Hazard Assessment of Potential Debris Flow Using Linear Combination Based on Analytic Hierarchy Process (AHP)—a Case Study for Changhua County, Taiwan

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***Abstract*— The present research uses a simple and direct method to assess the hazard rating of potential debris flows in Changhua County of Taiwan based on field investigation and numerical simulation. Taking 7 potential debris flow areas in Changhua County as the research objects, linear combination is utilized to evaluate the hazard rating of debris flow disaster in disaster-prone areas. In addition, Analytic Hierarchy Process (AHP) is applied to design the expert questionnaire for determining the factor weight, and pair-wise comparison is used to calculate the eigenvector as the weights of criteria. The calculated weights are further used for the hazard assessment. In addition, scenario simulations by FLO-2D can offer information which was not obtained in the current investigations. The priority of hazard rating in the 7 potential debris flow areas can be obtained based on this assessment.**

***Index Terms*—hazard assessment, potential debris flow, Analytic Hierarchy Process (AHP), FLO-2D**

I. Introduction

The phenomenon of global warming and its climate change impacts are becoming increasingly apparent. When there are typhoons or extremely heavy rainfall, the sediment in upstream watersheds that are affected by heavy rainfall not being drained often results in flood or debris flow that endangers public life and property safety. Field investigation in disaster-prone areas and analysis of the importance of disaster factors can be applied to better evaluate the risk of disaster. These results could be a reference for subsequent disaster prevention activities.

In regard to relevant research, Hung and Chen [1] evaluated the vulnerability to flood disasters of the Ta-Chia river watershed in Taiwan based on the evaluation indices of exposure, sensitivity and adaptation, and response. Raaijmakers *et al*. [2] also applied multi-objective evaluation to examine flood risk perception and mitigation, and Boamah *et al*. [3] used Generalized Linear Models (GLM) to examine how personality disposition, social network, and socio-demographic factors mitigate the complex relationship between stressful life experiences of floods and the adoption of coping strategies among communities in Nigeria and Tanzania. As for debris flow disasters, a multi-criterion decision analysis method and fuzzy synthetic evaluation are applied to determine the weight of their factors using the analytic hierarchy process method for hazard assessment [4].

In this study, a FLO-2D model was used to conduct the simulations of potential debris flows. The FLO-2D model was developed by the University of Colorado for research on debris flow and flooding, and an enhanced version was developed by the FLO-2D Company as commercial software that has been approved by the United States Federal Emergency Management Agency (FEMA). The previous study [5] applied FLO-2D to simulate a debris flow that occurred in the Songhe Community in Taiwan for risk assessment purposes and the results indicated that FLO-2D is reasonably well developed and effective for actual case applications [6], [7].

Global warming in the past years has resulted in climate changes. To cope with future climate changes and natural environment changes, much planning and thinking need to be adjusted. The current study investigates catchments of potential debris flows in Changhua County. Based on the collected results and surveys, the hazard assessment was established using an expert questionnaire in AHP and numerical simulation. These results could assist local governments in realizing the disaster-prone risk weights in administrative regions to use as reference when developing mitigation plans.

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II. Methods

A. Linear Combination

Linear combination [8] is used for the hazard assessment of potential debris flow in this study. When evaluating the appropriateness of factor attributes for the evaluated subject, the relative weight of each factor is given in linear combination. AHP is applied to design the expert questionnaire for determining the factor weights, the pairwise comparisons are used for calculating the eigenvector for the weight of each criterion [9], and these weights are evaluated to determine the priority of potential debris flows for monitoring and management.

The questionnaire survey in this study is divided into two parts. The first part was to confirm the sufficient evaluation factors for evaluating the hazard assessment of potential debris flow. Through the expert questionnaire with Delphi Method, the factor structure for hazard assessment was preliminarily developed, in preparation for receiving the expert opinions about the structure. The expert questionnaire in the second part evaluates the relative importance among factors so as to determine the hierarchical matrix in AHP. After completing the first phase, the statistical results are the reference for the questionnaire survey at the second phase in order to compare the relative importance among criteria for reference of the final weight.

