Integrating Empirical and Dynamic Approaches on Prediction of Debris Flow Hazard Zone

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ABSTRACT
In this paper, the prediction of potential debris flow hazard zone has been studied. Empirical and dynamic approaches have been integrated to solve the problem. It turned out that the presented method can successfully replicate the influential zone of a debris flow disaster event with an acceptable error. Meanwhile, the method has proved to be more precise to predict debris flow hazard zone which was confirmed by comparing an empirical method with a case study. To conclude, the study may improve the delineation of potentially hazardous zones approximately associated with debris flows and provide very helpful information in hazard prevention system.

RÉSUMÉ
Dans cet article, la prévision des coulées de débris de la rique zone potentielle a été étudiée. Les approches empiriques et dynamiques ont été intégrées pour résoudre le problème. Il fait la méthode présentée à bien reproduire la zone influente d'un catastrophe coulé de débris même avec un erreur acceptable. Entre-temps, la méthode s'est révélée plus précis pour prédire les coulées de débris de la zone risquée. En conclusion, cet étude pourra améliorer de la délimitation des risques zones potentielle probable,ce qui est associée avec les coulées de debris, puis fourni des informations très ustiles dans le système de la prévention des risques.

1 INTRODUCTION

Occasional rainfall, steep relief, and adequate debris flow materials are three major components to form a debris flow event in a potential debris-flow creek. The topographic, geological and hydrologic characteristics of Taiwan are corresponding to the three components of occurrence of debris flows. Taiwan is therefore frequently beset by debris flow problems during typhoon and heavy rainfall. These fast-moving flows accompanying mud and rock are capable of destroying houses and lives, washing out roads and bridges, or obstructing streams and roadways. To mitigate and manage hazards induced by debris flows, it is necessary to simulate the debris flow route and deposition process. The simulation result is very important for determining a possible affected area which is an essential element for producing hazard maps (Petrascheck and Kienholz, 2003).

The prediction of debris-flow affected areas may be divided into empirical-statistical and dynamic methods (Rickenmann and Koch, 1997;Rickenmann et al., 2003). Although empirical-statistical methods are easy to utilize, they should only be applied to certain conditions. Dynamic approaches are physical based and consider the momentum and energy conservation of the flow. Though the dynamic methods have better simulation performance than the empirical-statistical methods, a major difficulty in developing dynamic models for potential hazard area prediction is the choice of appropriate model parameters.

An empirical method initiated by Iketani and Uehara (1980) to identify the debris-flow hazard zones is adopted by the Soil and Water Conservation Bureau (SWCB) of Taiwan currently. This empirical method is consisted of some certain rules and an equation which is a function of the debris flow volume and slope angle below the apex of a debris flow fan. However, the computed zonation of debris flow hazard is often underestimated or overestimated owing to complex topography as compared to historical typhoon events. In this study, empirical and dynamic approaches have been integrated to solve the problem. A numerical model developed by O'Brien (2006) as the dynamic approach was chosen to predict areas potentially endangered by debris flows for downstream guarded areas for potential debris-flow creeks. The empirical approach was applied to obtain appropriate input values for significant parameters in the numerical model. The integrated model applied to a study region for calibration and validation of the model.

2 DESCRIPTION OF STUDY AREA

The study area is located in Hualien County, eastern coast of Taiwan as shown in Figure 1. Hualien County faces the immense Pacific Ocean in the east and leans against the grand Central Mountain Range in the west. The area is on the boundary of the Philippine and Eurasian Plates. Because the plates collide, the metamorphic rock is very common here. Besides, because of the strong erosion, we can see sea terraces, river terraces, alluvial fans, meanders, and river valley basin everywhere.

