APRELIMINARY STUDY OF DEBRIS FLOW RISK ESTIMATION AND MANAGEMENT IN TAIWAN

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ABSTRACT

With limited resources, authorities should establish a disaster management system to cope with slope disaster risks more effectively. During 2006 and 2007 the Soil and Water Conservation Bureau (SWCB) completed the basic investigation and data collection of 1,503 potential debris flow creeks in Taiwan. In 2008, a debris flow quantitative risk analysis procedure was proposed and conducted on 50 creeks of the 20 villages. Four types of risk elements were identified, with the fragility curve of each kind applied. Through studying the historical hazard events of the 20 villages, numerical simulations of debris flow hazards with different magnitudes were conducted, the economic losses of each scenario were calculated. When taking annual exceeding probability into account, the annual total risk of each creek was presented. The number of fatalities and frequency were also calculated and compared with the tolerable death rate of 3.5×10^{-4}, and the F-N curves were divided into 3 categories: Unacceptable, ALARP and Broadly Acceptable. In order to reduce risk, structure or non-structure mitigation options could be suggested.

Key Words: Debris flow, Risk management, Risk analysis, F-N curve

INTRODUCTION

The awareness of debris flow was not aroused until 1996, when Typhoon Herb struck Taiwan. With the investigation and collection of data since then, the impact of debris flow hazard could be minimized through efficient planning and management. These methods include: (1) slope land development restriction, (2) classification and introduction of technical specification, (3) reduce hazard possibilities with engineering/structure methods, and (4) development of early warning system.

Most debris flow hazard could be avoided through debris flow analysing, forecasting and early warning, The Soil and Water Conservation Bureau (SWCB), Taiwan's authority in charge of debris flow management, began the supervision of debris flow mitigation since 2000. In the years, SWCB set up the debris flow emergency and response system, conducted and supported numerous evacuation acts during typhoon or rain seasons, reduced the debris flow hazard effectively.

But recent extreme rainfall occurred more frequently, in several countries debris flow frequency and magnitude increased. In Taiwan, the natural hazard management cycle, Mitigation-Preparedness-Response-Recovery, of Federal Emergency Management Agency (FEMA), USA was widely accepted, but the concept of risk management was still lacking in debris flow management. With the introduction of risk management, debris flow hazard decision making and resources could be conducted and distributed with efficiency.

This paper presents a debris flow quantitative risk assessment framework with risk analysis procedure, the result of risk calculation and ranking were also provided.

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DEBRIS FLOW RISK MANAGEMENT

Risk management of debris flow

UNDRO (1979) defined risk around various components as in Eq. (1), which has been widely accepted and applied for research on natural disasters (Peduzzi *et al.*, 2002; Granger, 2003; European Commission, 2004):

$$R = H \times E \times V \tag{1}$$

UNDRO (1979) defined the components in Eq. (1) as followed (cited by Glade, 2003 and Papathoma-Koehle *et al.*, 2007):

R: Risk, referring to the expected number of lives lost, persons injured and damage to property or disruption of economic activity due to a particular event.

H: Natural hazard, defined as the probability of occurrence of a potentially damaging event within a specified time and given area.

E: Elements at risk, including population, buildings and engineering structures, infrastructure areas and lines, public service utilities and economic activities.

V: Vulnerability, related to the (potential) results from event occurrence expressed with qualitative, semi-quantitative or quantitative methods in terms of loss, disadvantage or gain, damage, injury or loss of life.

For debris flow hazards, H, E and V could be explained as followed:

H: Inundation area, debris flow depth and velocity.

E: Discussion of types and numbers of buildings, resident, corps and other valuable structures and utilities within the possible inundation area.

V: Discussion of fragility curve and possibility of damage of different types of elements at risk.

Australia had adopted a landslide risk management process (AGS, 2000), based on the process, this paper outlined a debris flow risk management framework (Fig.1).

Risk management of debris flow includes three parts: risk analysis, risk evaluation and risk treatment. Risk analysis is the nucleus of the procedure, it estimates the level of risk, and decides if the risk is acceptable. The result suggests which risk treatment should be taken.