To acquire the relative weight among factors, the solution for a numerically analyzed eigenvalue could be applied to acquiring the maximum eigenvalue ($\lambda_{\max}$) of the comparison matrix and the corresponding eigenvector. Saaty [9] proposed four approximate approaches to calculate the eigenvector: (1) Average of Normalized Columns, (2) Normalization of the Row Average, (3) Normalization of Column Reciprocal Average, and (4) Normalization of the Geometric Mean of the Rows. For calculation, this study uses MatLAB, which is suitable for the vector matrix algorithm. The window interface programming codes are self-developed, the functions built in MatLAB are used for directly calculating the eigenvalue and eigenvector, and the maximum eigenvalue and the corresponding eigenvector are regarded as the weight of the evaluated factor.

After completing the process, the weights of evaluation factors could be set based on AHP and the expert questionnaire survey results to calculate the hazard rating according to the weight and the evaluation factors [10]:

$$H.R. = \sum w_i x_i \tag{1}$$

where *H.R.* is the result of hazard rating, w_i is the weight of corresponding factor *i* according to AHP, and x_i is the evaluation score of factor *i*, which could set the evaluation standard by integrating the expert consensus through the expert questionnaire.

B. Simulation Model of Debris Flow

Scenario simulations of debris flow were calculated using the FLO-2D model. The general constitutive fluid equations including the continuity equation and the equation of motion (dynamic wave momentum equation) are [11]

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = i \tag{2}$$

$$S_{fx} = S_{ox} - \frac{\partial h}{\partial x} - \frac{\partial u}{g\partial t} - u\frac{\partial u}{g\partial x} - v\frac{\partial u}{g\partial y} \tag{3}$$

$$S_{fy} = S_{oy} - \frac{\partial h}{\partial y} - \frac{\partial v}{g\partial t} - u\frac{\partial v}{g\partial x} - v\frac{\partial v}{g\partial y} \tag{4}$$

where *h* is the flow depth (m); *u*, *v* are the depth-averaged velocities in the *x*- and *y*-axis directions (m/s); *i* is the excess rainfall intensity (mm/hr); S_{fx}, S_{fy} are the friction slope components according to Manning's equation of the *x*- and *y*-axis directions; S_{bx}, S_{by} are the bed slopes of the *x*- and *y*-axis directions; and *g* is acceleration of gravity (m/s^2).

Since the most significant difference between debris flow and hyperconcentrated flow lies in the larger proportion of solid sediment content, the fluid sediment volume concentration is the most direct method to define debris flow. Most of the design values for sediment volume concentration, except a few field observed values, is calculated with the equation of Takahashi [12] Theory as the criterion. Based on Bagnold's concept of dilatant fluid, Takahashi established the debris flow sediment volume concentration with the following equation:

$$C_D = \frac{\gamma_w \tan\theta}{(\gamma_s - \gamma_w)(\tan\phi - \tan\theta)} \tag{5}$$

Equation (5) is suitable for calculating the saturated (balanced) sediment concentration of debris flow forefront. In this equation, ϕ = sediment internal friction angle, which is closely correlated with sediment characteristics, with values between, θ = bed slope, γ_s = soil particle unit weight, and γ_w = clear water unit weight.

The debris flow rheological parameter is estimated with the equations suggested by FLO-2D users' manual [11]. Since there is no empirical formula for debris flow rheological parameters in the Changhua areas, the testing result of Jan et al. using a tube rheometer for Shenmu Village in Nantou County, Taiwan, which was obtained in a previous study [13].