Hualien County is mountainous with a long and narrow territory. The area below 100 meters elevation occupies 9 percent of County's land area; terrain with hillslope angle less than 5% covers 12.7 percent. Because of limited plain areas, urban developments on slopeland have become inevitable. Besides, typhoons with heavy rainfall frequently attack Hualien County every year during the period mainly from June to October and bring bountiful rainfall. Thus, due to the geomorphological and hydrological characteristics, landslides, debris flows and flood disasters prevail in the region during typhoon season. Figure 1 shows the distribution of potential debris-flow creeks in Hualien County. The county contains 160 potential debris-flow creeks in total spread within 13 towns as shown in Figure 1. In the past, debris flows occurred in some of potential debris flow creeks, especially in Tonmeng village, Dasing village, Fongyi village, and Jiancing village and resulted in many people dead and serious property damage. Therefore, the study of debris flows has become an important and challenging task in the area.

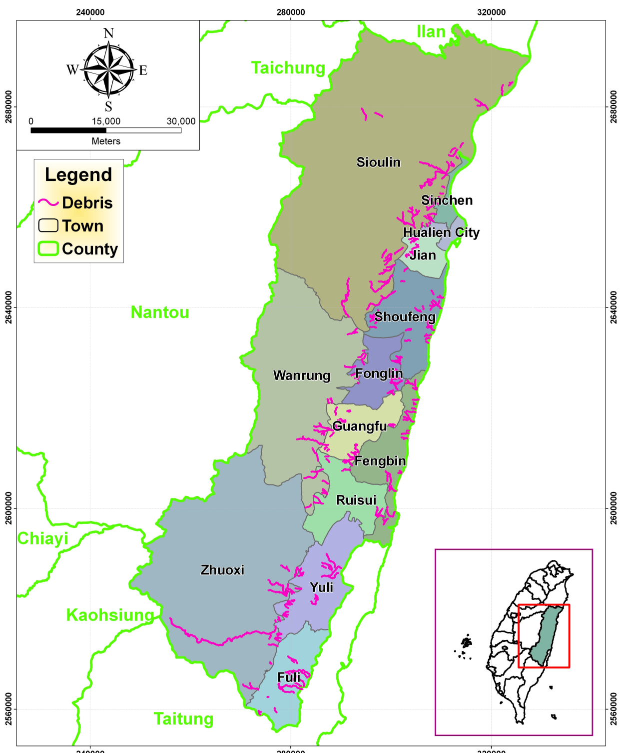

Figure 1. Location of study area and distribution of potential debris-flow creeks in Hualien County

3 THE METHOD USED IN TAIWAN

Debris flow hazard zone delineation is very important for disaster prevention, In Taiwan, the Soil and Water Conservation Bureau is responsible for the task. The criteria for delineating debris hazard zone have been defined by the organization and adopted in potential debris-flow creeks in Taiwan currently. To compare the method with our proposed method, the method will be introduced as follows.

The Debris flow fan flooding begins to occur at the fan apex, which is the highest point where flow is last confined, and then spreads out as sheetflood, debris slurries, or in multiple channels along paths that are uncertain. The fan apex may be at the mouth of valley or downstream of the topographic apex and may change during a flood event due to deposition and erosion. The procedure for determining the depositional extent of debris flow is to assign the location of debris-flow fan apex first. Subsequently, the debris-flow fan is drawn from the apex point with a radius of the fan and 105 degree of angle as shown in Figure 3, in which the radius L is given as the following equation.

$$\mathrm{Log}(L)=0.42\times \mathrm{Log}(V\times \tan\theta)+0.935 \qquad [1]$$

L is named as the depositional length as well; θ is the slope angle at the downstream of a potential debris-flow creek ; V is the debris flow volume (V is determined by the empirical equation $V=70.992A^{0.61}$)□A is the area of a debris-flow watershed (km^2).

Eq. 1. shows that the depositional length depends on the slope angle and the area of watershed, which is derived from a fully empirical approach and does not vary with rainfall intensity.

