The Comprehensive Slope-land Disaster Magnitude Assessment for Landslide and Debris Flow

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The frequency of the extreme event increases recently. These event cause serious impact to the slopeland area, especially landslide and debris flow disasters. Two disasters occur during the one event at the same place causes more serious disasters than a single disaster does and made the bigger threaten to the community and transport infrastructure. This study aims to discuss the scenario simulations of landslide and debris flow and to estimate the disaster magnitude. The data connection between landslide and debris flow was considered by aerial photograph classification and numerical simulations. One analysis framework was addressed and the debris flow disaster event occurred at Hualien county during typhoon Saola in 2012 was determined as the study area. The utility of the framework and the disaster magnitude were therefore estimated. The result shows that the framework established in this study successfully described the data connection between landslide and debris flow numerical simulations. The effect area and landslide volume estimation were shown better result through the analysis process. The simulation result also shows that the parameter sets and the DTM resolution are two key elements to affect the estimation result.

Key words: Flo-2D, TRIGRS, landslide volume, disaster magnitude, extreme event

1. INTRODUCTION

Taiwan is with very high slope-land disaster potential, especially the slope-land area. Heavy rainfall triggers rock fall, debris flow, and landslide in the flood season and causes serious disasters. These hazards are main threats in the mountain area that occur at the same time and cause the interaction influences to the community or significant infrastructures, such as roadways or bridges. Researchers intend to analyze the hazard potential and estimate the probable disaster magnitude of the historical events so that the latter disaster prevention strategies can be designed.

[*Chang et al.*, 2011] developed a comprehensive framework including landslide and debris flow assessment models to estimate the affected ranges. Topographic features were utilized, including topography, geology, rainfall intensity, accumulated rainfall and the landslide inventory from multi-period images. The differences from the image classification cause the estimation result errors. The Water Resource Agency focused on disaster impact by climate change in four main catchments in Taiwan. They considered sediment-related hazards, including soil erosion, landslide and debris flow, but estimated the two main hazards by logistic regressions, respectively. The similar method was also utilized by [*SWCB*, 2013]. They discussed the slopeland disaster potential under climate change scenario. The disaster influences was referred independently so that the total disaster influences by different hazards is still unclear. [*Lin et al.*, 2014] estimated the sediment runoff volume by LIDAR image to simulate the probable influenced area by debris flow in the same catchment. Recent researches show that the idea of considering different sediment-related hazards in the same catchment and discussing the interaction or the causal relation are more important nowadays. However, the methodology of a comprehensive framework containing two more disasters is always complicated. Besides, a large number of materials and field investigation data are necessary to verify the parameter sets, and it also possible to provide more precisely results. For the emergency uses, a rapid and approximately result is necessary to estimate the probable disaster magnitude, especially for debris flow disasters.

Typhoon Saola attacked Taiwan on August, 2012. One of the debris flow disasters occurred at the torrent without debris flow disaster before. From the field survey, the disasters occurred at least 3 times. The former debris flow brought a number of rocks more than 10m height, accumulating at the downstream area. The latter debris flow flew down and made a turning curve at the slope toe. The sediment covered about 30 buildings in the He-Zhong community and affected the highway No.9 and railways. In order to clarify the disaster reason of this event, authors described a scenario simulation in the previous study [*Chen et al.*, 2012; *Wang et al.*, 2012; *Wu et al.*, 2012]. However, the sediment volume estimation still has a large difference from the numerical simulation result with field survey result. A more precisely result can be achieved if the assessment method is improved.

Due to the reason referred, the authors aim to establish a data connection framework to rapidly estimate the probable sediment volume by an extreme rainfall event. This framework will also clarify the influenced area by debris flow. The debris flow disaster event in He-Zhong community during Saola typhoon is determined as the case to examine and calibrate the framework feasibility and to discuss the restriction and improvement of this methodology.

2. STUDY AREA

He-Zhoung area is located at north part of Hualien County in the eastern Taiwan. This area is at the most north sub catchment of Taroko catchment (**Fig. 1**). Most part of this sub catchment is mountain and the plain area is between the mountain and the coastline. The elevation is between 0m and 1069m. The area of this sub catchment is simply 9.84ha but the average gradient is very sharp. Communities are shown as linear distribution in this region and the transportation facilities, including highway and railway, are the only way in and out to the community. Therefore, the community is easily isolated if the transportation is disrupted.