Risk analysis of debris flow

The nucleus of risk management procedure is risk analysis. Risk analysis estimates the level of risk, and decides if the risk is acceptable, and it's result suggests which risk treatment should be taken. Both qualitative and quantitative risk analysis could be applied to debris flow. This paper proposed a debris flow quantitative risk analysis (QRA) procedure (Fig.2) based on the debris flow management process (Fig.1). The debris flow risk analysis procedure includes three parts: scope definition, risk identification and risk estimation. The procedure could be break down into 10 steps and demonstrated as follows:

1. Determine the area of interest: The first step of debris flow risk analysis is to determine the area of interest and information gathering, include geographical location and creeks within the region. The availability of high resolution aerial photo would be a great assistance for elements at risk identification. Also historical debris flow hazard information would be a plus for simulations.
2. The types of losses to be analysed should consider the purpose of the analysis, the importance of the loss and the availability of the information. Losses could be divided into two parts, direct and indirect loss. The former include property loss (building, interior, public facilities, corps) and human casualties. The latter include production disruption, transportation disruption, psychological effects and inconvenience during recovery. This paper focuses on direct loss only.
3. The purpose of collecting debris flow occurrence factors were to provide basic information for debris flow frequency analysis, hazard analysis and numerical simulation. Stream length, catchment area, formation, lithology and geological structure, historical hazard records, landslide size and distribution, transport, deposition zone materials, structure types and numbers, digital terrain models (DTM) and rainfall information should be collected.

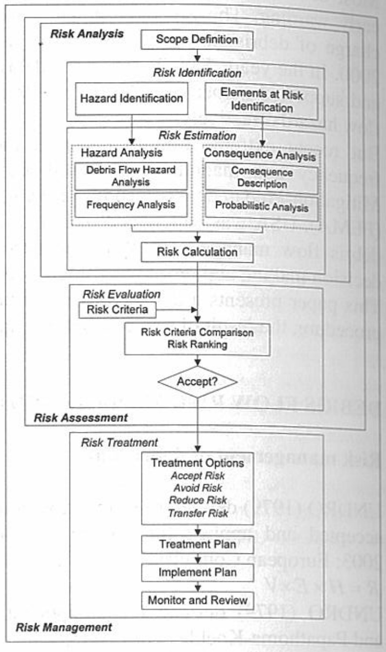

Fig. 1 The process of debris flow risk management (after Australian Geomechanics Society, 2000)

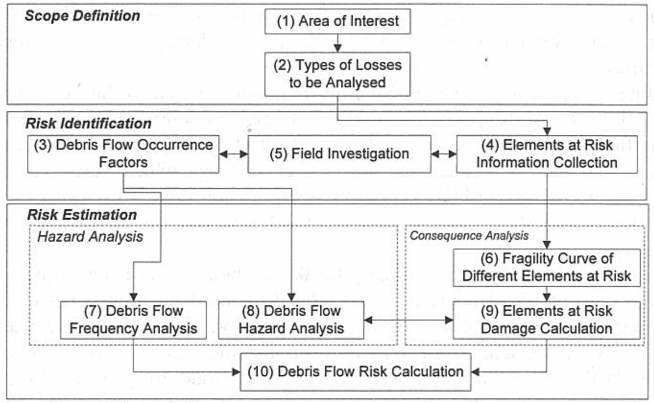

Fig. 2 Debris flow risk analysis procedure

4. Elements at risk include the buildings, resident, bridges, roads, corps within the possible inundated area of the debris flow stream, the information gathered include the type, name, area, size and their economic values. The values of buildings were gathered from local governments or architecture associations, values of constructions such as road, bridge or dams were obtained from engineering units, values and price of corps were gathered from agriculture authorities. All elements at risk were integrated into different GIS layers for further risk analysis and calculation.
5. Much information were gathered from field investigation, which include the properties and status of elements at risk (building type and stories, road width, occupant in the buildings, types of crops), the status of the stream, GPS information of elements at risk. For DF174 creek of Taipei County, the elements at risk were displayed as in Fig.3. Also, the magnitude and inundation area of historical debris flow hazard (occurred in Nov., 2000) were gathered through eyewitnesses interview and historical data (Chen *et al.*, 2004), for historical hazard event was provided for parameter calibration and verification.

