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Assessment Framework for Vulnerability and Exposure Based on Landslide Hazard Mapping

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Synopsis

This paper describes the relationships between exposure, hazard mapping, and vulnerability analysis, and represents the initial hazard mapping results of the exposure analysis. Based on different scales, vulnerability can be divided into five layers. Several connections of these five layers, the levels of vulnerability are defined, as vulnerability of the individual, village, country, and central government. Landslide susceptibility is calculated to evaluate exposure based on hazard mapping methods, including logistic regression and discriminant analysis. Finally, the results made from the discriminant analysis are considered acceptable upon comparing these with the aerial photographs.

Keywords: logistic regression, discriminant analysis, hazard mapping, vulnerability, exposure

1. Introduction

The importance of vulnerability is now a major concern in disaster mitigation. It has been found that factors that lead to disasters, not only include destructive natural hazards, but also vulnerability factors, such as environmental and social aspects, and human activities. The definition made by United Nations in the International Strategy for Disaster Reduction (ISDR, 2004) is representative, which is that vulnerability is a set of conditions and processes resulting from physical, social, economical, and environmental factors that increase the susceptibility of a community to the impact of hazards. Several extended models cited this definition. Wisner et al. (1994) mentioned that vulnerability is generated for economic, social and political processes. Turner II et al. (2003) evaluated vulnerability from exposure, sensitivity, and resilience. Bohle (2001) divided vulnerability into internal and external parts, the internal part being the ability to cope with the hazard; the external part being the exposure to risk and shocks.

Some of the definitions and methodologies proposed an ambiguous concept that vulnerability is limited to one time scale and one element or community. However, it is apparent that vulnerability changes with the time or with different levels, although there are few studies that mention this. Consequently, the first part of this study clarifies framework of vulnerability and indicates the relationship of its parts.

On the other hand, it is now common to express the probable danger level of natural hazards via the hazard map. The hazard map shows the associated danger level of a given area has been widely applied for preventing disasters, which shows the associated danger level of a given area. It is also a good tool for inhabitants to distinguish and understand how and what kind of natural hazards threaten them.

Some precise methods for hazard mapping have been proposed by some authors, such as Chang (2007), Chen and Wang (2007), who tried to predict the landslide probability by artificial neural networks. Wang and Liu (2000) used fuzzy model to identify the danger grade of debris flow according to form factor of watershed, valley slope, and geology. On the other hand, the statistical methods were also used, such as discriminant analysis and logistic regression.

A singular isolated factor was considered significant to landslides in the majority of these previous studies. However, it has been shown that landslides are triggered by the interaction of the factors with each other (DPRI, 2003). We use the logistic regression method for prediction to represent these interacting factors. We also use discriminant analysis for comparison.

Generally speaking, we present landslide susceptibility as opposed to landslide probability. Landslides are triggered by many factors including human activities and environmental factors, such that it is difficult to assign a certain probability on the basis of occurrence. Therefore, we propose to evaluate landslide susceptibility (i.e.: relative probability between grid cells as opposed to absolute occurrence-based probability).

2. The Concept and Framework of Vulnerability

Based on the definition referred to in many studies (see Sec. 1), the risk for natural hazards is the interaction of hazard and vulnerability, which can be described as the probability of the harmful event, including the loss of the life, persons injured, property damaged, and economic activity disrupted. The harmful event in this case is limited to sediment disasters in the consideration of risk of the natural hazard. Therefore, hazard pertains to one sediment event, and was used in a limited sense; a hazard is defined as the range and frequency of the historical event.

On the other hand, we accept the definition of vulnerability made by ISDR (2004), although we consider that it should be explained further. Based on Birkmann (2007), vulnerability can be explained as several layers at different scales (Fig. 1).