III. Results

Located in the middle of western Taiwan, Changhua County is a roughly trapezoidal piece of land with a north-south distance 44 km, a northern east-west width of about 12 km, a southern width of about 40 km, and an area of 1,074.40 km^2. The slopeland of Changhua County covers Changhua City, Fenyuan Township, Huatan Township, Dacun Township, Yuanlin Township, Shetou Township, Tianzhong Township, and Ershui Township on the Bagua Plateau with a total area of 13,200 hectares. Taking 7 potential debris flow areas in Shetou Township, Tianzhong Township, and Ershui Township as the research objects (Fig. 1), a linear combination method is utilized to evaluate the hazard rating of debris flow disaster in these areas.

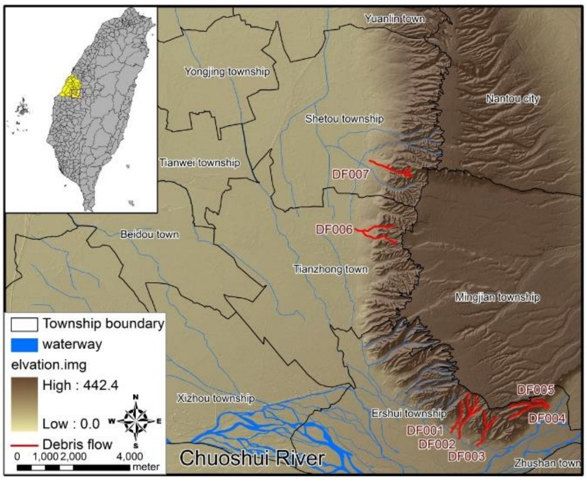

Figure 1. Study areas.

In this study, taking 7 potential debris flow areas in Shetou Township, Tianzhong Township, and Ershui Township as the research objects, a linear combination method is utilized to evaluate the hazard rating of debris flow disaster in these areas, and 12 experts were consulted for the expert questionnaire. The three most important factors, which were acquired with AHP, are Protected Targets, Landslide Disaster Sign, and Potential Geological Disaster. The relative importance of other factors are A-1 Slope, weighted 14.99%, A-2 Potential Debris Flow, weighted 13.80%, A-3 Potential Geological Disaster, weighted 16.32%, A-4 Disaster History, weighted 12.80%, A-5 Landslide Disaster Sign, weighted 20.32%, and A-6 Protected Targets, weighted 21.77%. The weights of the evaluated items as well as the simulation and field investigation results were used for the Geographic Information System (GIS) overlay mapping in order to receive the hazard rating evaluation result. For example, the data of A-1 Slope were obtained through the Spatial Analyst tools of ArcGIS.

In addition, the FLO-2D model was applied for the numerical simulation. The triangular unit hydrograph is utilized for calculating the runoff hydrograph as the inflow conditions when simulating debris flow, and the sediment volume concentration of debris flow and the empirical formula are used for estimating the rheological parameter of debris flow. Matching the simulation results and the field investigation results, the factor weights in AHP expert questionnaire were used for GIS overlay mapping to establish the hazard rating evaluation.

This study used a grid size 10m×10m of Digital Elevation Model (DEM) to establish the computational domain. Meanwhile, the catchment runoff obtained using the triangular unit hydrograph method was calculated to simulate the inflow hydrograph of debris flow. The modeling results (Fig. 2) using FLO-2D according to these inflows can be used to predict potentially inundated areas as well as flow depth and velocity of debris flow. Because there are no preservation objects in the catchment of DF007, the numerical simulation was omitted in this study. The hazard rating of potential debris flows in Changhua County can be obtained from the linear combination with AHP based on the field investigation and situation simulation (Table I). The scores of A-3 Potential Geological Disaster were obtained based on the simulation results of FLO-2D model. Through GIS overlay mapping, the scores were determined as shown in Table I using the average of debris flow depth for judgment basis. For instance, the score is 1 if depth > 1.5 m; then 0.75 when depth is between 1.5 m and 1 m; 0.5 for depth is between 1 m and 0.5m; 0.25 if depth < 0.5 m, and zero implies the simulation was omitted. In Table 1, a higher total score indicates a higher degree of risk through more aspects of affected factors. These results may be useful for local governments to consider the priority of treatment measures or evacuation plans.

