DOI: 10.4408/IJEGE.2011-03.B-103

AN APPLICATION OF THE FLO-2D MODEL TO DEBRIS-FLOW SIMULATION - A CASE STUDY OF SONG-HER DISTRICT IN TAIWAN

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ABSTRACT

Taiwan is an island located in the subtropical zone where typhoons often bring heavy rainfall. In addition, streams and geology results in a high susceptibility to debris flow. Especially after the Chi-Chi earthquake on September 21, 1999, the geological condition of the mountain area located in the central part of Taiwan has been more susceptible to natural disasters of debris flow. Fractured geological units and landslides caused by frequent earthquakes provide abundant source material for debris flow. Following a typhoon or heavy storms, debris mixed with water form debris flows. Many studies have examined the triggering criteria, flow routing and deposition of debris flow in order to reduce the impact and losses caused by debris flow.

In this research, parameters and processes needed for a numerical simulation method for debris flow routing and depositions are formulated to provide a reference for hazard zone mapping. A two-dimensional model (FLO-2D software) was used to simulate a debris flow and flood, and the accuracy of the simulation, including flow depth, velocity and volumetric sediment, was analyzed using data collected on the rainfall and terrain. The case study in this research consists of three phases. In the first phase, debris flow data, including information on topography and rainfall from typhoon Mindulle in 2004 collected from First River Basin of Song-Her District in Taiwan, were compiled to establish a database of factors that influence debris flow. For the second phase, a numerical simulation was performed using FLO-2D with the results presented as area of debris-flow inundation, maximum deposit depth, and deposit volume. The simulation results were then compared with the aerial photos and the micro geomorphological study. Finally, suitable conditions for using this model, and the suggestions for future research are discussed.

Key words: Debris Flow, FLO-2D, Rheological Parameters, Micro geomorphology

INTRODUCTION

Due to the extrusion of Philippine Sea Plate and the Eurasian Plate, the island of Taiwan was formed with one third of its area located in mountainous zones higher than 1000m. Owing to the scarcity of usable land, many housing units and farmhouses are built at the hillsides and on the hills. Earthquakes and typhoons occur frequently in Taiwan because it is on the Circum-Pacific Earthquakes Belt and Western-Pacific Typhoon Path. The average annual rainfall is more than 2500 mm and is due to severe rainstorms caused by typhoons. Moreover, after the 921 Chi-Chi earthquake, weak geology, steep topography, and land use in steep terrain has caused frequent debris flow in mountain areas, in which people also suffered from debris flow during plum rains and typhoon seasons. In recent years, natural disasters such as landslides, debris flows, and mudflows usually occur in mountainous areas during and after typhoons and rainstorms in Taiwan.

Debris-flow deposition is greatly influenced by material parameters. Time consuming and expensive sampling and laboratory experiments are needed to model debris-flow deposition.. The maximum particle size of a field sample needs to be reduced so that the material properties can be performed in the laboratory experiments. Numerical simulation was performed using FLO-2D on the results presented as area, maximum deposition depth, and deposition volume.

In June, 2004, Typhoon Mindulle caused 72 serious floods in the central Taiwan, bringing about an accumulated rainfall of 1670 mm. There were also several serious debris-flow disasters in mountainous regions of Song-Her District. This study used the FLO-2D Model, developed by O'Brien and Julian in 1998, which coordinates rainfall data and a digital terrain model (DTM) to predict debris-flow properties of volumetric sediment, flow depth and rate of debris-flow deposition. Actual rainfall data was gathered during Typhoon Mindulle to simulate debris flows in the Song-Her District using the FLO-2D model, and the results were compared to data on the actual area of debris-flow deposition determined by aerial photography and the micro-topography.

Results from this research will determine the area of influence from the First River Basin of Song-Her District debris flow to provide basic information for the local evacuation and rescue route planning for debris flows. The methodology developed in this research may be used to determine hazardous zones, to estimate the effectiveness of the Flo-2D model, and provide guidelines for future construction.

METHODOLOGY

INTRODUCTION OF FLO-2D MODEL THEORY

O'Brien *et alii* (1993) developed a two-dimensional flooding routing model (FLO-2D), which is a valuable tool for delineating flood hazards and simulating flood wave attenuation and debris flows.