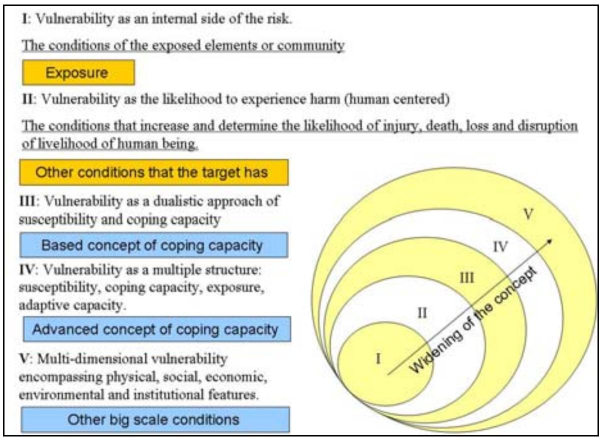

Fig.1 The concept of vulnerability (modified from Birkmann, 2007)

The first layer is the core level, which indicates conditions of the exposed element or community. The second layer includes the conditions that increase or decrease the probability of the harmful event. We define this as the other condition that the vulnerability level can lead to loss. Factors generated from layers 1 and 2 are connected to the vulnerability level of community or groups, which suffer by natural hazards directly. The risk assessment in this study also considers the assessment of the village vulnerability level.

The layer 3 is the dualistic approach of susceptibility and coping capacity. The latter includes the basic infrastructure and equipment that are able to support or be located in the community. In the layer 4, the vulnerability includes the multiple factors, such as susceptibility, coping capacity, exposure, and adaptive capacity. We define it as the advanced concept of coping capacity which includes the engineering and non-engineering strategies. Because the local government tends to supervise the mitigation activities and the rescue operations, we generalize the vulnerability level for the local government as layer 4. The layer 5 contains all large scale factors in the vulnerability, including political, environmental, ecological, and institutional factors. Generally, the central government leads the mitigation program and landuse program. Therefore, this is viewed as the vulnerability of the central government.

The main concern in our framework is limited to the community or village. Any mitigation program conceived by the central government must decrease the loss in these areas. This is shown in Fig. 2, containing the vulnerability for the small areas. Within the village or community, some of the factors contributing to vulnerability are identified.

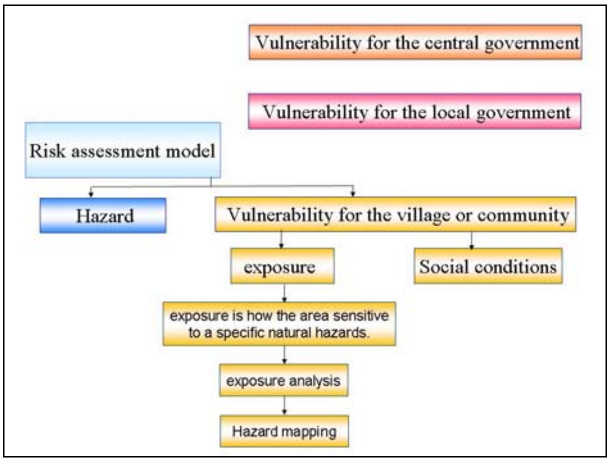

Fig.2 The framework of the vulnerability

A hazard is a potential for physical events, phenomena, or human activities, which may cause the loss and can be shown by location, intensity, and probability (ISDR, 2004). Historical data can be used to represent the probability and magnitude of a hazard. Alternatively, hazard maps can be generated based on risk assessment models to traditionally show estimates of the same probability and magnitude. However, risk is the function of vulnerability and hazard. We see in Fig. 2 that exposure, which is how sensitive an area is to a natural hazard, is a factor in vulnerability. Therefore, similar to the probability that we associate to a natural hazard, exposure can be quantified as a probability. We can thus evaluate this probability of exposure via methods normally performed for hazard mapping.

3. Description of the study area

Fig.3 shows the location of Chenyoulanxi basin, which is located in the middle of Taiwan and is one sub-basin of the country's widest basin, Dousuixi catchment. This catchment has the highest sediment concentration in Taiwan. Naturally, the most common disasters in this area are of this type. The area of the Chenyoulanxi basin is 441 km^2, the

Chenyoulanxi River flows from south to north and drains into the main Dousuixi streams. Geologic features include a fault passing through the basin, which divides the area into the right and left banks and the different geologic components of the two sides. Naturally, there are many accumulated fans distributed beside the banks, due to the steep slope that easily erode. It is also one of the main reasons that the landslide occur frequently.