According to the geological investigation result and the map by Central Geological Survey, [*MOEA*, 2007], the geological contribution in study area includes metamorphosed limestone, gneisses, and alluvium and without fault crosses (**Fig. 2**). These geological materials are metamorphic rock and have high rock hardness, so that the erosion is hard to occur. The historical landslide database shows that very few landslide events occurred between 1989 and 2013. The aerial photograph also represents very few bare land could be found. Before this disaster event during typhoon Saola, one torrent, which is Hualien DF026, is defined as the torrent with high debris flow disaster potential and its influenced area cover part of the community. Hualien DF166 at the north side of the He-Zhong community was defined as torrent with debris flow disaster potential after typhoon Saola and its threshold is 250mm. The length of the torrent is 2.35km and the upstream area is almost covered by forest.

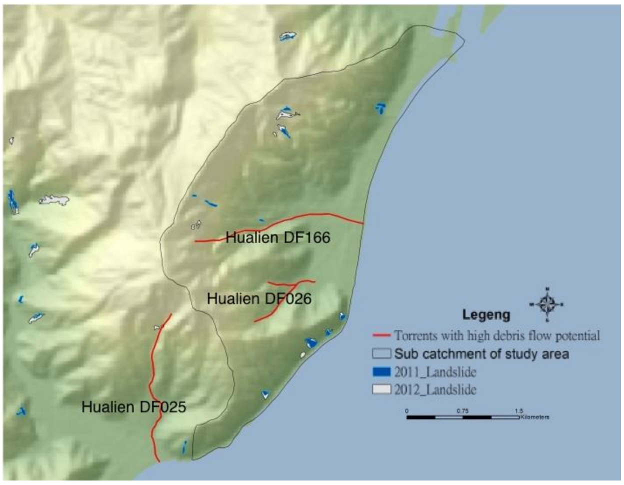

Fig. 1 The study area and the torrents with debris flow potential

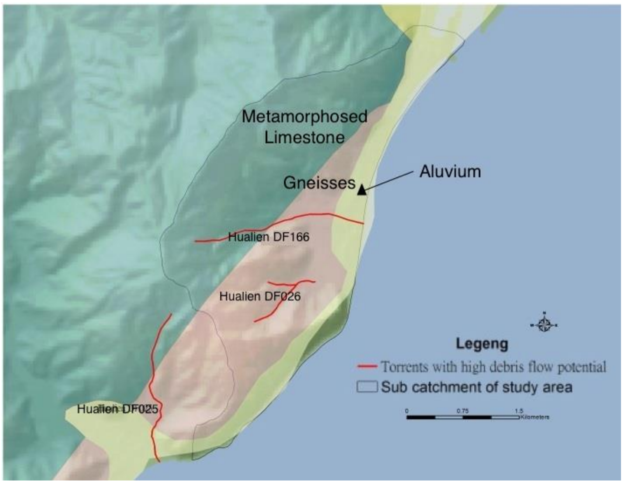

Fig. 2 The geological map study area

3. DATA CONNECTION FRAMEWORK AND MATERIALS

3.1 Data connection framework

A framework to describe the data connection among hydrological triggering slope-land disasters was carried out in **Fig. 3**. Generally the sediment movements have many different types on the slope, such as rolling, sliding, and flowing. The mechanism of these movements is complicated in the real case when two or more types occur at the same time and it is hard to describe their interaction in a model. Our target is to determine a simple and clear framework to make the rapid estimation of the sediment volume, so we determined the sediment movement types of highest frequency and the most necessarily, including slope erosion, shallow landslide and debris flow. These movements are triggered by rainfall.

The main conception of the methodology starts from landslide occurrence by rainfall. Landslide and soil erosion occur and generate the debris, part of the sediment will move to the main stream by a certain proportion. So the sediment delivery ratio helps to classify the probable sediment volume enter the main stream. Besides, the other part of the sediment will transform to debris flow with stream discharge. The influenced area by debris flow at the slope toe or the area with gentle slope and part of the sediment at the fan close to the main river will enter the river. The total sediment volume entering the main river flow to the downstream or entering reservoir and will affect the discharge to the downstream part of the main flow. This part of the total sediment volume is estimated by sedimentation yield rate and whether the sub catchments in the flow path are easily eroded or accumulated. Therefore, the main purpose of this analysis process is to estimate how much sediment volume will move to the reservoir or the downstream. In this study, we firstly look at the data connection from the landslide and debris flow is effective or not.