Simulation of debris flows requires rheological models (or constitutive equations) for solid-liquid mixtures. The rheological property of a debris flow depends on a variety of factors, such as water concentration, solid concentration, cohesive properties of the fine material, particle size distribution, particle shape and grain friction (Imran *et alii*, 2001).

The following conditions are assumed in order to simplify the model operation of FLO-2D:

1 using the shallow water equation, the Leibnitz rule, to interchange the order of integration and differentiation to simplify the continuity and the momentum equations;
2 steady flow;
3 hydrostatic pressure distribution;
4 steady flow resistance equation.

There are two restrictions in this model.

1 The model cannot modify scoured depth.
2 The model cannot simulate shock wave and hydraulic jumps.

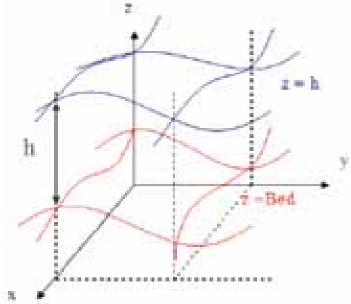


Fig. 1 - Definition of coordinate system for two-dimensional governing equations

Although FLO-2D model has some assumptions and restrictions. Su (2002) used the model for debris-flow routing in Da-Xing in Taiwan and found that the down-stream deposit and velocity distribution were accurately estimated using the FLO-2D model.

FLO-2D CONTROL FORMULA

Using the notation and coordinate system given in Fig. 1, the governing equations are shown as follows:

The continuity equation is:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = i \quad (1)$$

h: depth of debris flow
u: velocity components in the x-direction
v: velocity components in the y-direction
i: rainfall intensity
t: time

$$S_{fx} = S_{bx} - \frac{\partial h}{\partial x} - \frac{\partial u}{g\partial t} - u\frac{\partial u}{g\partial x} - v\frac{\partial u}{g\partial y} \quad (2)$$

$$S_{fy} = S_{by} - \frac{\partial h}{\partial y} - \frac{\partial v}{g\partial t} - u\frac{\partial v}{g\partial x} - v\frac{\partial v}{g\partial y} \quad (3)$$

The momentum equations is:
S_{fx}, S_{fy}: friction slope;
S_{bx}, S_{by}: bed slope;

g: gravitational acceleration.

Equations (2) and (3) represent the momentum equations of the force equilibrium on the X- and Y axes, respectively. This non-dimensional implication further discusses the effects of acceleration involving friction slope affected by material intensity on contact (rheological model), bed slope of gravity, pressure gradient, local acceleration and convective acceleration.

The dynamic wave model is an intact momentum equation as shown in Eq. (2) and (3). However, the diffusion wave model is obtained when ignoring the items 3 through 5 after the equal sign in Eq.(2) and (3), whereas the kinematical wave model ignores the items 2 through 5 in the same equations. While FLO-2D is available for the analysis of the above three models, only the diffusion wave model was used in this study.

RHEOLOGICAL EQUATION

The FLO-2D numerical code is used to simulate debris-flow deposition, velocity and area of inundation.

This model uses the quadratic rheological model presented by O'Brien & Julien (1988), which includes yield shear stress, viscous shear stress, cohesive yield stress, and turbulent shear stress. Five important parameters are chosen, including the slope of channels, concentration by volume, yield stress, viscosity, and density of sediment. The analysis result shows that the slope of channels and the concentration by volume are the most important parameters of the debris flow routing in FLO-2D.

$$S_f = S_y + S_v + S_{td} = \frac{\tau_y}{\gamma_m h} + \frac{K\eta u}{8\gamma_m h^2} + \frac{n^2 u^2}{h^{4/3}} \qquad (4)$$

where:

S_y: yield slope; S_v: viscous slope; S_{td}: turbulent-dispersive slope; τ_y: Bingham yield stress; η: Bingham dynamic viscosity; γ_m: unit weight of debris flow; K: resistance parameters for Laminar flow; n: Manning's roughness coefficient; h: depth of debris flow; u: velocity components

INTERPRETATION OF MICRO-GEOMORPHOLOGY

The DEM data for the First River Basin of Song-Her District were obtained big disaster caused by typhoon Mindulle in 2004. If a value of pre-disaster DEM is less than the value of the post-disaster DEM deposition has occurred. The depositional area, maximum depositional depth, and depositional volume at the basin can thus be defined. Simulation results are compared with aerial photos and micro-topography.