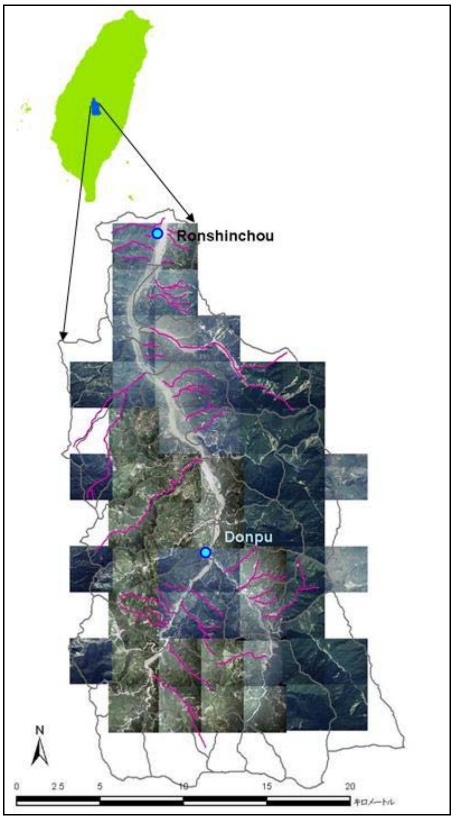

Fig.3 The Chenyoulanxi basin

Seven catastrophic typhoons passed and brought heavy rainfall, each of them causing serious debris flows and landslide events from 1996 to 2005, according to the reports published by the Bureau of Water and Soil Concentration of Taiwan. This agency designated 34 torrents in this area that are potentially dangerous. The maximum rainfall intensity during this period reached 237 mm per hour, and the maximum year total precipitation in this watershed was 2909 mm in 2004. Due to the combined geologic and hydrologic conditions, the Chenyouranxi catchment is therefore considered the most disaster-prone area in Taiwan.

4. Methodology of the hazard mapping

Landslides are triggered by many factors. Occasionally, these occur due to some unique factor or group of factors that interact, including environmental factors and human activities. Most of the factors however have common components, such as slope and geologic features. In order to incorporate the factors responsible for landslides, the first step is to convert the factors under the same unit.

For instance, we define landslide odds as the ratio of area in which landslide occurred to that in which no landslide occurred. This ratio can be quantified in terms of corresponding DEM grid cells. We divide one triggering factor into several categories, and calculate the landslide odds for each category. The logistic regression is mainly applied to the landslide data identified in 2004, after the serious typhoon event that occurred in the beginning of July.

Five factors are chosen in the study, which are geology, aspect (whether on the east or west face of a slope), slope, and the distance from the river and the fault. Only 20% of the grid cells of the area are in the analysis to increase the accuracy of the statistical analysis result.

4.1 Logistic regression

Logistic regression has been widely used in prediction for numerous applications in recent years, especially in predicting natural hazards. This is due to the ability of logistic regression to describe the relationship between independent and dependent variables. The binary logistic model is a simple model that explains how landslides are affected by many factors. The relationship among the factors is shown in the correlation coefficient. The model of the logistic regression is shown as equation (1) and (2) (Chen, 1999):

$$p = \frac{e^{f(x)}}{1 + e^{f(x)}} \quad (1)$$

$$\ln \frac{p}{1-p} = f(x) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k \quad (2)$$

Where:

P = the probability of a certain event happens,

X = independent variables

P is a probability between 1 and 0. When the P is between 0 and 0.5, the grid cell is judged that the landslide does not occur, and on the other hand, when the P is between 0.5 and 1, the grid cell is judged that the landslide will occur.

4.2 Discriminant analysis

Discriminant analysis is a kind of dependence method to distribute the independent variables that belong to a category. This is performed on the categories made as dependent variable previously, such as the probability that a landslide occurs in a cell.

Discriminant analysis is a way used in many applications to describe how dependent variables give an influence to the independent variable. The main method of discriminant analysis is to find the discriminant score and to decide to which category the object value should belong. Fisher's method is used in the identification.

In this case, we assume there are two data sets, X_1 and X_2. Fisher's method finds the maximum of factor $S(a)$ (eq3),

$$S(a) = \frac{\overline{Y_1} - \overline{Y_2}}{S_Y} \quad (3)$$

Where:

$\overline{Y_1} - \overline{Y_2}$ = the variance between the data set 1 and 2,

S_Y = the variance between the averages of set 1 and 2,

according to the max S(a), $\overline{X_1}$, $\overline{X_2}$, and the regression function (eq4),

$$l(X) = \alpha^t X \quad (4)$$

we could differentiate is a value X_0 to a category (Lin, 2007).