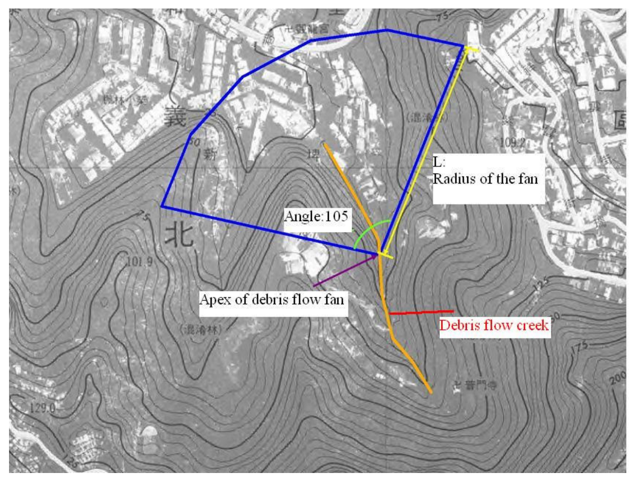

Figure 2. Debris flow fan delineated by Hiroshi Iketani equation

4 THE NEW PROPOSED METHOD

The location and size of an affected area induced by debris flow in a potential debris-flow creek usually depend on hydrologic and physiographical conditions of the creek. A suitable model to predict the debris-flow hazard zone should be dynamic and take into account those conditions. The method used and developed in this study is intended for improving drawbacks and limitations of the previous empirical method. The new proposed method will be stated as follows.

4.1 Prediction of Debris-flow Hazard Zone with Dynamic Model

A numerical model developed by O'Brien (2006) as the dynamic approach was chosen to predict areas potentially endangered by debris flows for downstream guarded areas for potential debris-flow creeks. FLO-2D has been successfully used for practical cases of debris flow simulations around the world. The model is a two dimensional flood routing model that can simulate flows over complex topographies and roughness on urbanized alluvial fans. Hyperconcentrated sediment flows such as mudflows and the transition from water flows to fully developed mud and debris flows can be simulated.

FLO-2D routes a flood hydrograph using the full dynamic wave momentum equation to accurately predict the area of inundation. The fluid viscous and yield stress terms are accounted in the model for hyperconcentrated sediment flows. The basic equations used in the model include the continuity equation

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=i \qquad [2]$$

and the two-dimensional equations of motion

$$S_{fx}=S_{ox}-\frac{\partial h}{\partial x}-\frac{u}{g}\frac{\partial u}{\partial x}-\frac{v}{g}\frac{\partial u}{\partial y}-\frac{1}{g}\frac{\partial u}{\partial t} \qquad [3]$$

$$S_{fy}=S_{oy}-\frac{\partial h}{\partial y}-\frac{v}{g}\frac{\partial v}{\partial y}-\frac{u}{g}\frac{\partial v}{\partial x}-\frac{1}{g}\frac{\partial v}{\partial t} \qquad [4]$$

in which h = flow depth; u and v = depth-averaged velocity components along x and y coordinates; i = excess rainfall intensity; S_{fx} and S_{fy} = friction slope components along x and y coordinates; S_{ox} and S_{oy} = bed slope components along x and y coordinates; and g = gravity acceleration.

The total friction slope can be expressed as

$$S_f=S_y+S_v+S_{td}=\frac{\tau_y}{\gamma_m h}+\frac{K\eta w}{8\gamma_m h^2}+\frac{n^2w^2}{h^{4/3}} \qquad [5]$$

in which S_y = yield slope; S_v = viscous slope; S_{td} = turbulent-dispersive slope; γ_m = specific weight of the sediment mixture; K = resistance parameter; η= viscosity; τ_y = yield stress; w = depth-averaged velocity. Eq. 5 evaluates rheological behaviour of hyperconcentrated sediment flows. In addition, the yield stress τ_y and the viscosity η vary principally with sediment concentration, and can be expressed in empirical relationships as

$$\tau_y=\alpha_1 e^{\beta_1 C} \qquad [6]$$

$$\eta=\alpha_2 e^{\beta_2 C} \qquad [7]$$

in which C = volumetric sediment concentration; α_i and β_i = empirical coefficients defined by laboratory experiment.