REGIONAL OVERVIEWS

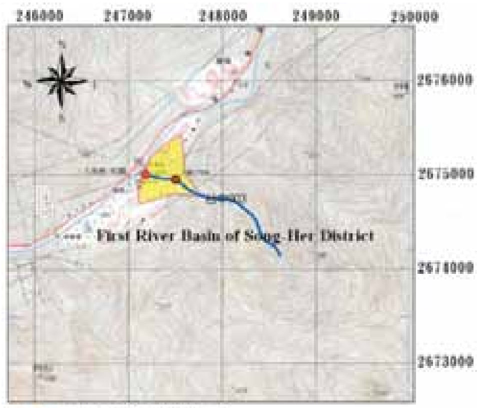
REGIONAL INVESTIGATION

Topography and stream

This study investigates the potential debris flows of First River Basin. The first River Basin of Song-Her District is located in Herping in Taiwan. Herping is a mountainous township located in eastern Taichung County, and occupies the largest part of the county by area (half of the entire county). The height in the township is about 2230 m. There are approximately 1000 km^2 in Herping. The geography of this study in the region is shown in Fig. 2 (Fu-Xiong Engineering Consultants, Inc., 2005).

Wingrid software on a DTM (digital terrain model) grid system was used to obtain the watershed used in the simulation. It shows that basin of Song-Her Districtin is flat, long and narrow (Fig. 3). It is easy to deposit quantities of earth and stones because the topography is long and narrow, when the sediment transporting along the stream.

First River Basin of Song-Her is classified as having debris-flow potential. The river basin number 003 has an area of 375 hectares and a length of 4430 m. After the 921 Chi-Chi earthquake in 1999, many landslides have occurred in the First River basin of Song-Her watershed area. According to the investigation, the landslides are still active due to abundant rainfall provided by typhoons. The unstable soils in the landslide initiation areas are the main soil sources of debris-flow. Recent observation there is a high possibility that more debris flows will happen again.



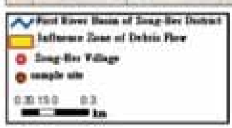


Fig. 2 - The geography of First River Basin of Song-Her District site (intergrated planning and designing for the Song-Her District of Herping townshipe in Taiwan, Fu-Xiong Engineering Consultants,Inc., 2005)

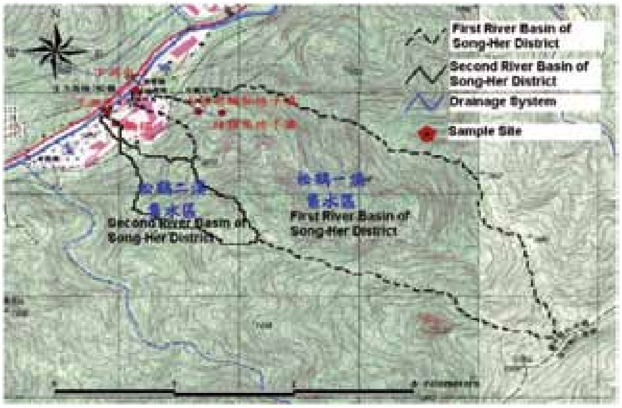


Fig. 3 - The watershed region of First River Basin of Song-Her (The plan debris flow-003 designated soil and water conservation area of Herping township in Taiwan, Soil and Water Conservation Bureau Council of Agriculture, 2005)

Fig. 4 - Aerial photography on Song-Her District site (after typhoon Mindulle in 2004)