The main part of the process is divided into three parts, landslide potential analysis, debris flow simulation, and sub-catchment upstream part of debris flow recognition. The landslide potential analysis is by TRIGRS model. A threshold value is necessary to define and transform the safety factor from TRIGRS to landslide volume. The Flo-2D numerical model is for analyzing the influenced area by debris flow. The debris flow discharge is one of the necessary data for this model. We estimated the debris flow discharge by considering how much sediment in the upstream of the torrent becomes the debris flow material. Therefore, aerial photograph recognition is provided.

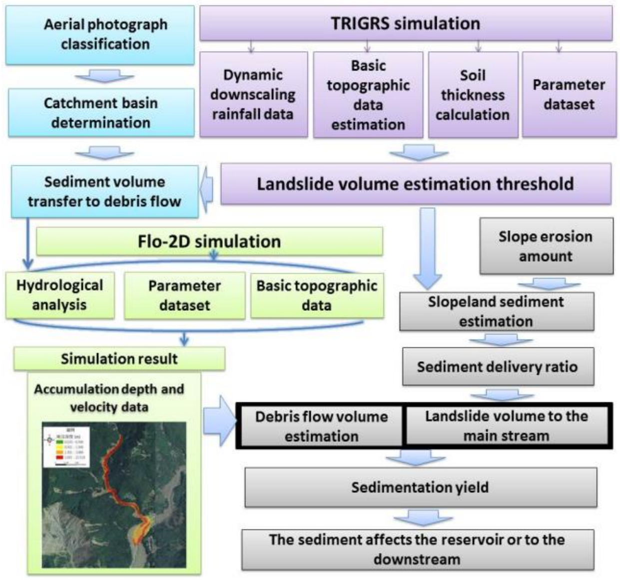

Fig. 3 The assessment framework for landslide and debris flow

3.2 Data and Materials in this study

Some of the significant data and materials are required for the two numerical models and the aerial image interpretation in this study, including image data, rainfall data, and topographic data.

Digital Terrain Model (DTM) data is the main material used for simulation. The gradient data, the sub catchment analysis, elevation data are from DTM data. Two DTM data with different resolution were used in order to compare if the resolution affects the simulation result or not, which are 40m resolution by Aerial survey office, Forestry bureau and 30m resolution by ASTER (**Fig. 4**). The contour map shows the differences of the two data. Aerial survey office produced the 40m DTM data in 1989 and the 30m DTM data from ASTER was produced in June, 2009. The data by ASTER is newer but 40m data is still used generally due to the different DTM production methods and the strict modification on the quality. From **Fig. 4**, 30m DTM data matches more with the community distribution after overlaying with the aerial photograph. DTM data is used to produce topographic data, such as slope gradient, contour data, and sub catchment delineation by spatial analysis module in ArcGIS software.

The rainfall observation data is provided by central weather bureau [*CWB*, 2012]. The rainfall data is used to calculate the discharge and is the input data. We collected the rainfall data from the nearest rainfall station, the He-Zhong rainfall station in two types: a. the daily rainfall between May and October from 2003 to 2010; b. total 61hr hourly rainfall data during typhoon Saola, from July 30th to Aug. 2nd (**Fig. 5**).

$$FS = \frac{tan\theta}{tan\alpha} + \frac{c - \phi(Z,t) r_w tan\Phi}{r_s Z sin\alpha cos\alpha} \quad (1)$$