Data required for the model simulation include a digital terrain model, channel geometry, estimates of channel and floodplain roughness, inflow flood hydrographs or rainfall, and rheological properties of the sediment water mixture. For the rheological properties, the volumetric sediment concentration and yield stress are the most important parameters and are not easy to measure from field investigation. Especially, there are 160 potential debris-flow creeks in Hualien County. It is of importance to select representative values for the above parameters for each debris-flow creek. This can help characterize debris-flow on alluvial fans in a range of varied environments.

4.2 Determination of Rheological Parameters of Debris Flow with Empirical Method

When examining parameters related to debris flows, it is important to identify the volumetric sediment concentration and yield stress, which dominate the behaviour of debris flows. This study made use of empirical approaches to determine the input values for the two variables in a given potential debris-flow creek.

The volumetric sediment concentration is the equilibrium concentration (C_D) divided by the volume concentration of solid fraction on the bed (C_b), in which C_b can be estimated from the porosity of solid fraction on the bed; and C_D can be referred to Takahashi's method (Takahashi, 1980). Takahashi proposed a method to estimate the equilibrium concentration through a static equilibrium analysis,

$$C_D=\frac{\rho_w\tan\theta}{(\rho_s-\rho_w)(\tan\phi-\tan\theta)} \qquad [8]$$

where θ is the inclined angle of the channel bed and ϕ is the internal friction of debris; ρ_s and ρ_w are densities of solids and water, respectively. Since the equilibrium concentration is dependent on the bed inclination only for specific debris, the volumetric sediment concentration in a given potential debris-flow creek is a function of the channel slope.

For the determination of yield stress, the study utilized real cases to calibrate the variable by means of back analyses to fit field evidence from historical debris-flow disaster data. Based on the calibration results, we may establish an empirical equation between the yield stress and other variables such as the drainage area, channel slope, or geology of creek bed. Prior to the calibration work, other parameters, which are not significant to this variable based on the results of parameters sensitivity studies, used in the model were retrieved from literatures and field investigation. The calibration for this variable was made using data from real debris-flow events, which occurred in three debris-flow-prone creeks (Hualien 061, Hualien 069 and Hualien A112, respectively) in Hualien County during the typhoon Toraji. The collected data include DEMs, observed debris-flow influenced areas by comparing aerial photos before and after the debris flow event, rainfall data during the typhoon Toraji occurred in

July 2001. By adjusting values of the yield stress in the model to fit the observed hazard zone, Figures 3, 4, and 5 show comparison results of debris-flow affected areas from aerial photo interpretation and model simulation in the Haulien 061 creek, Hualien 069 creek, and Haulien A112 creek, respectively. The solid polygon in three figures represents debris-flow influenced areas delineated from aerial photos. The calibration results indicate the error between simulated and observed is within 10% with the check of influenced areas and 20% with the check of overlapped area referred to the area of polygon.

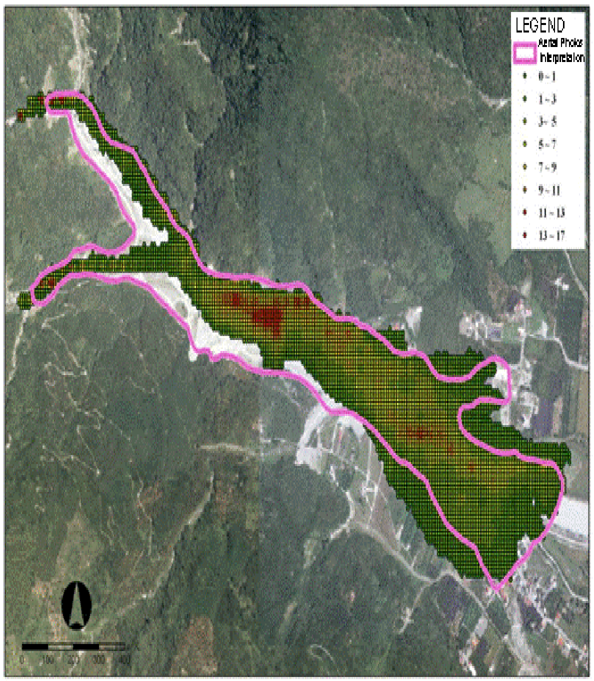

Figure 3. Comparison of debris-flow affected area from aerial photo interpretation and model simulation in the Haulien 061 creek in Dasing village