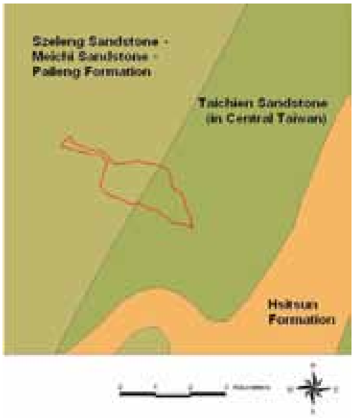


Fig. 5 - The stratigraphy of debris flow-003 designated by the soil and water conservation area of Herping township in Taiwan (Soil and Water Conservation Bureau Council of Agriculture, 2005)

Due to the minimal distance between the river and village, future debris flows in this area may dam the river and cause a serious disaster. On July 2, 2004, heavy flooding from typhoon Mindulle caused serious disaster in both Song-Her and Boh-Ai villages as shown in Fig. 4.

Stratigraphy in the First River Basin of Song-Her

According to the 1:500,000 scale geologic map published by Central Geological Survey, MOEA (Central Geological Survey, Ministry Of Economic Affairs, 1986), synclines and anticlines of Da-jian Sandstone and Paileng formation constitute the strata in this watershed (Fig. 5).

Surface soils in the First River Basin of Song-Her

There are two different kinds of colluvial soils and lithosols in this area. Lithosols compose the main soil of the upper stratum. The soil distribution in this study area is shown in Fig. 6 (Soil and Water Conservation Bureau Council of Agriculture, 2005).

DATA OF RAINFALL

Typhoon Mindulle caused 72 serious floods in central Taiwan in June, 2004. The path of the typhoon is shown in Fig. 7. The rainfall distribution from 7/2 to 7/3 in 2004 at Song-Her raingauge station is shown in Fig. 8. The observation of the maximum hourly rainfall at Song-her workstation is shown in Table 1.

RESULTS AND DISCUSSIONS

This study investigates the potential debris flows of First River Basin (No. 003) in Herping, Taichung during rainfalls due to typhoon Mindulle to simulate stream discharge and debris-flow occurrence. The following sections present the results of this study.

DATA PRETREATMENT

Digital elevation model, DEM

DEM data for the First River Basin of Song-Her Dis-

Fig. 6 - The Surface soils of debris flow project 003 in the soil and water conservation area of Herping township, Taiwan (Soil and Water Conservation Bureau Council of Agriculture, 2005)

Fig. 7 - The path of typhoon Mindulle (Typhoon Database, Central Weather Bureau, 2004)

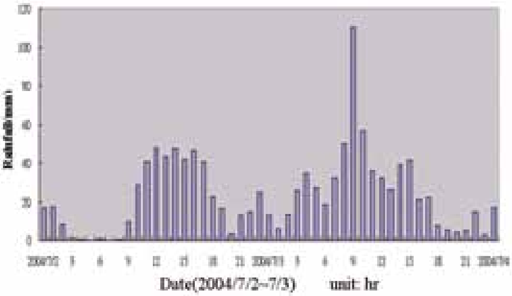


Fig. 8 - Rainfall distribution from 7/2 to 7/3 in 2004 at Song-Her workstation

site	Raingauge Observation Station	2004(7/2~7/3) 72 flood. 2004 maximum hourly rainfall (mm/hr)	maximum daily rainfall (mm/day)
Song-Her District in Taiwan	Song-Her	110.0	516.0

Tab. 1 - Observation of the maximum hourly rainfall at Song-Her workstation

trict were obtained after the debris-flow disaster caused by typhoon Mindulle in 2004 from the Agricultural and Forestry Aerial Survey. The DEM has a 20m resolution and was used simulate the debris flow using FLO-2D.

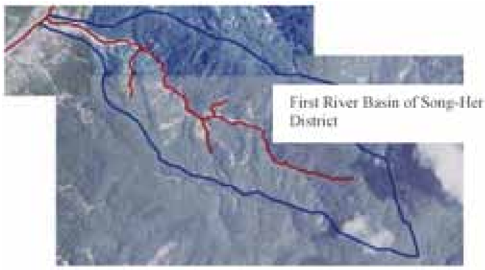


Fig. 9 - First River Basin at Song-Her District

<u>Watershed delineation</u>

The DEM data encompassed the entirety of the studied watersheds, and a database of factors that influence debris flows was compiled to aid in digital simulation of the debris flows.