5. Results and discussion

Results from logistic regression and discriminant analysis are shown as the Tables 1 and 2 based on the statistics program SPSS. We used trial and error to find out what combination of the interaction has the biggest effect to the landslide susceptibility in the result of logistic regression. Table 1 shows the coefficients of the interacting factors. The factor of aspect and slope is the most dominant, indicating that this is the factor that has the most influence to landslide exposure. However, if we do not consider the interaction of factors, it is the distance from the fault that is the biggest influence. This finding matches with the result of discriminant analysis. We also found that the interpretation ability of the model to the landslide happen or not is almost same whether the interaction factor is considered or not. On the other hand, it should be noted that the coefficient of logistic regression is negative for slope and aspect. The negative coefficient means that this interaction of these factors is influential to landslide and decrease in this coefficient indicates decreased landslide probability.

On the other hand, Fisher's linear discriminant functions were used to judge the result obtained from discriminant analysis (Table 2). The largest landslide num value indicates that distance from the fault is the most influential factor.

Table 1 The result of logistic regression

	B	S.E.	Wald	df	Sig.	Exp(B)
aspect_od	16.239	4.505	12.994	1	.000	11285123.6
fault_od	96.931	2.974	1062.411	1	.000	1.250E+042
geo_od	24.412	.151	26169.539	1	.000	4.00E+010
river_od	25.273	.448	3176.836	1	.000	9.46E+010
slope_od	29.970	4.219	50.459	1	.000	1.04E+013
aspect_od by slope_od	-219.230	116.498	3.541	1	.060	.000
Constant	-8.146	.196	1729.434	1	.000	.000

Table 2 The result of discriminant analysis

	landslide num	
	.00	1.00
aspect_od	3994.001	4000.278
fault_od	30849.440	30939.598
geo_od	221.572	247.454
river_od	1145.445	1173.153
slope_od	400.960	419.163
(Constant)	-653.509	-659.687

Fisher's linear discriminant functions

The probability of landslide over the whole area was calculated based on the coefficients (from logistic regression and discriminant analysis) and landslide odds. One landslide exposure map based on logistic regression is shown in Fig. 4. The resulting range of the Chenyoulenxi catchment was obtained from this map and is shown in Fig 5. Similarly, a landslide exposure map was generated from discriminant analysis shown in Fig. 6, leading to the Chenyoulaenxi range in Fig. 7.