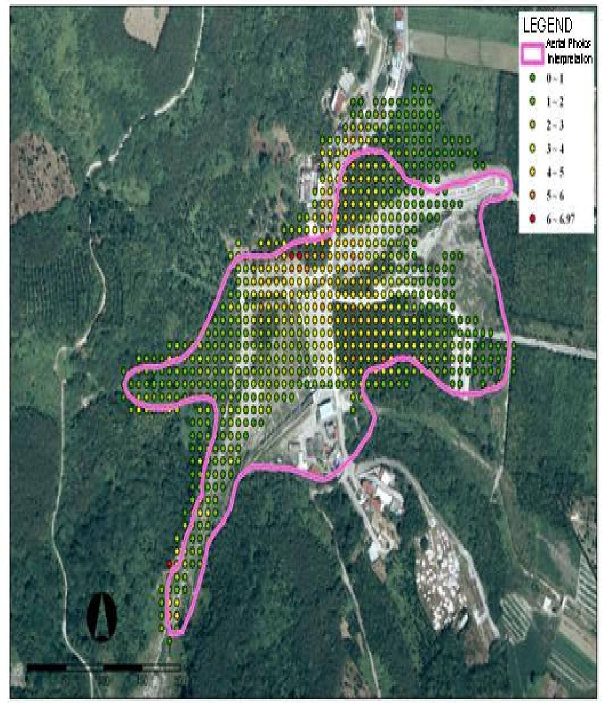

Figure 4. Comparison of debris-flow affected area from aerial photo interpretation and model simulation in the Haulien 069 creek in Jiancing village

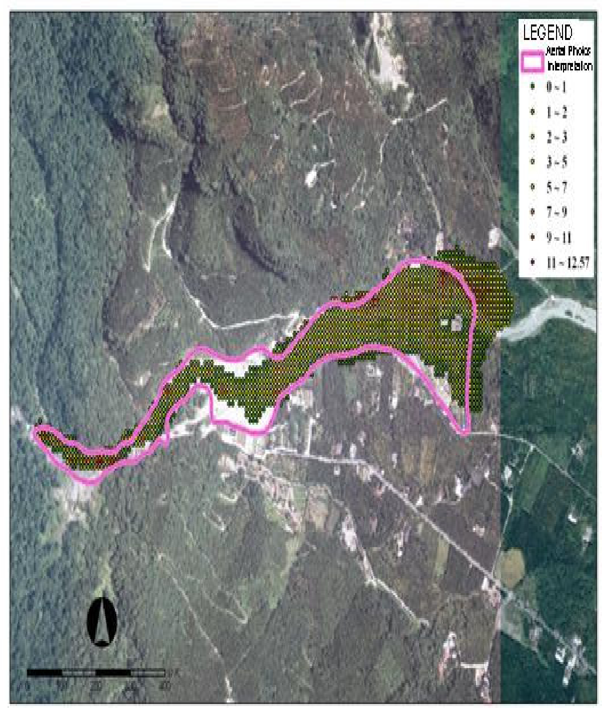

Figure 5. Comparison of debris-flow affected area from aerial photo interpretation and model simulation in the Haulien A112 creek in Fongyi village

Table 1 shows the calibration results of the yield stress for three debris-flow creeks. The drainage area, average slope of creek bed, and lithology on the creek bed for each creek are also listed in the Table. Comparing the yield stress with physiographical characteristics of the creeks, it turned out that the yield stress varies with the slope angle only. The yield stress tends to increase with the slope angle. Based on the outcome, the study suggests that the relationship between the yield stress and the slope angle can be classified into three different categories as shown in Table 2. The table is beneficial to the selection of the yield stress in modelling debris-flow hazard zone with different slope angle.

