Debris Flow Risk Assessment and Land-Use Planning – A Case Study of Jhonglun Hot Spring Area

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***ABSTRACT*:**, The Jhonglun Scenic Area in Chiayi County, is famous for its hot spring, the region was hit by debris flow with tremendous losses and resulted with dramatic change of the landscape during Typhoon Morakot in 2009. The most effective strategy for reducing natural hazard risks is through land-use planning. Following the concept of Risk=Hazard*Exposure*Vulnerability, this study conducted risk identification through the collection of landslide inventory and history debris flow hazard mapping of Chiayi DF051 potential debris flow torrent. Together with elements at risk information from field investigations, the risk analysis was conducted with several return periods debris flow simulation to recognize the possible economic losses and fatalities by debris flow. The identified high risk areas in Jhonglun Scenic Area were compared to the current special district planning to understand the spatial distribution of high risk areas. The result shows that some of the designated zones were among the areas with high debris flow risks, which further indicates that land-use planning should consider the consequences of natural hazards. The result of this study provides one of the first steps for land use planning restrictions within the potential debris flow region.

KEYWORDS: debris flow, risk analysis, land-use planning

1. INTRODUCTION

Natural hazard is defined as a natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR, 2009a). As for natural disaster risk, risk can be defined as the likelihood, or more formally, the probability that a particular level of loss will be sustained by a given series of elements as a result of a given level of hazard. The elements at risk consist of the population, communities, the built environment, the natural environment, economic activities and services which are under threat of disasters in a given area (Alexander, 2000).

According to UN statistics, Taiwan is among the highest absolute GDP (Gross Domestic Product) (140 billions USD), as well as the highest relative GDP (33%) exposure due to precipitation or earthquake triggered landslides (UNISDR, 2009b). Especially during Typhoon Morakot in 2009, the numerous landslides and debris flows have resulted in tremendous economic losses and casualties for society.

This study aims to provide an example about how land-use planning could affect the natural hazard risk within debris flow area, also the importance of risk assessment and risk management to reduce risk.

1.1 Debris flow risk assessment and management

UNDRO (1979) defined natural hazard risk by Eq. 1 as:

$$Risk = Hazard \times Exposure \times Vulnerability \tag{1}$$

This definition had been applied for natural hazard risk analyses in various fields, particularly in areas with respect to flood, landslide and debris flow hazards (Varnes 1984; Glade 2003; Bell and Glade 2004; Hufschmidt et al., 2005; Papathoma-Köhle et al., 2007; Huttenlau and Stötter, 2011; UNISDR, 2011).

For debris flow risk in Taiwan, Tsao et al. (2012) 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.

The risk management framework for natural hazard had been adopted in several nations or regions around the world (Australian Geomechanics Society, 2000; Fell et al., 2005; Hufschmidt et al., 2005). In Taiwan, a debris flow risk management framework (Fig.1) was proposed in 2008 (Tsao et al., 2010). From the framework of Fig.1 (include risk analysis and risk evaluation) the selected risk treatment should be conducted after risk assessment.

Risk avoidance was among the possible risk treatments, and land-use planning is among the most effective tool to reduce natural hazard risk by avoiding risk (Glavovic and Saunders, 2010; RCC, 2011). Land-use planning had been applied in several European countries to reduce landslide or debris flow risk for years. In Switzerland, to reduce debris flow risk a set of regulations in the local land-use plan and building code defines what is possible in red, blue and yellow zones (Zimmermann, 2004). From Eq. 1 it is straight forward that by the carefully planning of land-use could reduce the possible exposures (elements at risk) within hazardous areas, which in turn effectively reduce the degree of risk.