The DEM was analzyed as follows:

1 The vector form of digital elevation for each basin is converted to gridded data.
2 A grid-based unit flow direction was determined by ArcView spatial analyst- hydrologic modules.
3 A flow accumulation grid was calculated.
4 The watershed was delineated.

Finally, the shape of the watershed is determined. The Fig. 9 shows the watershed outline of the First River Basin at Song-Her District.

<u>Flow Outlet</u>

In this study, it was found that debris flow mainly scoured and deposited material above the watershed outlet. Below the wathershed outlet, only deposition occurred. The location of the waterhsed outlet is very important in the application of the FLO-2D debris-flow simulation model.

Guidelines for locating the watershed outlet was provided by Hui (2006), which shows that the First River Basin at Song-Her District was interpreted by micro-topography. If the value of pre-disaster DEM minus disaster DEM is negative, it indicates an area of deposition, whereas if it is positive, it reflects an area of erosion. The range selected in the balanced area of the deposition and erosion is the outlet of flow at the

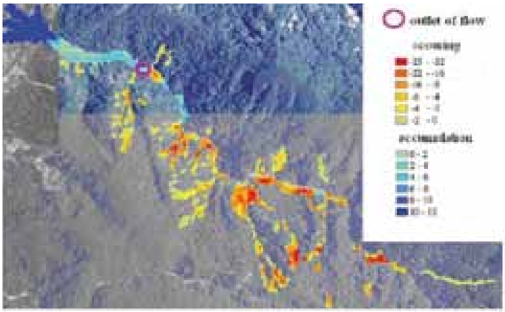


Fig. 10 - Debris-flow erosion and deposition of the First River Basin at Song Her District

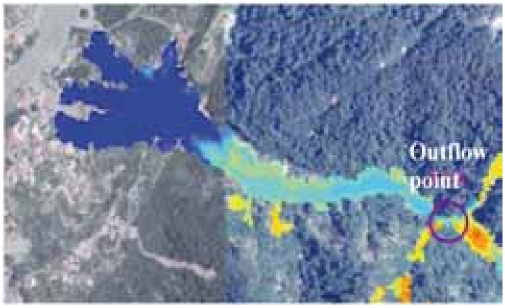


Fig. 11 - Outlet of the First River Basin at Song Her District

weight of moist-soil (kg)	2110
volume (m^3)	1.0
density of field (ton/m^3)	2.11
dry density of field (ton/m^3)	1.85
water content (%)	14.1
Gravel Content (%)	78.1
<#200 sieve analysis (%)	1.5
particle size <0.1mm (%)	2

Tab. 2 - The parameter of field test

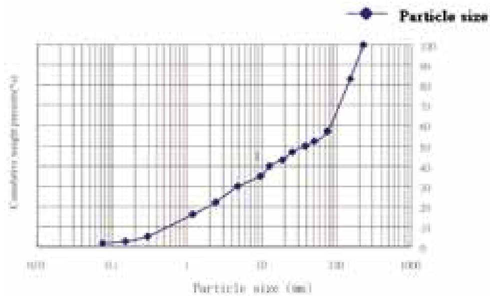


Fig. 12 - Curve of particle size distribution for sieve analysis of the field sample

basin (Fig. 10). The areas of erosion and deposition and the watershed outlet is shown in Fig. 10 and 11.

After the hydrologic analysis of the DEMs of Song-Her District, it was automatically divided into functional divisions of watershed areas using WinGrid software, and also for basic analysis of the study area by using ArcView software's contour lines, aspect, slope and other functions. The DEM data were then transferred into a word file using FLO-2D software program to determine the Manning coefficient n value, and the output of the FLO-2D program.

PARAMETRIC STUDY ON THE DEBRIS FLOW SIMULATION

1 Volumetric Concentration of Sediment:
The volumetric concentration of 70% was used in the study based on the field investigation after the debris flow disaster. Samples of the debris-flow deposit contained higher gravel content and larger gravel size.