Table 1 Calibration results of yield stress for three potential debris-flow creeks

Name of creek	Lithology	Drainage area (ha)	Slope angle (degree)	Yield stress (Pa)
Hualien 061	Metamorphic rock	1429	15.6	1000~1200
Hualien 069	Metamorphic rock	59	18.8	2000~2500
Hualien A112	Metamorphic rock	746	10.8	600~800

Table 2 Relationship between yield stress and bed slope

Slope angle (degree)	Suggested yield stress (Pa)
>16	2500
12~16	1200
<12	800

5 MODEL VALIDATION

5.1 Debris Flows in Hualien A124 and Hualien 072 Creeks

On July 28, 2008, a major storm by Typhoon Fenghung passing across the eastern part of Taiwan brought heavy rainfall with the maximum rainfall intensity about 73.5mm/hr and 24-hour accumulated rainfall about 500 mm at Shilin Rainfall Station. The accumulated rainfall was over the maximum record in history from the statistical data between 1995 and 2008. Consequently, it caused numerous debris flows in Taiwan and resulted in losses of lives and properties. In Hualien County area, debris flows occurred in the Hualien A124 creek located in Dama village and Hualien 072 creek located in Shuhu village and led to losses of properties and heavy debris deposits around the outlet of debris-flow creeks. Figures 6 and 7 show the before and after photos of Typhoon Fenghung in the Hualien A124 creek and in the Hualien 072 creek, respectively. Before photos of Typhoon Fenghung were taken in summer, 2007, and after photos were taken in one week after the typhoon. A difference before and after the event was found that riverbed became wider and deeper. The raise of riverbed induced by debris deposits caused damage of properties and the cross section of an existing bridge that was prominently reduced.

Before | After

Before | After

Figure 6. Before and after photos of Typhoon Fenghung in the Hualien A124 creek

Before | After

Before | After

Figure 7. Before and after photos of Typhoon Fenghung in the Hualien 072 creek

5.2 Numerical Simulation and model verification

To verify the accuracy of the presented model, the replication of the past debris-flow hazard zone caused by Typhoon Fenghung for Hualien 124 and Hualien 072 creeks was carried out in this study. The integrated numerical model as described in previous sections was applied to simulate debris flow hazard zone. The volumetric sediment concentration and yield stress for two creeks were determined by Eq. 8 and Table 2, respectively. Other parameters used in the model were obtained from the in situ investigation. Rainfall data for Hualien A124 and Hualien 072 were collected from the rainfall records of Taian and Shilin Rainfall Stations during Fenghung Typhoon, respectively.

Figures 8 and 9 show the numerical calculation hazard zones. The model verification results for the case of Haulien A124 indicate the error between simulated and observed is 9.09% with the check of influenced areas and 13.40% with the check of overlapped area referred to the area of aerial photos interpretation. The presented method can successfully replicate the influential zone of the debris flow disaster event with an error less than 15%. The model verification results for the case of Haulien 072 indicate the error between simulated and observed is 9.17% with the check of influenced areas and 28.27% with the check of overlapped area referred to the area of aerial photos interpretation. The verification result for the case based on influenced area is quite well. However, the verification result based on overlapped area is not good. The reason may be derived from the Flo-2D model's limitation on simulating lateral erosion of the channel bank. Comparisons of debris-flow hazard zone predicted by the SWCB method and presented method for the case of Hualien A124 and Hualien 072 were also performed in Figure 8 and Figure 9, respectively. The debris-flow hazard zone predicted by the SWCB method was underestimated for the case of Haulien A124 and overestimated in transverse direction for the case of Haulien 072. This resulted in large errors in identifying the debris-flow hazard zone for debris-flow-prone creeks.