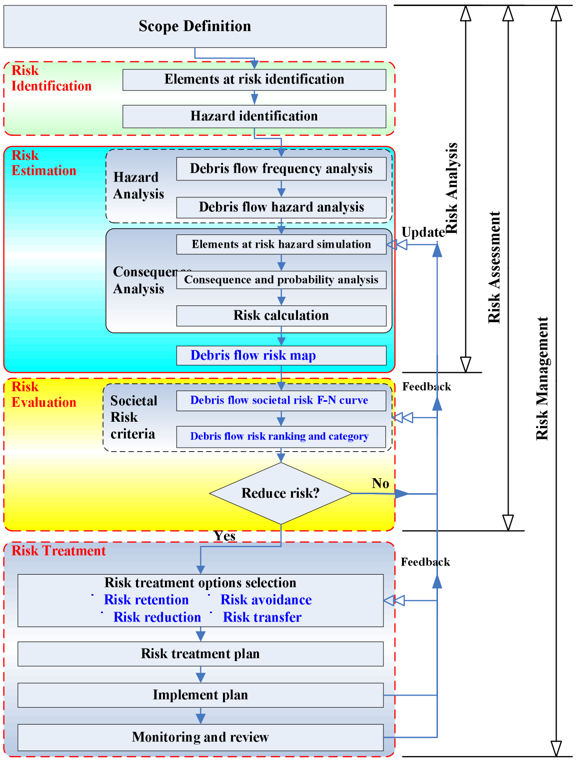

Fig. 1 Debris flow risk management framework (after Australian Geomechanics Society, 2000; Tsao et al., 2010)

However, in Taiwan the method for implantation the idea of risk reduction in land-use planning was still in a preliminary stage, also the tool for quantifying the necesity of land-use planning was still lacking. This study proposed a quantitative risk analysis (QRA) procedure to highlight the importance of proper land-use planning.

2. METHODOLOGY AND STUDY AREA

2.1 Quantitative risk analysis

Quantitative risk analysis was applied for landslide and debris flow risk analysis worldwide (Dai et al., 2002; Bell and Glade, 2004; Fuchs et al., 2007; Friele et al., 2008), Tsao et al. (2010) proposed Eq. 2 for quantitative debris flow risk analyses in Taiwan.

$$L_{prop|H} = \sum_{j} P_{S|H,\,j} \times P_{T|S,\,j} \times V_{prop|S,\,j} \times E_{prop,\,j} \qquad (2)$$

where $L_{prop|H}$ = the summation of all damages to each element at risk, under a certain debris flow hazard event; j = the total number of the elements; $P_{S|H,j}$ = the probability of the spatial impact of a debris flow event on each element at risk exposed; $P_{T|S,j}$ = the probability of temporal impact on each element at risk; $V_{prop|S,j}$=the vulnerability of each type of element at risk; $E_{prop,j}$ = the economic value of each element at risk. When discussing debris flow risk analyses for buildings exposed, the variable $V_{prop|S}$ becomes a vital component and represents the vulnerability of buildings exposed to a debris flow impact.

This study followed the concept of Eq.2 and the ten steps of risk analysis in Fig.2 (Tsao et al., 2010) for conducting risk assessment.

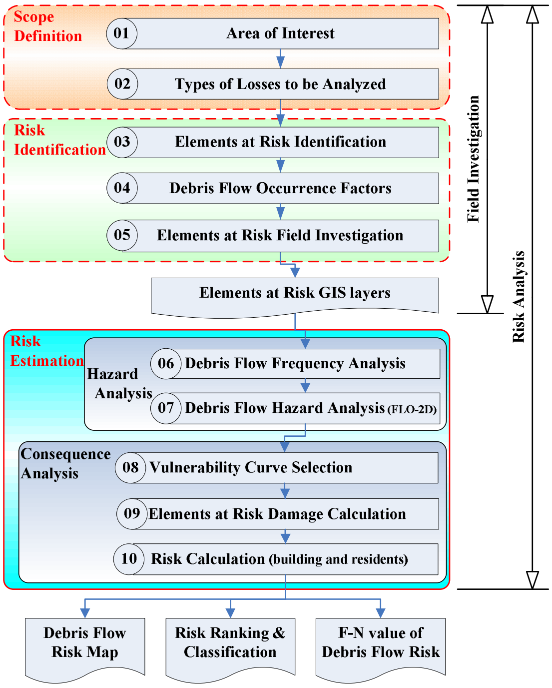

Fig. 2 Debris flow risk analysis procedure (after Tsao et al., 2010)

Fig.2 includes the following procedures:

1. Risk identification

Field investigations were 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 was stored in GIS format.

2. Hazard analysis

In this study the two-dimensional commercial model FLO-2D, which was adopted in Taiwan for debris flow simulation (Hsu et al., 2010; Lin et al., 2011), was used for simulation. Rainfall data were gathered for input, several return periods of simulation were conducted (5, 10, 25, 50, 100, 200 years) to understand the flow velocity, inundation height and inundation area of each torrent.

3. Consequence analysis

The vulnerability curve for each type of elements at risk was selected. This study applied the vulnerability curves in previous studies (Tsao et al., 2010; Lo et al., 2012). Overlaying the simulation result with elements at risk GIS layer and calculate with vulnerability curve to determine the damage value, both economic losses and fatalities were generated to annual average loss.