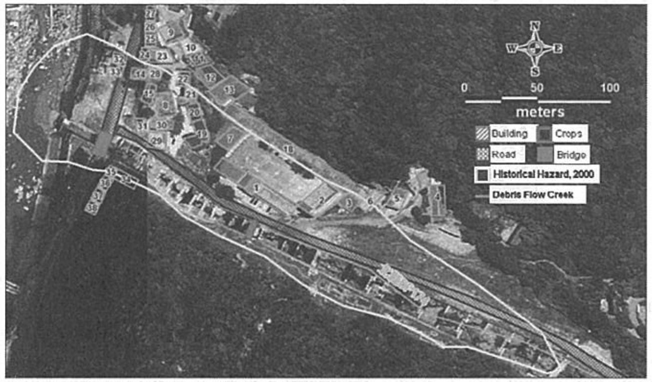

Fig. 3 Elements at risk of DF174 creek, Taipei County

6. To define the vulnerability for elements under different debris flow intensity, the fragility curve for each type of elements at risk were selected for this study. Vulnerability

represents the amount of damage related to the specific damage potential of the considered element at risk. The damage ratio is ranged from 0 (no damage) to 1 (total lost). Some of the fragility curves were explained as follow:

(1) Buildings: The damage ratio of building is mostly related to the deposition depth of debris flow. In Austria, the vulnerability of brick masonry and concrete buildings to debris flow was suggested by Fuchs (2008). This study applied the same curve and suggested another for wooden and sheet-metal buildings, which were commonly seen in Taiwan. For concrete or brick buildings, depth greater than 3m is consider a total loss, for wooden and sheet-metal buildings, it's 1.5m. The fragility curves were shown in Fig.4.

(2) House interiors: Debris flows usually break into houses and damage the interiors, the damage ratio of house interior is also related to the deposition depth of debris flow. Consider the height of TV, closet and refrigerator, a fragility curve was suggested as Fig.5. When the depth is greater than 1.5m, the interiors were considered a total loss.

(3) People: Wallingford (2006) proposed a flood risks model for people, taking the density of debris flow (in this study assume 1.8 t/m^3), depth, velocity in consider, when depth of debris flow reaches 1.25m, the possibility of death is very high. The suggested fragility curve was shown in Fig.6.

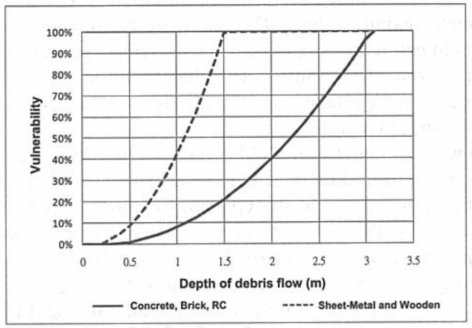

Fig. 4 Fragility curves for buildings for debris flow hazard

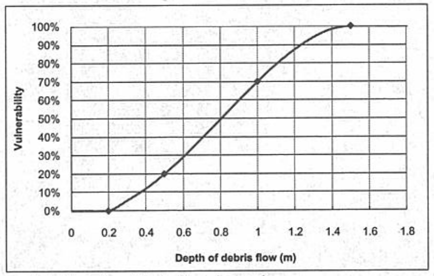

Fig. 5 Fragility curve for house interiors for debris flow hazard

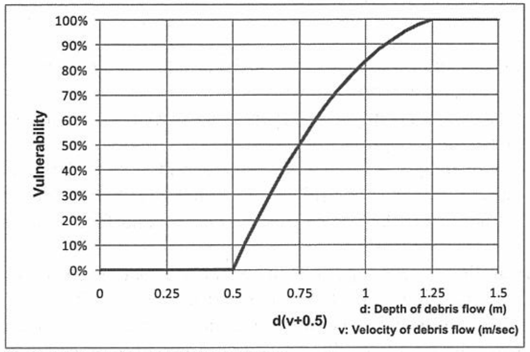

Fig. 6 Fragility curve for individuals for debris flow hazard

7. Debris flow frequency analysis could be fulfilled by two approaches. First, through hazard history data or debris flow inventory to obtain annual occurrence frequency. Second, though the trigger mechanism to estimate the possibility of rainfall intensity for triggering debris flow.
8. For Debris flow hazard analysis, several numerical models were available, this study used the two dimensional simulation model FLO-2D (O'Brien *et al.*, 1993) to simulate debris flow inundation area and magnitude. FLO-2D was widely applied for debris flow simulation in Europe (Huebl *et al.*, 2001; Mikos *et al.*, 2006), North America (Bertolo *et al.*, 2005) and Taiwan (Chen *et al.*, 2004; Lin *et al.*, 2005). Taking deposition range, depth and velocity into account, the damage of elements at risk could be calculated. Five return period events (5, 10, 25, 50, 100 and 200 years) were simulated, one of the inundation result for DF174 creek was shown in Fig.7, the information of each grid (5m*5m) was saved in a GIS layer.