2 Rheological coefficients:
Both τy, η, and C_v can be obtained using equation 5 and 6.
The relationship between yield stress, τy, and concentration by volume, C_v, is shown in eq.(5)

$$\tau_y = \alpha_1 e^{\beta_1 C_v} \quad (5)$$

The relationship between dynamic visosity, η and concentration by volume, C_v, is shown in eq.(6)

$$\eta = \alpha_2 e^{\beta_2 C_v} \quad (6)$$

From the rheological coefficient test in the field and referring to FLO-2D Users Manual (O'Brien, 2004), as well as substituting the α_1, β_1, α_2, β_2, and C_v values into the equations (5) and (6). Then the initial value (τ_y , η) of rheological coefficient of simulation can be obtained.

3 Manning's *n* value:
Both the parameter of the field test and the curve of particle size distribution can be obtained as shown in Table 2, and Fig. 12, respectively. Another curve of particle size distribution by Fu-Xiong Engineering Consultants, Inc. (2005) can be found in Fig. 13. The results of the sediment collected in the field are then analyzed as shown in Table 3.
The result of Manning's value, n, which is 0.032 is shown in Table 4.

4 Specific gravity:
Shim (1999) indicates that the specific gravity of sedimentary rocks between 2.01~2.78. The specific gravity with high block content was determined to

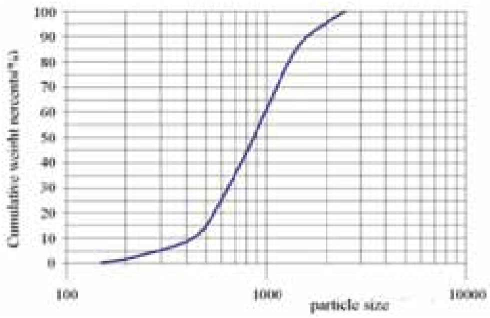


Fig. 13 - Curve of particle size distribution around the First River Basin at Song-Her District (Fu-Xiong Engineering Consultants, Inc., 2005)

particle sizes	d_{90} (cm)	d_{75} (cm)	d_{65} (cm)	d_{50} (cm)
First River Basin of Song-Her District Site	162	128.5	112	87

Tab. 3 - The investigate and analyze result of sediment in the field

scholar	equation	First River Basin of Song-Her District
mei-bi-mu	$0.001216d_{90}^{1/6}$	0.0284
Lane-Carlson	$0.0156d_{75}^{1/6}$	0.0350
San Line River	$0.0142d_{75}^{1/6}$	0.0319
Einstein	$0.0132d_{65}^{1/6}$	0.0290
Strickler	$0.015d_{50}^{1/6}$	0.0316
Mean value		0.0312

Tab. 4 - The result of Manning's n value

Input data		Initial value	
Bingham yield stress τ_y (Pa)	α_1	1202.2	0.0811
	β_1		13.72
Bingham dynamic viscosity η (Pa-s)	α_2	1.21	0.000462
	β_2		11.24
Manning's Roughness Coefficient n		0.0312	
Specific Gravity of debris flow G_s		2.7	
Resistance Parameters for Laminar Flow K		2285	
volumetric concentration of sediment C_v		0.7	

Tab. 5 - Parameters of initial value simulated by FLO-2D

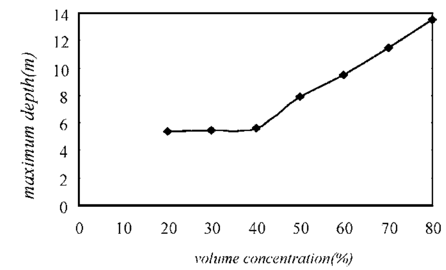


Fig. 14 - The relationship of volume concentration and maximum depth with the debris flow

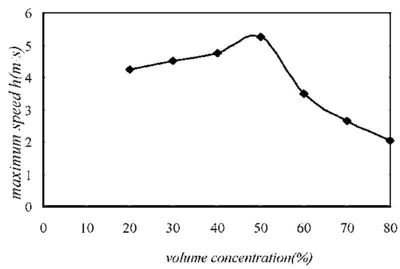


Fig. 15 - The relationship of volume concentration and maximum speed with the debris flow

be 2.70 in this study. The parameters of initial value of simulation by FLO-2D are shown in Table 5.

