposures (building layout) are set as inputs to represent different scenarios: (1) layout at 2008 (before Typhoon Morakot); (2) assumed the layout of the 3rd periodical overall review had been executed; (3) assumed the layout of the 4th periodical overall review had been executed. The building information gathered through field investigation and remote sensing interpretation include building area, plate number, number of floors, construction material, usage type, direction of openings, number of residents, to calculate the

spatial probability, temporal probability and the value of the buildings.

According to the layout of the 3rd periodical overall review, 2 hotel districts (marked as A and B in **Fig. 5a**) and 1 commercial district (marked as C in **Fig. 5a**) will be developed, the building coverage ratio and floor area ratio in hotel district are 30% and 60% respectively, for commercial district are 60% and 180% respectively [*Chiayi County Government*, 2009]. This study assumed a 6-storeys hotel with 40 guest rooms and capacity of 90 guests and staffs in the hotel district (marked as A) and a 5-storeys hotel with 40 guests and staffs in the other hotel district (marked as B). For commercial district (marked as C) a roll of four 2-storeys shops (each with 6 staffs) was assumed. The information and economic cost of these buildings are calculated with unit price information from Taiwan Architects Association and stored in GIS format.

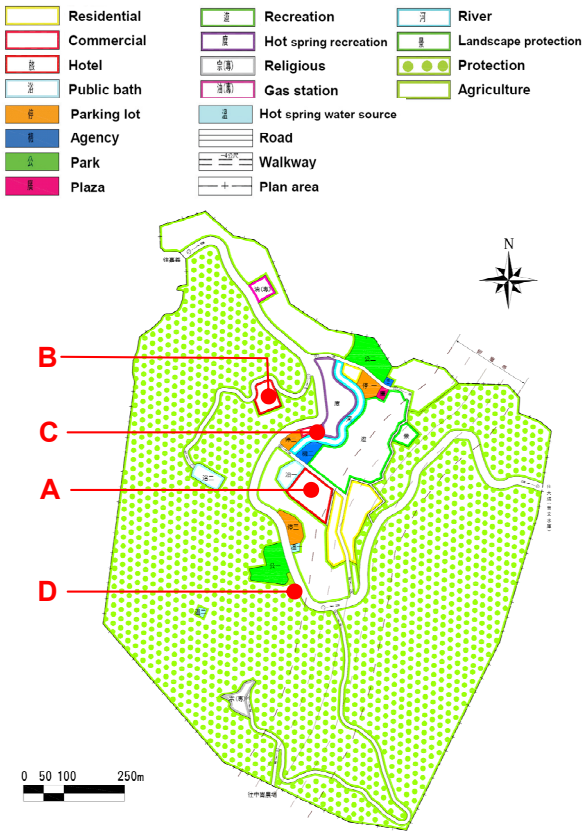

Fig. 5a Layout of the 3rd periodical overall review of the Jhonglun Scenic Area (see 3.2 for the explanation of A, B, C, D)