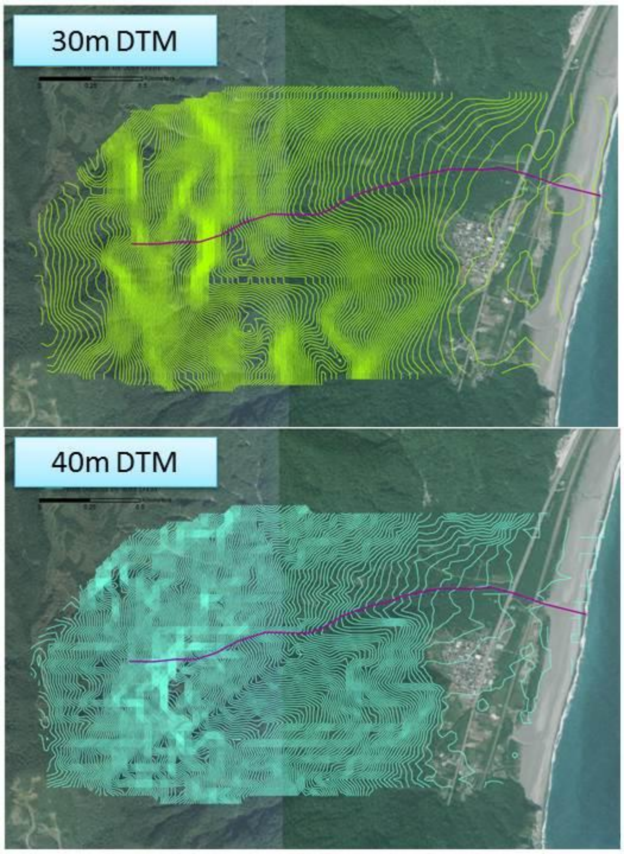

Fig. 4 Contour from different resolution DTM data

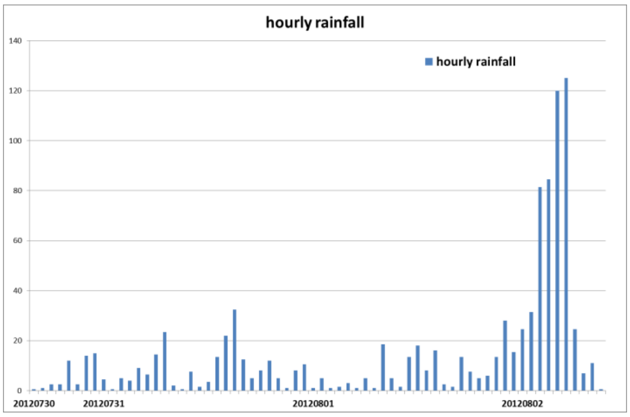

Fig. 5 The hourly rainfall of the He-Chong rainfall station during typhoon Saola

4. NUMERICAL SIMULATION MODELS FOR LANDSLIDE AND DEBRIS FLOW

4.1 TRIGRS model for landslide simulation

TRIGRS model (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model) was developed by USGS (US Geological Survey) in 2000. This model focuses on the total cohesion and the friction angle value and establishes the safety factor (*FS*) distribution of the infinite slope. The *FS* equation is shown as follows,

where α is slope gradient, r_w is unit weight of water, r_s is unit weight of soil, $\varphi(Z, t)$ is groundwater pressure head, and *c* and ϕ are the soil shear strength parameters.

This model analyzes the water level of pore water pressure and groundwater level over a period of rainfall event. The *FS* value will increase if the soil cohesion and friction angle is larger. The landslide occurrence is based on the changes due to pore water pressure by slope infiltration at different soil layer. This model basically is applied for shallow rainfall-induced landslide. The assumption of this model shows that this model is sensible to the initial depth of the groundwater, such as nearly saturated soil, a well-documented flow field and relatively isotropic, homogeneous hydrologic properties (Baum et al., 2002). In our simulation, the groundwater level is the same with the soil depth.

Many parameters are necessary for TRIGRS model, including rainfall data, soil thickness, groundwater depth, hydraulic conductivity, hydraulic diffusivity, initial soil infiltration, and stratum strength parameter. Some of the parameters could be acquired from the field investigation or in literatures, but some is calculated by equations. The following session will explain how we get these parameters.

4.1.1 Soil thickness

The soil thickness is one of the key factors affects whether the slope is stable or not. The soil thickness data depends on detailed field survey and boring investigation data or is estimated by empirical formula. So far no field investigation data is provided of this area, we defined soil thickness by formulas. Firstly, we adopted the soil thickness-slope gradient relation by [*Khazai and Sitar*, 2000]. But the result shows that areas that the defined landslide are occurred only at two ranges, the slope gradient is 30-40 degree and the gradient is over 60 degree. Therefore, the empirical formula by [*Chen et al.*, 2010] was determined in this study (**Table 1**).