2.2 Study area

Jhonglun Scenic Area located in Chiayi County and is famous for its hot spring (Fig.3). After the discovery and excavation of hot spring wells in the region during 1980s, local government has announced the planning of ‘Jhonglun Scenic Area’ in 1985, and the aftermath overall reviews of the plan in 1990, 2000 and 2009 (Chiayi County Government, 2009). The total area of the scenic area planning is 108.9 Ha, which includes nearly the entire watershed of Chiayi DF051 potential debris flow torrent. The area distribution of the scenic area is shown in Tab.1 and Fig.4.

Table1 Land-use planning areas of Jhonglun Scenic Area (Chiayi County Government, 2009)

	Item	Area (Ha)	Percentage (%)
Land use district	Residential	1.67	1.53
	Commercial	0.13	0.12
	Hotel	1.28	1.18
	Public bath	0.58	0.53
	Recreation	3.1	2.85
	Hot spring recreation	1.03	0.95
	Scenic protection	0.23	0.21
	Religious	0.33	0.3
	Gas station	0.25	0.23
	Protected	82.25	75.53
	River	0.76	0.7
	Agriculture	8.06	7.4
	Sub total	99.67	91.52
Public facility	Administration	0.23	0.21
	Parking area	0.68	0.62
	Hot spring well	0.08	0.07
	Park	1.43	1.31
	Square	0.06	0.06
	Road	6.75	6.2
	Sub total	9.23	8.48
	Total	108.9	100

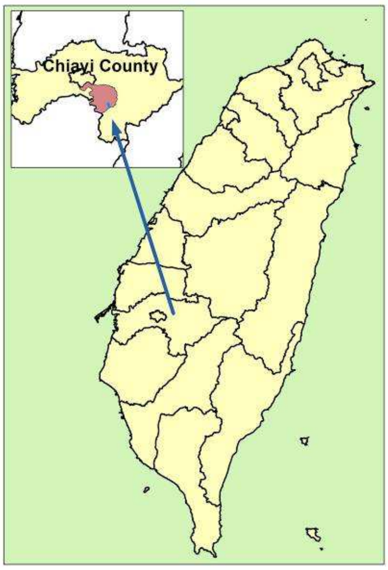

Fig. 3 Location of Jhonglun Scenic Area

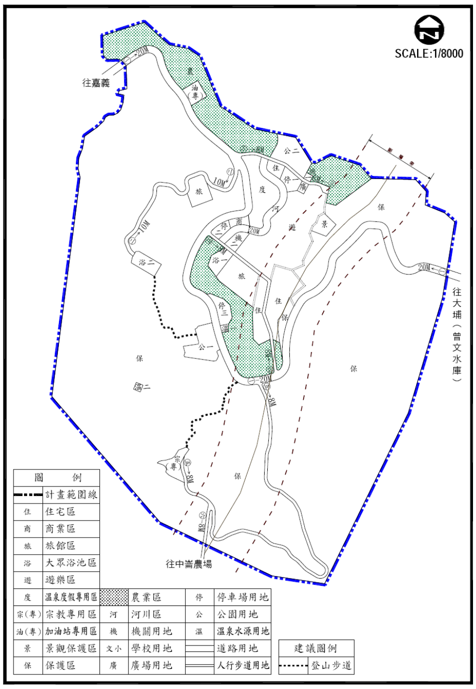

Fig. 4 Layout of Jhonglun Scenic Area Plan (Chiayi County Government, 2009)

The average elevation in the area is between 300 and 600 meters, 76.8% were slopes greater than 30%. According to the Soil and Water Conservation Law the development on these slopes were forbidden. The geology formation within the region is mainly consisted with mudstone or Shale, both were relatively weak in strength. The eastern and southern part of the region was 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 planning were set at 248,480 visitors annually and local government planned to invest more than 140 million TWD (approximately 4.6 million USD) in 5 years to complete the public facility and infrastructures.

The exposures within the study area would increase if the proposed Jhonglun Scenic Area land-use planning had been executed, especially in two new hotel districts and 1 commercial street. To compare the differences in exposures (and of course, the outcome of risk analysis) this study assumed a 6-storeys hotel with capacity of 90 occupants and staffs in the first hotel district and a 5-storeys hotel with 40 occupants and staffs in the second hotel district. For commercial district a roll of four 2-storeys shops (each with 6 staffs) was assumed. The economic cost of the buildings was calculated with unit price information from Taiwan Architects Association.