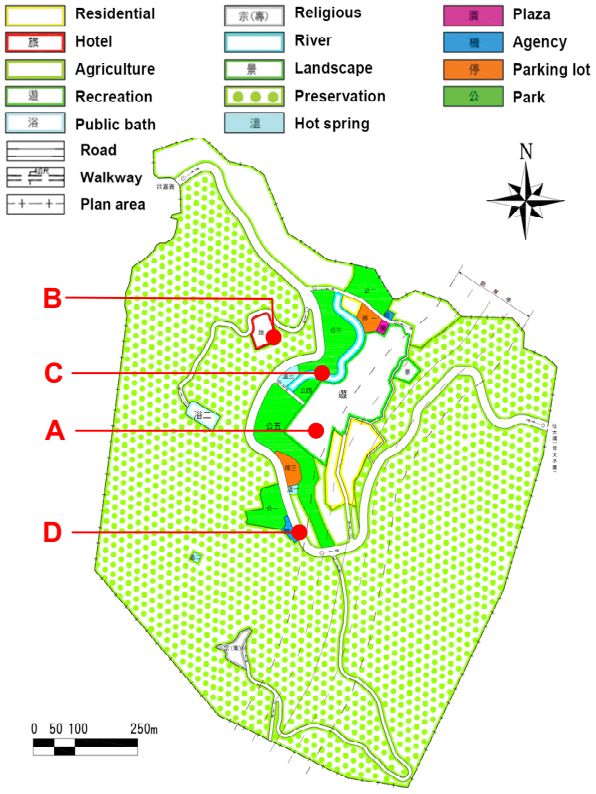

Fig. 5b Layout of the 4th periodical overall review of the Jhonglun Scenic Area (see 3.2 for the explanation of A, B, C, D)

According to the layout of the 4th periodical overall review, which followed the guideline of "national conservation priority" reconstruction policy, areas affected by debris flow during Typhoon Morakot were modified to park or recreation area with low-intensity land-use. One of the hotel district (marked as A in **Fig. 5b**) and the commercial district (marked as C in **Fig. 5b**) were modified to park, one protected area (marked as D in **Fig. 5b**) was modified to police station with 50% building coverage ratio and 100% floor area ratio. These were also updated in building GIS layers to reflect the changes of exposures.

3.3 Landslide and debris flow hazard

Although the Soil and Water Conservation Bureau did not identify and announce the torrent in the study area as potential debris flow torrent (Chiayi DF051) until 2009, the watershed was already showing signs of debris flow hazard potential. Through interpretation of satellite images and aerial photos of different period (**Fig. 6**), this study established the landslide inventories in the watershed and the statistics are listed in **Table 3**. In 1989, there were already 38 landslides with total area of nearly 11 Ha, which represented 3.81% in landslide ratio. The landslide area increased after

0612 heavy rain in 2005 and skyrocketed to 54 landslides and 12.15% of total watershed after Typhoon Morakot (2009).

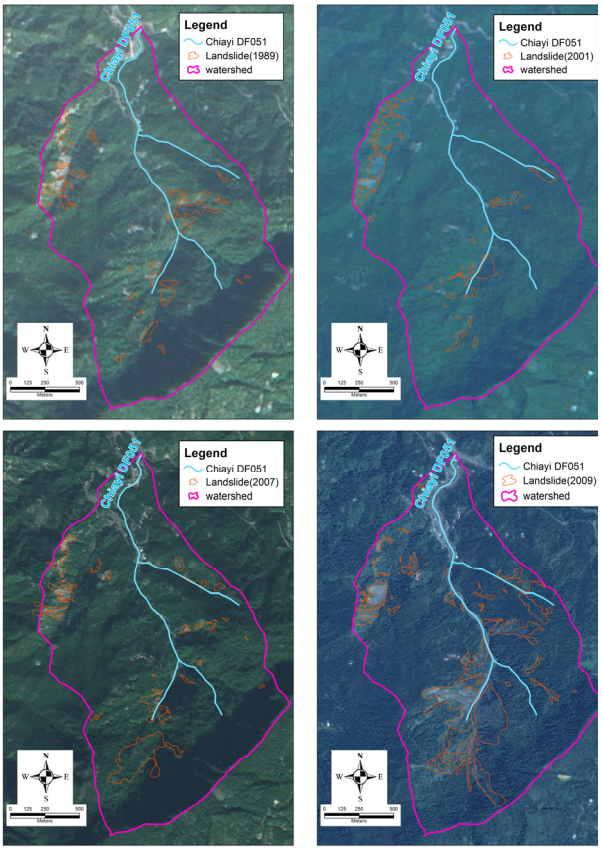

Fig. 6 Landslides and satellite images of the Chiayi DF051 watershed in different years

Table 3 Landslide statistic of the Chiayi DF051 watershed

Year	Event	Number of landslides	Total landslide area (Ha)	Landslide ratio (%)
1989	Before Chi-Chi earthquake	38	10.99	3.81
2001	After Typhoon Nari	41	10.10	3.50
2007	After 0612 heavy rain	60	15.18	5.26
2009	After Typhoon Morakot	54	35.05	12.15

Fig. 7 UAV photo of Chiayi DF051 torrent after Typhoon Morakot (source: SWCB, Taiwan)

Through interview with the local residents, aerial photo interpretation, and historical data collection, this study is able to identify at least two debris flow events in the study area.