Sensitivity Analysis

The data and parameters collected in the field from the First River Basin at Song-Her District in Taichung after typhoon Mindulle were adopted to conduct a sensitivity analysis with FLO-2D.

The results are shown as follows:

1 The influence of volumetric concentration.

The effects of volumetric concentration on maximum depth are shown in Fig. 14 and 15, respectively.

(a) When volumetric concentration of sediment is less than 50, maximum debris-flow velocity was found to increase. This is due to resistance force being smaller than the driving force of the debris flow.

(b) When volumetric concentration of sediment is greater than 40, the maximum flow depth increases (Fig. 14), but the maximum flow velocity decreases with higher volumetric concentration as shown in Fig.

(c) Many factors in the FLO-2D simulation model are influenced by volumetric concentration of sediment.

2 The influence of Manning's Roughness Coefficient, n. The effects of Manning's Roughness Coefficient on the depth and the velocity of debris flow are shown in Table 6 and 7 and Fig. 16. The tables and figures show that as Manning's Roughness Coefficient, *n*, increases, the debris flow depth increases, whereas the flow velocity decreases.

SIMULATION RESULTS

Simulation results are compared with aerial photos and micro-topography study. The result of micro-

Manning's n value	0.4	0.2	0.1	0.05	0.025
Maximum depth (m)	11.74	11.66	11.55	11.46	11.42
Deposition volume (m^3)	869180	857360	856700	845930	845510

Tab. 6 - The relationship of Manning's n value and the depth of debris flow

Manning's n value	0.4	0.2	0.1	0.05	0.025
maximum flow velocity (m/s)	2.37	2.44	2.51	2.59	2.68

Tab. 7 - The relationship of Manning's n value and the velocity of debris flow

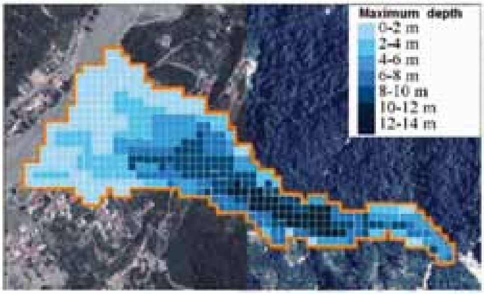


Fig. 16a -Manning's n value =0.4

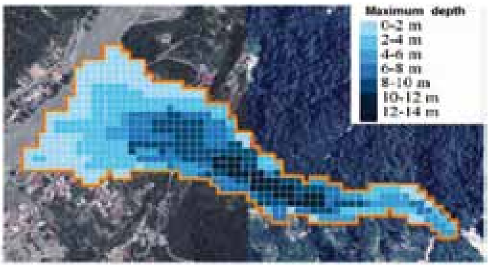


Fig. 16b -Manning's n value =0.2

topography is shown in Fig. 17.

The depositional area, maximum depositional depth, and depositional volume are shown in Table 8, and the comparison of depositional volume is shown in Table 9. The depositional volume is 798,800 m^3 as shown in Fig. 18. There is a minimum of 5% difference in depositional volume between micro-topography and the simulation result with yield stress of 2,500 Pa and Bingham dynamic viscosity (n) of 10 Pa-s by FLO-2D.