Table 1 The slope gradient and the soil thickness relations (Khazai and Sitar, 2000; Chen et al., 2010)

Slope gradient (degree)	Soil thickness (m)	Soil gradient (degree)	Soil thickness (m)
< 30	2.0	<20	1.59
30-40	1.5	20-30	3.38
40-60	1.0	30-40	4.37
>60	0.5	40-50	2.55
		>50	1.12

4.1.2 Geology stratum strength parameter

TRIGRS model requires different groups of the parameters by geological materials are able to be input, so that the results reflect the stratum characteristics on slope stability. We only considered one stratum of the study area since the sub catchment is very small and the geological contribution is simple. Therefore, only one group of the parameter is occupied.

4.1.3 Other parameters

Other parameters include cohesion, friction angle, soil unit weight, hydraulic conductivity, and diffusion coefficient. These parameters are occupied according to the scenario settlement and the on-site condition. Firstly, we determined the possible parameter sets from the literatures that the parameters were modified by lab test and field investigation. Then these parameters were modified again according to the assumed rainfall scenario. The parameters in **Table 2** is the finally result [*Hsu*, 2013].

Table 2 Parameters adopted in literatures

Parameter	value
Cohesion (kPa)	7.751
Friction angle (^{o})	29
Soil unit weight (N/m^3)	2.35*10^4
Hydraulic conductivity, Kz (m/s)	1*10^{-4}
Diffusion coefficient, D (m^2/s)	2/10^{-2}

4.2 The aerial image classification

The remote sensing data is general used for topographic recognition, including aerial photographs, satellite images, and radar images. Recently, LiDAR image is one of the good choices to recognize the detail topographic features, especially the cracks and scours hard to be found by other material. But the references also mentioned that the landslide recognize by LiDAR data is available while the landslide is larger than 1ha. On the other hand, the aerial photograph is another choice. The landslide recognized by aerial photographs is available when the landslide area is smaller than 2.5ha [*Lin*, 2013].

The debris flow composition includes occurring area, flowing area, and accumulation area. The topographic features of these three parts are easily recognized through the aerial images. Aerial photograph is a material that acquire easily. The multi-occurrences of debris flow is also easy to be found; satellite image is also a good tool for image interpretation. Here we intend to use the aerial photographs in Google Earth to recognize the sub catchment and confirm by post-disaster image and satellite image because the aerial images in Google Earth sometimes is possibly full of cloud. Besides, the sub catchment delineated in ArcGIS is good for calibration. However, the area of the study area is too small that impossible to generate this data. This is also one of the reasons why the image interpretation is significant in this framework.

The main target is to clarify the occurrence part of debris flow. But we should start from the whole three parts of debris flow because sometimes it is hard to recognize only one part of them. The topographic features of these three parts should not be recognized separately. Each part of them is the important features helping us to recognize the whole torrent.

Some of characteristics of debris flow on aerial photographs can be summarized as follows [*Zhang et al.*, 2012; *Pan et al.*, 2012]:

4.2.1 Occurrence part

The occurrence part is formed as the bowl shape structure with some landslide areas and gullies inside. Gullies inside are as fish bone or branch shape. Few vegetation is inside the bowl shape structure and the water erosion can be observed.

4.2.2 Flowing part

The flowing part is the place the debris flow flows or rolls. The gradient of this part is sharp and the gullies are deep due to the large rocks. The flowing part on the images is shown by the large rock distribution or the obvious shadow. Moreover, a special spatial phenomenon is also obvious that debris flow accumulation at the flowing part is with high river path but low river side.

4.2.3 Accumulation part

Normally the accumulation part is the area with low gradient, which is less than 10 degree. The fan shape is normally at this area. The apex of the fan is the outflow point of debris flow and the gradient becomes lower from this point. Sometimes the fan is hard to recognize on the image because of the recovery works after disasters.

According to these characteristics, the occurrence part of Hualien DF166 was defined and shown in **Fig. 6**.