1. During Typhoon Nari, 2001, there was a small scale of debris flow event in the torrent and affected one residential house.

2. During Typhoon Morakot, 2009, more than 1,500 mm of rainfall triggered several landslides, the following debris flow destroyed a bridge and buried several houses, and the abandoned elementary school was half buried in debris, and one resident was killed. **Fig. 7** shows the status of the study area after Typhoon Morakot.

Also in the report of the 3rd periodical overall review of the study area [*Chiayi County Government*, 2009], the chapter of Urban Hazard Mitigation Planning reveals that *"Chayi County Government had identified the 5th neighborhood in Jhonglun village as a potential debris flow prone area"*, however the information was not further utilized into mapping of debris flow inundation area, so in the 3rd overall review it was unable to have proper strategies and could only suggest to *"set the building line back for 10 meters when facing the torrent"*. The setback distance is inadequate when consider the inundation area would usually greater than 10 meters when larger magnitude debris flow occurred.

4. RESULTS

4.1 Quantitative risk analysis result

The consequence analysis of elements at risk (exposure) has been conducted following the 10 steps in **Fig. 2**, the annual average economic losses of buildings and fatalities were calculated from the results of 6 return period debris flow simulation (**Fig. 8** shows 100 and 200 years). From the comparison of **Fig. 8** and **Fig. 5**, we can find out that the simulation result of 100 and 200 years return period have covered large part of the area, which was the scenario during Typhoon Morakot.

Three sets of exposures were overlaid with the simulation result and applied with vulnerability curves to calculate the risk in each scenario and generated into annual average losses, the result is shown in **Table 4** and **Fig. 9**.

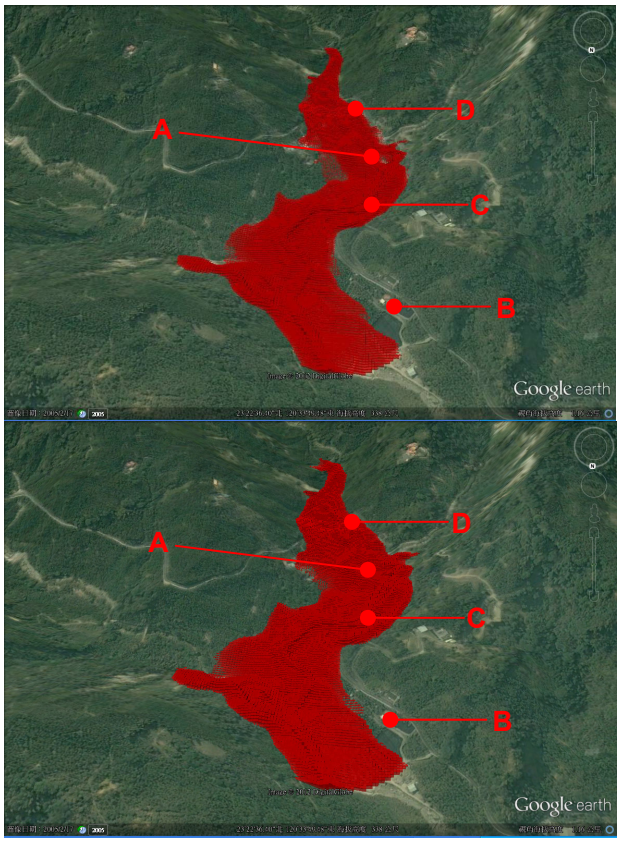

Fig. 8 Different return period debris flow numerical simulation results of Chiayi DF051 torrent (top: 100 years; bottom: 200 years)