CONCLUSIONS

1 Manning's Roughness Coefficient has an extremely significant effect on debris-flow processes

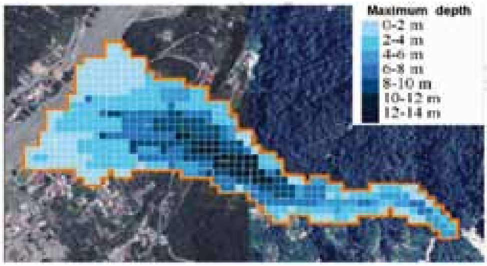


Fig. 16c- Manning's n value =0.1

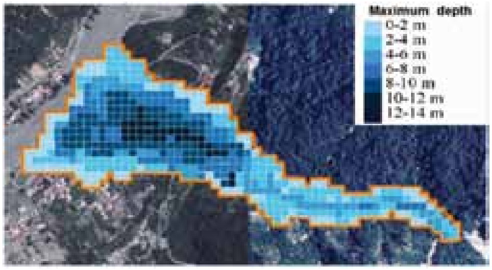


Fig. 16d -Manning's n value =0.05

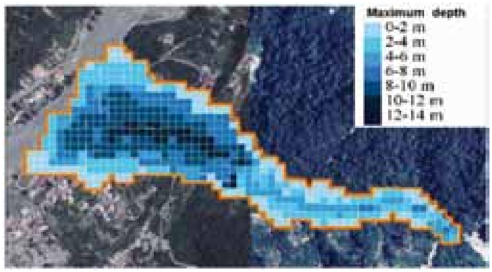


Fig. 16e- Manning's n value =0.025

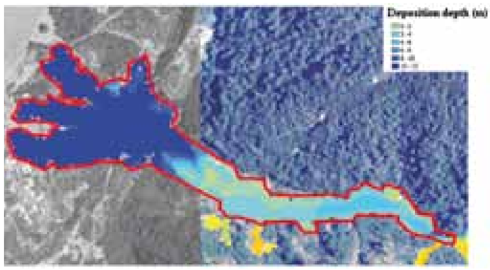


Fig. 17 - Result of micro-geomorphology

and final deposition morphology. An increase of Manning's Roughness Coefficient would lead to a decrease of the distances of debris-flow runout and an increase of the maximum deposition depth. However, during the flow process, debris-flow velocity would be decreased.

2 The specific gravity of debris-flow materials had a lesser effect on the success of the FLO-2D simu-

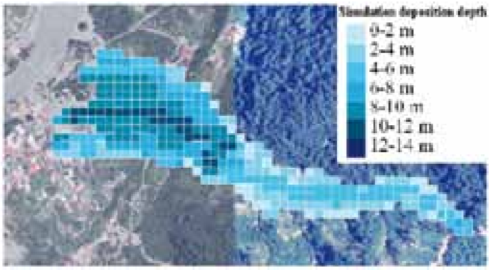


Fig. 18 - Simulation with yield stress 2500 Pa

lation. An increase of specific gravity of debris-flow material granules caused an increases of the debris-flow runout and debris-flow velocity.

3 Volume concentration is found to have affected the material parameters (e.g. yielding stress and viscosity coefficient) of debris fluid and amplification of debris flow. An increase of the volume concentration leads to elevated sediment volumes, and therefore these parameters need to be simplified in order to do the digital simulation of the debris flow.

4 The results of the simulation and the micro-topography features in the present study suggested that the closest parameterizations of debris flow materials were as follows: a yielding stress of 2500 Pa, a viscosity coefficient of 10 Pa-s, a Manning's Roughness Coefficient of 0.0312, laminar flow retarded coefficient of 2285 and a specific gravity of debris-flow material of 2.7.

5 A case study was performed to progress the digital simulation through the model and the parameters of the present study. At the same time, simulation results were compared to aerial photos and a micro-topography study. The results suggest that the simulation adequately modeled debris-flow

	The maximum deposition depth (m)	Deposition area (m^2)	Deposition volume (m^3)
micro-geomorphology	12.32	140000	756400
initial value τ_y=1202.2 Pa	10.03	148500	652300
τ_y=3000Pa	13.09	148570	842500
τ_y=3500Pa	11.18	149000	814600
τ_y=2500Pa	11.43	148000	798800

Tab. 8 - Simulation Results

	Difference of deposition volume (%)
Initial value τ_y=1202.2 Pa	13
τ_y=3000Pa	11
τ_y=3500Pa	7
τ_y=2500Pa	5

Tab. 9 - Comparison of Deposition Volume
Note: Difference of deposition volume (%) = (the results of micro-geomorphology - the results of simulation) / the results of micro-geomorphology

deposition; however, the differences in debris-flow deposition volume and maximum deposition depth between the simulation study and the in situ condition were still present.

ACKNOWLEDGEMENTS

Finanical support from National Science Council, Republic of China (NSC-96-2625 -Z -005-002-MY3) is gratefully acknowledged. Special thanks are extended to Professor Chao-Yuan Lin for offering GIS software program. The graduate student Sung-Tsuen Chen was helpful in reorganizing the data of FLO-2D.

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