2.3 Landslide and debris flow hazard

Although the Soil and Water Conservation Bureau did not identify and announce the wild creek as potential debris flow torrent (Chiayi DF051) until 2009, the watershed was already showing the signs of future disasters. Through interpretation of satellite images and aerial photos of different period (Fig.5), this study mapped out the landslide areas in the watershed. In 1989, there were already 38 landslides with total area of nearly 11 Ha, which represented 3.81% in landslide ratio. The landslide areas increased after 0612 heavy rain in 2005 and skyrocketd to 54 landslides and 12.15% of total watershed (Tab.2).

Table2 Landslide area statistic of the Chiayi DF051 watershed

Year	Event	Number of landslides	Total area (Ha)	Landslide ratio (%)
1989	Before Chi-Chi earthquake	38	10.99	3.81
2001	After Typhoon Nari	41	10.10	3.5
2007	After 0612 heavy rain	60	15.18	5.26
2009	After Typhoon Morakot	54	35.05	12.15

Through interview with local residents, aerial photo interpretation, and historical data collection, at least two events were identified in Chiayi DF051 torrent.

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 with one fatality. The torrent was still full of debris and under reconstruction after one year (Fig.6).

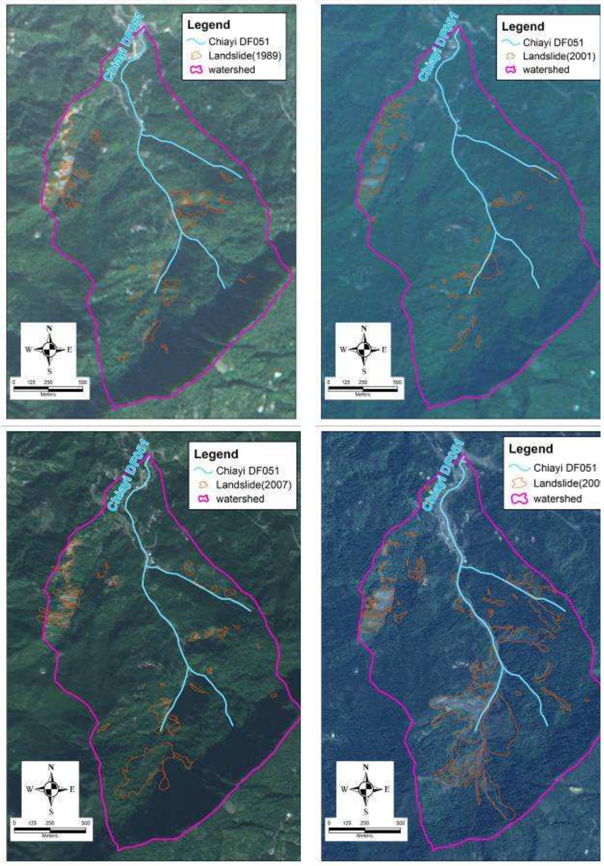

Fig. 5 Landslides and satellite images of the Chiayi DF051 watershed (1989, 2001, 2007, 2009)

Fig. 6 UAV photo of Chiayi DF051 torrent after Typhoon Morakot

3. RESULTS

3.1 Quantitative risk analysis result

The consequence analysis of elements at risk (exposure) was conducted following the 10 steps in Fig.2, the annual average economic losses of buildings, roads, bridges, crops were calculated from the results of 6 return periods debris flow simulation (Fig.7). From the comparison of Fig.7 and Fig.4, we could find out that the simulation result of 100 and 200 years return period had covered large part of the area, which was the scenario during Typhoon Morakot.

As mentioned in section 2.2, the elements at risk GIS layers of current condition and for the land-use planning of the proposed Jhonglun Scenic Area Plan were applied, the calculated results were shown in Tab.3 and Tab.4 respectively.