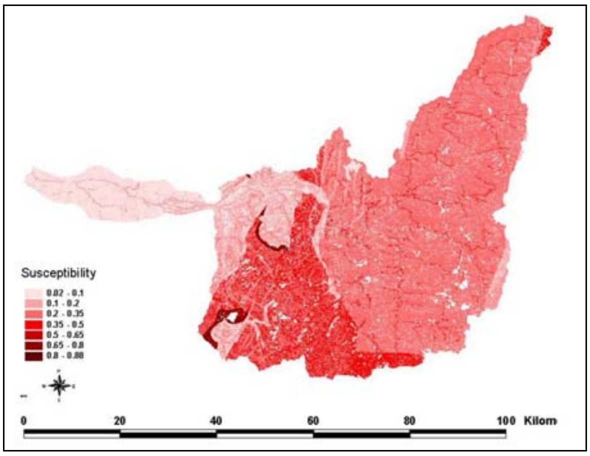

Fig.4 The result from logistic regression analysis

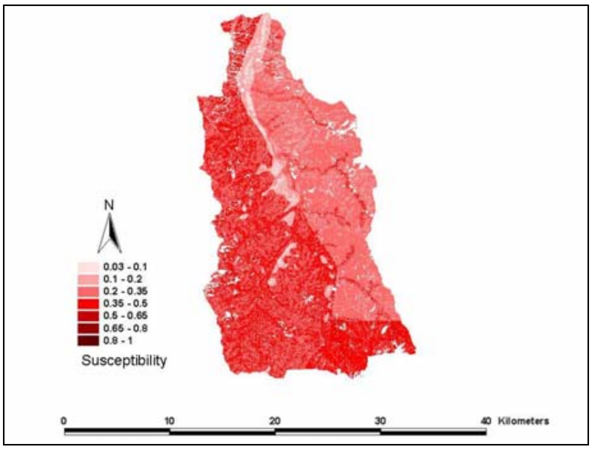

Fig.5 The result from logistic regression analysis

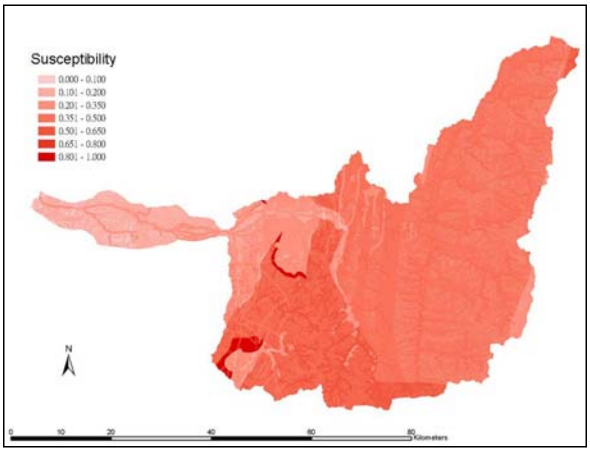

Fig.6 The result from discrimination analysis

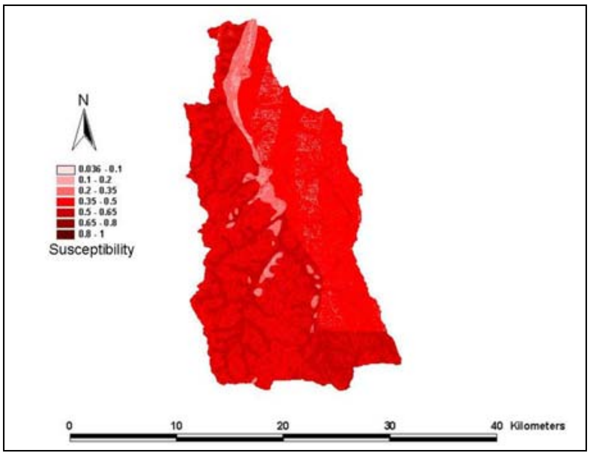

Fig.7 The result from discrimination analysis

Figs. 5 and 7 were compared with the aerial photographs of the real cases of landslides. Most of the landslides occurred along the streams, especially north part of the Chenyoulenxi catchment. Apparently, the result made by discriminant analysis is more precise than the one made by logistic regression. We therefore accept the result made from the former map. It is clearly shown in Fig. 7 that the catchment is divided into two areas, due to geology. The high exposure is mainly concentrated at the torrent area, which matches with the assessment made by Soil and Water Conservation Bureau.

From the same figure, we see that there are fewer areas with higher exposure; it is difficult to identify these areas from the map. In other words, some of the actual features remain unidentifiable. We need to choose other factors to have a higher resolution output that might be probable directions for the future study.

6. Conclusion

A framework of vulnerability was discussed, and a simple result of exposure assessment was referred to in the study, summarized as follows:

(1) Based on the basic theory definition by United Nations in the International Strategy for Disaster Reduction, and similar studies, vulnerability can be classified into 5 layers. Several connections of these five layers, corresponding to the levels of vulnerability were defined, such as vulnerability of the individual, village, country, and central government.

(2) Risk assessment mentioned is a prediction method limited in the small area, such as villages and communities in a catchment. Risk is the interaction of hazard and vulnerability.

(3) We considered exposure and social factors of the vulnerability for the small area. Exposure is how sensitive to the natural hazard an area is. We used hazard mapping method to evaluate exposure.

(4) To evaluate the landslide exposure, logistic regression and discriminant analysis were used. Results were compared to aerial photographs. We found that the result made from discriminant analysis is more precise than from logistic regression. The result also proved that the interaction factors do not have much influence to the landslide exposure.

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斜面災害地域ハザードマッピングに基づく脆弱性と曝災の評価

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要　旨

本稿では自然災害におけるリスク，脆弱性，曝災，ハザートマップについて，概説している。この研究では住民，地域，地方自治体、国など階層ごとに脆弱性を評価した。また，地域のリスクアセスメントにより，ハザートマッピンクと曝災の関係を筆者らは確認した。さらに，曝災を評価するため、ハザードマッピンクでロジスティックと判別分析手法を用いて，流域の斜面崩壊の確率を評価した。最後に，空中写真でこれらの手法を検証することにより，危険度評価に適切なモデルを提案した。

キーワード：ロジスティック，判別分析，ハザートマップ，脆弱性，曝災