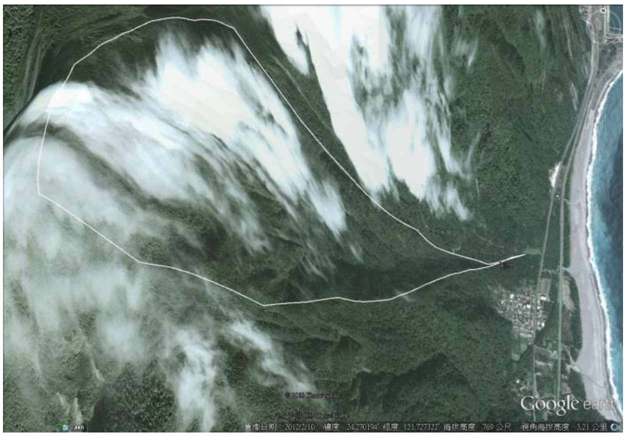

Fig. 6 Recognition of the debris flow occurrence area for Hualien DF166 on Google Earth

4.3 Flo-2D model for debris flow simulation

Flo-2D is a 2-dimension numerical model developed by O'Brien and Julian in 1998. This model is used to simulate the flooding under channel flow, floodplain management, and hydraulic calculation of bridge and detention pool scenarios. This model can also simulate the sediment concentration flow, such mudflow or debris flow because the quadratic rheological model, dynamic wave equation, and momentum equation were also considered in this model.

4.3.1 Parameter dataset

Flo-2D numerical model provides users to settle up various parameters according to the environmental conditions, such as sediment concentration, sediment specific gravity, laminar flow resistance, viscosity, and yield stress. We searched for the previous literatures and reports to determine these parameters. Some of the parameters without data will be cited from the parameter dataset of the nearby area and from the suggestions of the user’s manual [*O'brien*, 2006; *Chao et al.*, 2009; *Lai et al.*, 2011; *Su*, 2002]. Parameters are adopted and shown in **Table 3**.

Table 3 Parameters adopted in literatures

Parameters	Value
Sediment concentration	0.4
Sediment specific gravity	2.65
Laminar flow resistance	10,000
Yield stress	800 Pa
Viscosity	12Pa-s

4.3.2 Hydrologic analysis

The main purpose of the hydrologic analysis is to calculate debris flow discharge. The number of the debris flow discharge made a large influence to the simulation result. However, the debris flow discharge is simplified as the triangle hydrograph because the calculation processes of debris flow discharge is complicated, the restriction simulation model, and the real-time data is difficult to acquire due to lacking of observation data. Therefore, the return period of discharge was estimated by typhoon rainfall data and empirical formulas. Finally, debris flow discharge is calculated from torrent discharge and the bulking factor.

The return period of typhoon Saola estimation was analyzed by 72-hr rainfall from 2003 to April, 2012. The rainfall exceeds 100mm in 72hr will be defined as the extreme rainfall event and totally 160 records were determined. The best distribution of this rainfall station is Gumbel distribution, and the result is shown in **Table 4**. The accumulation rainfall during typhoon Saola is 927.5mm [*SWCB*, 2012], the return period is about 25 year.

Bulking factor (*BF*) is a simple relation of discharges between river and debris flow was mentioned in Flo-2D manual [*O'brien*, 2006]. It is the relation with sediment concentration, which is,

$$BF=1/(1-Cv) \tag{1}$$

where Cv is sediment concentration.

Table 4 The hydrologic frequency analysis result

Return period (yr)	150	100	50	30
Estimation rainfall (mm)	1298.1	1223.7	1096.2	1001.6
Return period (yr)	20	10	5	1.003
Estimation rainfall (mm)	925.9	794.4	657.2	61.6

5. SIMULATION RESULTS

Fig. 7 shows the safety factor distribution after 1-hr and 61-hr rainfall, respectively. The color corresponds *FS* value distribution. The color is from red color to blue color and the *FS* value is from 0 to 10. The difference of *FS* value before or after rainfall does not make many changes. The reason could be clarified by the in-site photo (**Fig. 8**). Most of the rocks and stones on the flowing part of the torrent are large. The diameter of some rocks exceeds 10m and very few landslide historical records in this area. These reason presents that probably those rocks do not generate naturally.