Table 4 Risk calculation result of different exposures under different return periods

Return period (yr)	Annual exceeding probability	2008		3rd overall review		4th overall review	
		Building losses (TWD)	Fatality	Building losses (TWD)	Fatality	Building losses (TWD)	Fatality
-	100%	-	-	-	-	-	-
5	20%	2,813,364	6.0003354	4,022,620	8.0007826	2,808,883	6.0003292
10	10%	3,321,983	6.0003354	4,846,325	8.6957452	3,239,135	6.0003292
25	4%	4,764,094	8.5019237	7,224,839	13.6769250	4,301,699	8.2260237
50	2%	15,721,437	32.3322729	39,853,405	74.0704675	9,756,510	15.3324252
100	1%	28,820,284	56.7245526	76,760,834	119.4350760	22,622,733	39.7247049
200	0.5%	37,693,597	64.5306026	125,492,901	172.7247376	31,568,967	47.5307550
Annual average losses		2,268,544	4.5919994	3,974,118	7.2817207	2,090,137	4.1559640

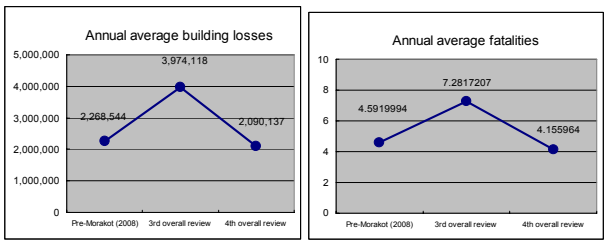

Fig. 9 Annual average losses under different exposures (left: building losses; right: fatalities)

4.2 Comparison

Table 4 shows that if the 3rd periodical overall review had been executed, the annual average loss of building might rise from 2.3 million to 4.0 million TWD (75% rise), and the annual average fatality might rise from 4.592 to 7.282 person (59% rise).

For the case of the 4th periodical overall review, which followed the guideline of "national conservation priority" reconstruction policy, the annual average loss of building is 47% lower compare with the 3rd overall review, even is 8% less than pre-Typhoon Morakot (2008). The annual average fatality is 43% less than the 3rd overall review, and is nearly 10% lower than pre-Typhoon Morakot.

From the layout of exposures of the 2 urban planning and hazard simulation result, we learn that in the 3rd overall review the commercial district and one of the hotel districts were located in the possible inundation area of debris flow, which increased the risk significantly. Moreover, in the review of urban planning, the proposed emergency shelters were community activity center and one of the hotel districts area (marked as A in **Fig. 5**), these 2 locations were under direct threat of debris flow.

In the 4th overall review, the spatial planning had reduced the land-use intensity of public lands, in which commercial and hotel districts were modified to park or recreation area with low possibility of human activities, thus the annual average risk become the lowest of the three, shows a good practice of risk avoidance treatment. However the lesson was learned after tremendous losses in Typhoon Morakot, if risk analysis and risk assessment of debris flow had been conducted after Typhoon Nari (2001), the outcome of the 3rd periodical overall review might be different, and losses in Typhoon Morakot might be lower.

5. DISCUSSIONS

Taiwan is located in a highly vulnerable zone, with high frequency earthquakes and strikes of typhoons. Thus, landslides and debris flow will still be the most common natural hazards in the future. However besides realizing the possible impact of natural hazard, establishing the regulation, classification, and restriction based on different level of hazard risk should be the next step, as shown in the examples of *Mikoš et al.* [2007] and *Zimmermann* [2004]. Through carefully reviewed land-use planning and building code regulation, most natural hazard risks can be avoided in advanced.

As this study shows, the results of quantitative risk analysis of landslide and debris flow hazard can provide valuable information for future land-use planning, which should be integrated into

Geological Act (Geological sensitive area) and National Land Use Planning Act in Taiwan in the future.

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