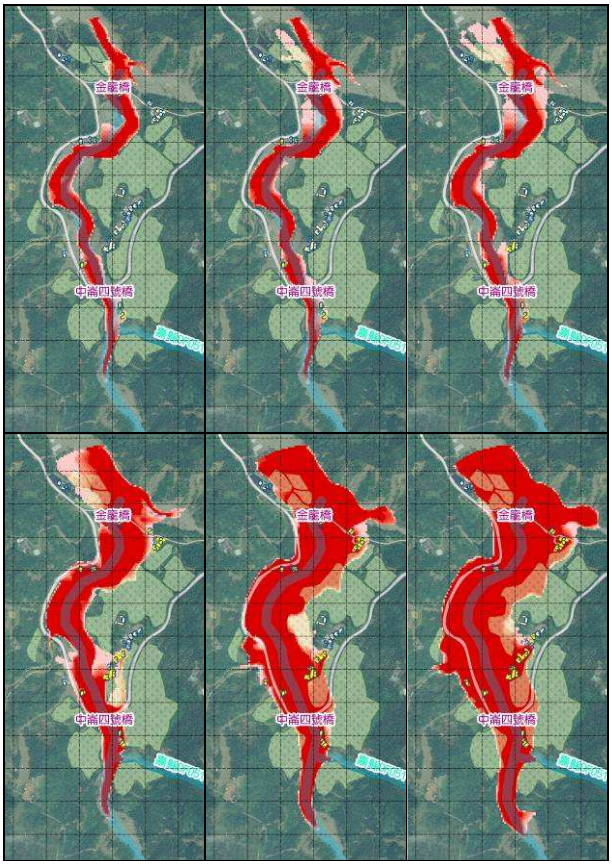

Fig. 7 Different return period debris flow simulation results of Chiayi DF051 torrent (from top left to bottom right: 5, 10, 25, 50, 100, 200 years)

Table3 Losses of elements at risk under different return periods of Chiayi DF051 torrent (current condition)

Return Period (year)	Annual Exceeding Probabilities	Losses of Buildings (TWD)	Losses of Bridges (TWD)	Losses of Roads (TWD)	Losses of Crops (TWD)	Total Losses (TWD)	Fatalities
-	100%	-	-	-	-	-	-
5	20%	1,369,863	2,024,007	573,413	64,819	4,032,102	-
10	10%	1,571,781	3,597,546	699,719	232,587	6,101,633	-
25	4%	2,221,755	4,734,081	944,135	573,066	8,473,037	0.0089894
50	2%	9,902,517	5,535,290	3,829,226	4,728,086	23,995,120	9.3299100
100	1%	22,889,237	9,671,976	12,565,199	20,802,955	65,929,368	33.7222000
200	0.5%	31,762,550	9,671,976	21,729,936	47,438,383	110,602,846	41.5282000
Annual Average Losses		1,230,665	1,567,719	557,781	416,237	3,772,402	0.4970457

Table4 Losses of elements at risk under different return periods of Chiayi DF051 torrent (Jhonglun Scenic Area Plan)

Return Period (year)	Annual Exceeding Probabilities	Losses of Buildings (TWD)	Losses of Bridges (TWD)	Losses of Roads (TWD)	Losses of Crops (TWD)	Total Losses (TWD)	Fatalities
-	100%	-	-	-	-	-	-
5	20%	1,664,566	2,024,007	573,413	64,819	4,326,805	3.9998922
10	10%	2,210,604	3,597,546	699,719	232,587	6,740,456	4.3473735
25	4%	3,990,289	4,734,081	944,135	573,066	10,241,571	6.7762521
50	2%	33,563,095	5,535,290	3,829,226	4,728,086	47,655,697	62.0710418
100	1%	70,470,524	9,671,976	12,565,199	20,802,955	113,510,654	107.4356504
200	0.5%	119,202,591	9,671,976	21,729,936	47,438,383	198,042,887	160.7253119
Annual Average Losses		2,415,497	1,567,719	557,781	416,237	4,957,234	4.5574377

3.2 Comparison

From Tab.3 and Tab.4 this study shows that after the execution of land-use planning, the annual average economic loss might raise from 3.7 million to 4.9 million TWD (a 30% raise), and the annual average fatalities might raise from 0.48 to 4.56 person (a 900% raise). In this case the land-use planning did not reduce the exposed risks but on the contrary located the exposures in high risk area.

The 'Regulations for the periodical overall review of Urban Planning' had specified that 'hazard history, characteristic, hazard susceptibility' should be carefully reviewed, and in this case the 3rd Overall Review had actually identified debris flow torrents, but because of the lack of tools and methodologies the proper suggestions for reducing debris flow risk could not be applied. The new land-use planning suggested that the two new hotel districts could be utilized for refuge shelter when typhoon alert is issued, however, the analysis result showed that one of the hotel district actually will become a high risk area. Therefore, if debris flow risk analysis and assessment were conducted, the outcomes of the land-use planning might be totally different.

4. DISCUSSIONS

Taiwan is located in a highly vulnerable zone, with high frequency earthquakes and strikes of typhoons. Thus, landslides and debris flow would still be the majority of natural hazards in the future. Through carefully reviewed land-use planning and building code regulation, most natural hazard risks could be avoided. As this study shows, the results of quantitative risk analysis of natural hazards could provide more information for future land-use planning, which should be integrated into Geological Act (Geological sensitive area) and National Land Use Planning Act in the future.

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