Then the authors try to find the differences before and after the rainfall event (**Fig. 9**). The largest change is about 0.731 that integrates at the two sides from the torrents inside the sub catchment we recognized in the previous session. Therefore, the authors estimated the landslide volume from the *FS* value changes data.

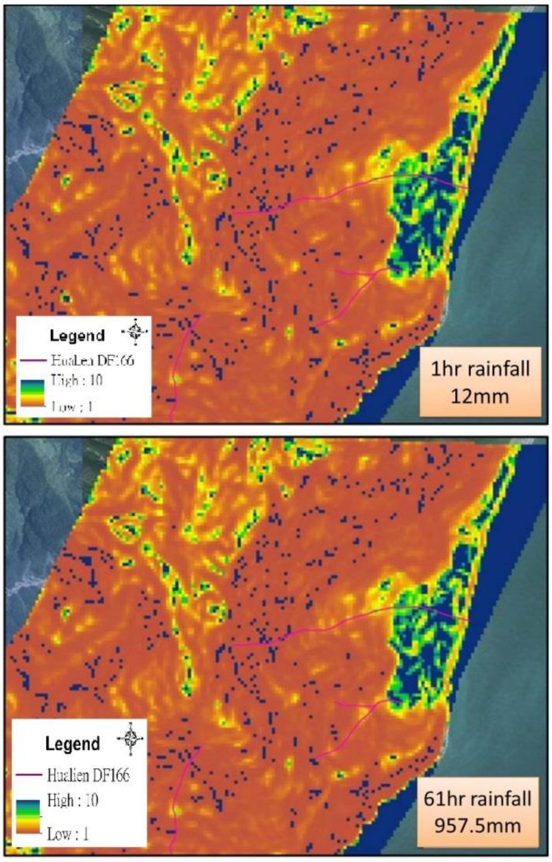

Fig. 7 The *FS* value distribution at 1hr and 61hr rainfall

Fig. 8 The rocks in the flow path are large (photo by Hong)

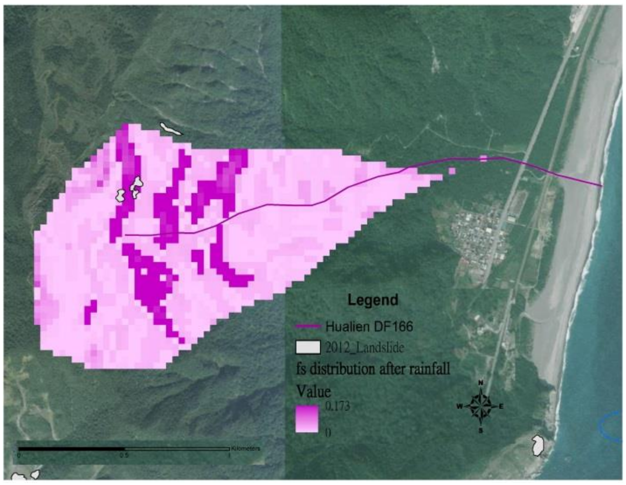

Fig. 9 The *FS* value changes at the occurrence area of Hualien DF166

Fig. 10, 11 shows the final simulation result connecting landslide and debris flow simulation results. The landslide distribution was transferred from *FS* value changes, the inflow point of debris flow and the upstream area are recognized from the aerial image interpretation, and the depth and velocity of influenced area are simulated by Flo-2D numerical model. The color shows the accumulation depth of debris flow, that the red area is more than 3m, orange area is 1.5m-3m, yellow area is 0.5m-1.5m, and green area is less than 0.5m. The simulation result shows that the rocks and the stones are easily accumulated at spot A (**Fig. 11**). The field investigation result also supports this result. The researchers found some large rocks over 10m are distributed at this spot. This is the probable reason that the curve turn of debris flow occurred. The simulation result also shows that the influenced area is totally inside the influenced range defined by government authority *[SWCB*, 2012], and result is also matches with the post-disaster field survey (the blue circle area in **Fig. 10, 11**) [*Wang et al.*, 2012; *Chen et al.*, 2012]. However, the result also represents that the prediction of the influenced range by the debris flow turning is still difficult. Two or more simulations and discussions on the topographic and geological conditions are necessary. This is the part should be improved in the future.