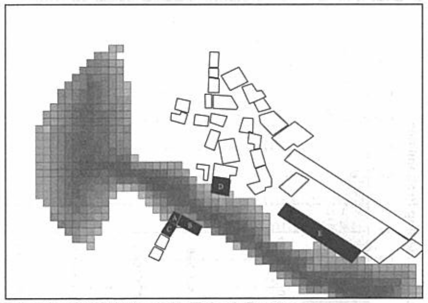

Fig. 7 Debris flow simulation result of DF174 creek, Taipei County

9. Elements at risk damage calculation were conducted with the combination of elements at risk GIS layers, FLO-2D simulation result GIS layers and vulnerability (fragility curve), with grids of 5m*5m in consider. The results were also stored in GIS layers.
10. Risk calculation combines consequence analysis and frequency analysis, the result estimate the cost-benefit of each risk treatment, which would benefit the decision for risk management. Both property damage and human life lost were calculated in this paper.
    (1) Property damage: The loss of four types of elements at risk was calculated using Eq. (2):

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

$L_{prop|H}$: The sum of damages of elements at risk, under specific debris flow hazard event, in NT dollars. J is the total number of the elements.

$P_{S|H,j}$: Probability of spatial impact of each element at risk. Within the inundation area, the value is 1, otherwise the value is 0.

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

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

$E_{prop,j}$: The economic value of each element at risk, in NT dollars.

The annual exceeding probabilities were obtained taking the inverse of return period as consider, Table 1 were the results of the total losses, annual average losses of DF174 creek, Taipei County, the curve is shown in Fig.8. Annual average losses were calculated from the ladder-shaped area under the curve and multiplied by annual exceeding probabilities.

Table 1 Losses of Elements at Risk under Different Debris Flow Hazard Event, DF174 creek, Taipei County

Return Period (year)	Annual Exceeding Probabilities	Losses of Buildings (NT $)	Losses of Bridges (NT $)	Losses of Roads (NT $)	Losses of Crops (NT $)	Total Losses (NT $)
-	100%	-	-	-	-	-
5	20%	14,222	-	196,742	-	210,964
10	10%	49,780	172,672	253,859	-	476,311
25	4%	88,993	585,245	292,136	-	966,374
50	2%	114,642	827,784	314,996	-	1,257,422
100	1%	145,941	1,101,047	337,750	-	1,584,738
200	0.5%	199,721	1,315,160	374,724	-	1,889,606
Annual Average Losses		13,223	61,186	128,723	0	203,132

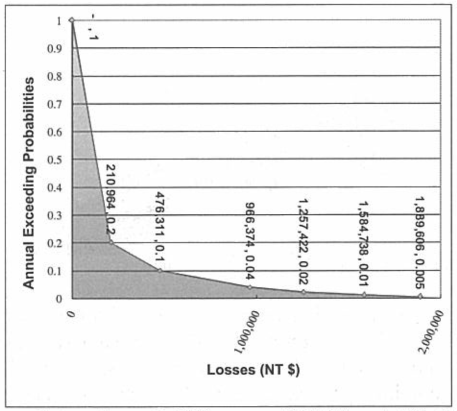

Fig. 8 Debris flow losses annual exceeding probabilities curve of DF174 creek, Taipei County

(2) Losses of human life: The loss of life was calculated using Eq. (3), which is similar to Eq. (2):

$$L_{people|H} = \sum_j P_{S|H,j} \times P_{T|S,j} \times V_{D|S,j} \times E_{people,j} \quad (3)$$

$L_{people|H}$: The number of deaths, under specific debris flow hazard event. J is the total number of the individuals.