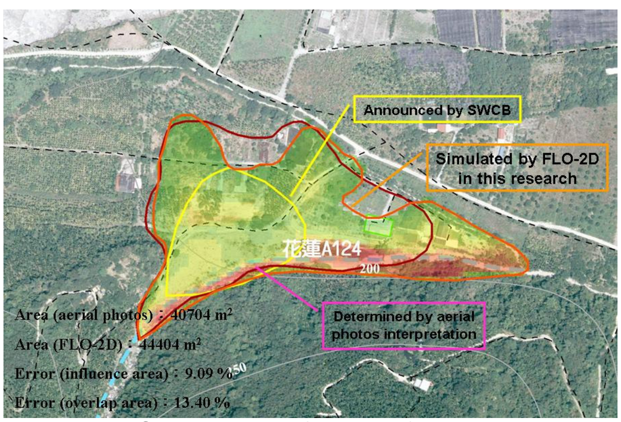

Figure 8. Comparison of debris-flow hazard zone predicted by SWCB method and presented method for the case of Hualien A124

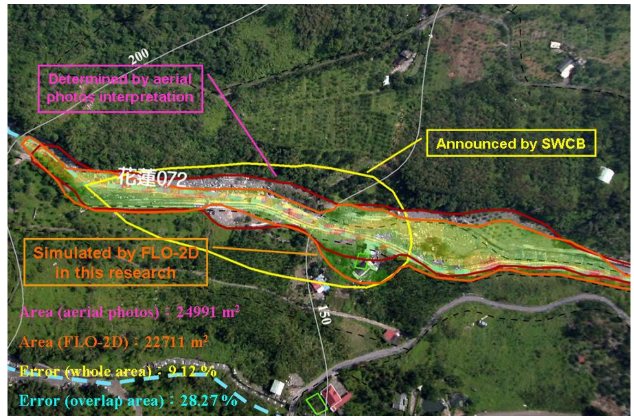

Figure 9. Comparison of debris-flow hazard zone predicted by SWCB method and presented method for the case of Hualien 072

6 CONCLUSIONS

Due to the increased frequency with which debris and hyper-concentrated flows occur and the impact they have both on the environment and on human life, these extreme events and related processes have to be paid attention. In Taiwan, an empirical method initiated by Iketani and Uehara (1980) to identify debris-flow hazard zones is adopted by the Soil and Water Conservation Bureau currently. This empirical method is a function of the debris flow volume and slope angle below the apex of a debris flow fan. Although the empirical method is easy to utilize, the delineating zone for each potential debris flow torrent is often underestimated or overestimated due to complex topography as compared to historical typhoon events.

In this study, empirical and dynamic approaches have been integrated to solve the problem. A numerical model named as FLO-2D developed by O'Brien (2006) as the dynamic approach was chosen to predict areas potentially endangered by debris flows for downstream guarded areas for potential debris-flow creeks. Empirical approaches were adopted and conducted to estimate the volumetric sediment concentration and yield stress, respectively, which are the most important parameters in the model. For the volumetric sediment concentration, Takahashi's equilibrium concentration was introduced, in which the sediment concentration is a function of channel slope. A relationship between the yield stress and the slope angle has been established through model calibration by means of back analyses to fit field evidence from historical debris-flow disaster data. Results showed the steeper the slope channel, the higher the yield stress.

In addition, the accuracy of Flo-2D for simulating debris flow hazard zones was verified through a comparison with field data which was collected from one recent debris flow disaster event triggered by Typhoon Feng-Hung starting from July 28 to 29, 2008. The disaster caused significant deposition on alluvial fans and channels in two potential debris-flow creeks which are Hualien A124 and Hualien 072, respectively. Results indicate that the model can successfully replicate the influence zone of the debris flow disaster event with an acceptable error and demonstrate a better result than the empirical model adopted by the Soil and Water Conservation Bureau of Taiwan currently.

With this verified model, the model appeared to be capable of predicting and delineating potentially hazardous zones approximately associated with debris flows in a range of varied environments for a selected frequency design flood event. Thus, this study provides the public agent or private sector the necessary information for executing the relevant policies and resource allocation on debris flow prevention.

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