Furthermore, the authors compared the simulation results that the debris flow flowing input point determined by empirical formula and by the image interpretation. The total accumulation sediment volume can be estimated from the grid-cell area and the soil thickness depth. The sediment volume by the empirical formula is 579,975m^3, and the sediment volume by image interpretation result is 704,400m^3. The latter result is more close to the estimation result by SWCB and the previous literature [*SWCB*, 2012; *Wang et al.*, 2012].

Finally, the results are compared by their DTM data resolution, including 40m and 30m data. The influenced area by 30m DTM data is better because the accumulation area is totally matches with the field survey results. The result also shows that the influenced area by the authority might insufficient if considering the probable range extended by second disaster (**Fig. 9**).

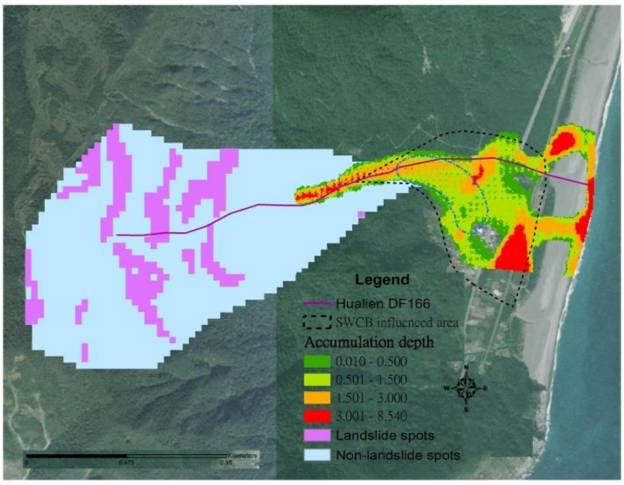

Fig.10 The simulation result by 40m DTM

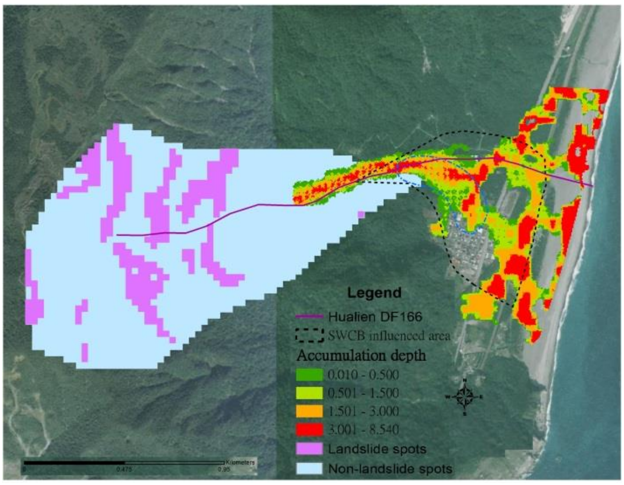

Fig.11 The simulation result by 30m DTM

6. CONCLUSION

The authors carried out a methodology for data connection of landslide, soil erosion, and debris flow. This method provides a rapid and simple way of estimating the sediment volume by the a rainfall-induced event. A case was utilized to calibrate this method. Some conclusions are therefore summarized.

(1) A framework describing disaster influences estimation of landslide and debris flow was carried out in this study. Landslide volume estimation was simulated by TRIGRS model and debris flow influenced area and sediment volume were analyzed and calculated by Flo-2D numerical model. The aerial photographs were utilized to recognize the debris flow catchment and represent the main methodology of data connection.

(2) The disaster event in He-Zhong community during typhoon Saola is the case to calibrate the data connection framework. The result shows that basically the method is possible to estimate the influenced sediment volume by sediment disasters, but the field survey data is still necessary.

(3) The landslide volume estimation was carried out by TRIGRS model. For the area with few landslide records, we estimated the landslide volume by the differences of safety factor. However, the transform between *FS* value and the landslide needs more discussion and analysis to prove its feasibility.

(4) The debris flow simulation was carried out by Flo-2D numerical model. The simulation results show that resolution of DTM data is one of the key factors. The debris flow simulation result is able to describe the probable influenced area by debris flow, the special accumulation result like the case in this study rely on considering second or multi events simulations.

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