$V_{D|S,j}$: Vulnerability of individuals (death ratio), ranging from 0 to 1.

$E_{people,j}$: The number of individuals.

Table 2 were the results of the total death, annual average death of DF174 stream, Taipei County. The calculation was similar with Table 1.

Table 2 Deaths under Different Debris Flow Hazard Event, DF174 Creek, Taipei County

Return Period (year)	Annual Exceeding Probabilities	Death
-	100%	-
5	20%	0.0009235
10	10%	0.0017498
25	4%	0.0021873
50	2%	0.0048098
100	1%	0.0229215
200	0.5%	0.0009235
Annual Average Death		0.0002701

(3) F-N Curve of debris flow hazard: With the annual average death available, societal risk, the F-N Curve (Frequency-Number of Fatalities Curve), could be plotted. F-N curve was first introduced in nuclear industry risk assessment (Kendall *et al.*, 1977), later was adopted in many countries to measure hazardous activity risk (Jonkman *et al.*, 2002). F-N curve was also introduced in slope or debris flow hazard risk assessment in Australia (AGS, 2000), Hong Kong and Canada (Friele *et al.*, 2008). For debris flow hazard, F-N curve could be defined as the annual frequency F of debris flows causing N or more fatalities versus the number N of fatalities. In this study, a steepness of 1 was adopted and accidental injury death rate of Taiwan in 2006, 3.5×10^{-4}, was set to be the standard in the F-N curve. Taking DF174 stream, Taipei County as example, the result of plotting F versus N is shown in Fig.9.

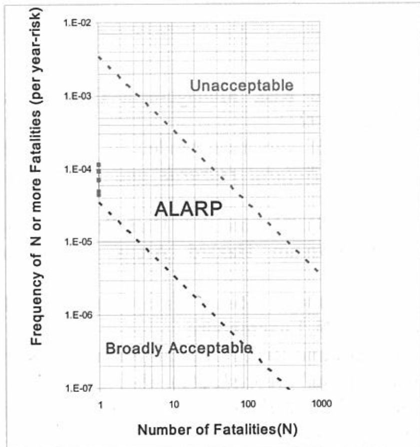

Fig. 9 F-N curve of DF174 creek, Taipei County

The F-N curve of Fig.9 was divided into three zones:

- Unacceptable: Risks are considered unacceptable and required treatment or mitigation.
- ALARP: As low as reasonably practicable, where risks from debris flow should be reduced, wherever it's practicable.
- Broadly Acceptable: Where risks can generally be tolerated.

For DF174 creek in Fig.9, the plot was within ALARP range, should still be deal with structure or non-structure methods to reduce risk.

CONCLUSIONS

Debris flow was and would still be a common hazard in Taiwan. With limited resources, a risk management system should be applied to manage the hazard. This study presented a preliminary framework for debris flow risk management, with 10 steps of debris flow risk analysis procedures proposed and demonstrated. In this study, we concluded that:

1. With risk breakdown into three components (hazard, exposure and vulnerability), a quantitative risk analysis is possible. This study gathered GIS, historical, field data of DF174 creek, Taipei County, and conducted debris flow risk analysis, with F-N curve plotted.
2. The accuracy and reliability of debris flow risk analysis depend on the completeness of basic data, though numerous debris flow hazard occurred in the past few decades, few data were remained for debris flow simulation verification, which made hazard analysis more difficult. In the future, debris flow hazard information should be recorded and mapped on
3. The accuracy and reliability of debris flow risk analysis is depended on the completeness of basic data, though numerous debris flow hazard had occurred in the past few decades, few data were remained for debris flow simulation verification, which made hazard analysis more difficult. In the future, debris flow hazard information should be recorded and mapped in GIS format and imported to database, for future hazard analysis and vulnerability research.
4. Census data, land and house information in GIS format became more and more popular in the mountainous region, which would be a great help for identifying elements at risk.
5. Risk value could be presented in economic value (for elements at risk such as properties) or death (for peoples), this study has presented results based on annual average loss/death, basic on the same standard, a risk ranking could be conducted after several debris flow creek went through the same risk analysis procedure.
6. F-N curve could be a tool for risk comparison and risk control for slope related hazard. With the collection of more historical data, a trend curve could be plotted, and long term risk control effectiveness would be available.

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