TABLE I. ASSESSMENT RESULTS OF 7 POTENTIAL DEBRIS FLOWS

Debris Flow No.	Score							Priority
	A-1 Slope	A-2 Potential Debris Flow	A-3 Potential Geological Disaster	A-4 Disaster History	A-5 Landslide Disaster Sign	A-6 Protected Targets	Total	
DF001	0.5	0.5	0.5	1	1	0.5	66.57	6
DF002	0.5	1	0.25	1	1	1	80.28	3
DF003	0.667	0.5	0.5	1	1	1	79.95	4
DF004	0.667	1	0.25	1	1	0.75	77.33	5
DF005	0.833	1	0.75	1	1	0.75	87.99	2
DF006	0.5	1	1	1	1	1	92.52	1
DF007	0.667	0	0	1	1	0.5	54.00	7

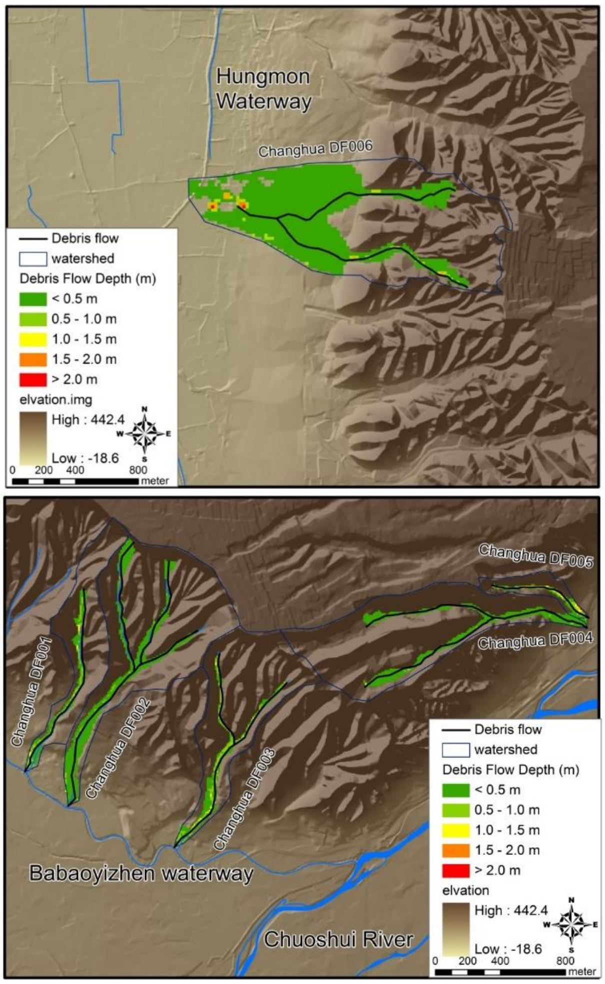

Figure 2. Simulation results of FLO-2D model: (Top) potential debris flow (DF006) in Tianzhong Township; (Bottom) potential debris flows (DF001-DF005) in Ershui Township.

IV. Conclusions

This study used the linear combination method to evaluate the risk of debris flows in Changhua County of Taiwan, and AHP was also applied to determining the factor weights. This study also carried out field investigations in accordance with the announcement published by the Soil and Water Conservation Bureau of Taiwan concerning potential debris flow information, including potential grade and preservation objects. Based on these field investigations and simulation results of FLO-2D, the hazard assessment of potential debris flows in Changhua County were determined through the linear combination method, in which the factor weights had been decided by AHP. Results indicate that DF006 should be a priority target. This study suggests that local government might reference the assessment results in order of priority from 1 to 5 to set up charge-coupled device (CCD) debris flow monitoring systems to assist disaster prevention and management avoiding injuries and losses.

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