HAZARD ZONE DELINEATION AND DAMAGE LOSS ASSESSMENT OF DEBRIS FLOW

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ABSTRACT

A systematic hazard zone delineation and damage loss assessment of debris flows at the downstream of watershed in Hua-Lien region, Eastern Taiwan were carried out by two-dimensional (2-D) finite difference numerical simulation techniques. Yield stress of debris flow, the most crucial rheological parameter for flow motion, was carefully inspected by sensitivity analyses. In addition, a set of input parameters which are representative for the flow motion and deposition of debris flows in Hua-Lien region were determined by back calculating the inundation zones of three catastrophic debris-flow events in 2001. Using the verified numerical procedures, the inundation area and the corresponding distributions of maximum flow depth and flow velocity at the downstream of debris-flow potential creeks can be simulated as close as possible under a specific rainfall intensity of return period. According to the simulation results, the hazard zone delineation and hazard damage loss assessment were performed on 162 debris-flow potential creeks in Hua-Lien County. By evaluating the hazard damage loss in advance of debris flows, it can provide the relevant public agencies or private sectors with the necessary information to draft the prevention/secure emergency plans of debris flow and disaster management policies such as the allocation of rescue resource and the evacuation path during debris flows. This study proposes a scientific and quantitative method which enables an efficient and effective assessment on hazard zone delineation and hazard damage loss of debris flow.

Keywords: hazard zone delineation, debris-flow potential creeks, damage loss assessment

INTRODUCTION

On June 23, 1990, the first severe debris flow event in Taiwan, Tung-Men debris flow, was triggered by typhoon Ofelia and unfortunately, the disastrous event claimed 35 lives and caused tremendous damage to public facilities and residential buildings in eastern Taiwan, Hua-Lien County. Further, after 921 Earthquake in 1999, the hill slopes in Taiwan are prone to disastrous sediment movements such as landslides and debris flows due to steep topography, fragile geological formation and heavy precipitation. In particular, on July 30, 2001, typhoon Toraji triggered catastrophic debris flows in Hua-Lien County and caused numerous losses of property and human life in Da-Sing, Jian-Cing and Dong-Yi villages.

As a consequence, in 2003, the Soil and Water Conservation Bureau (SWCB) of Taiwan launched a nationwide field investigation on the creeks situated at different watershed with debris-flow potential. According to the area of watershed (≥ 3 hectares), fragility of rock mass in watershed, fault length passing through the watershed, collapsed area of the slopeland situated at the upstream of watershed, the number of buildings and living peoples at the downstream of watershed to be protected, there totally 1552 creeks were inventoried and categorized into debris-flow potential creeks (or potential creeks) with low, medium and high potential levels. In addition, among the 1552 potential creeks, there are totally 162 potential creeks distributed at the Hua-Lien County, eastern Taiwan. Further, for debris-flow potential creeks, the hazard zone delineation and the hazard damage loss assessment are crucial to local government to draft hazard maps and emergent evacuation plans for the endangered communities.

Currently, the hazard zone delineations of the 1552 potential creeks in Taiwan were performed by SWCB using empirical model and field survey data. However, the model is unable to take the fluid mechanics of debris flows into account in predicting the hazard zone. To improve the accuracy of the hazard zone delineation in advance of debris flows, a more advanced and robust simulation technique is required such as finite difference numerical scheme FLO-2D (O’Brien et al., 1993 and O’Brien, 2006). Some researchers (Hübl and Steinwendtner, 2001;
Lin et al., 2005; Armento et al., 2008) have simulated the flow motion and sediment deposition behaviors of debris flows by the two-dimensional (2-D) numerical model FLO-2D for hazard zone prediction.

Although the possible applications, predictive capabilities and sensitivities analyses of FLO-2D model had been evaluated, the determination of rheological parameters remains the major difficulty to utilize the model (Coussot et al., 1998; O’Brien and Julien, 1998; Hübl and Steinwendtner, 2000; Kaitna et al., 2007; Bisantino et al., 2010). This is due to the fact that the involved debris-flow material frequently consists of a solid-water fluid mixture with large variation in solid particle size and engineering properties.

In particular, the material of debris flows in Taiwan is characterized by gravel-sand-silt-clay mixture (called gravel-type debris flow) and the rheological properties (Bingham’s yield stress and viscosity) are greatly dependent on the volumetric sediment concentration which is hard to determine in the laboratory and field site.

In addition, to the relevant government agencies, the hazard damage loss assessment of debris flows is important for making a community rehabilitation and disaster mitigation plans and those plans must be effective, efficient and economic for implementation. However, at present, in Taiwan it seems rare that the hazard damage loss assessment is made incorporating with high accurate hazard zone delineation. In this study, the accuracy of debris-flow hazard zone delineation was improved and a rational damage loss assessment was carried out using by the rainfall-runoff module and the hazard levels analysis module of FLO-2D model respectively. The most crucial rheological parameter of numerical model, the Bingham’s yield stress of debris flow, was also examined according to the simulation results of three catastrophic debris flow events in 2001. The yield stress considers the specific properties of sediment and topography of Hua-Lien region and can give excellent results of debris flow simulations in Hua-Lien region.

DEBRIS-FLOW POTENTIAL CREEKS IN HUA-LIEN REGION EASTERN TAIWAN

Figure 1 illustrates the debris-flow potential creeks identified by SWCB and which extensively distributes in the watersheds of Hua-Lien County. This region situates at the boundary of the Philippine and Eurasian Plates with frequent collision which alternatively results in a fragmented geological structure and a mountainous county. The geological material is characterized by fragile metamorphic rock. In addition, typhoons accompanied with torrential rainfall frequently invade Hua-Lien County due to it’s particular location situated to the west of Pacific Ocean and to the east of Central Mountain Range of Taiwan.

FLO-2D NUMERICAL MODELLING

In this study, FLO-2D numerical tool, physically based and considers the continuity, momentum and energy conservation of flow, was adopted to simulate the hazard zone (inundated zone) of debris flows. The FLO-2D model is a 2-D flood routing model and can be applied to simulate the flow motion of hyper-concentrated sediment flow with rheological properties over complex topography.

Governing Equations of Debris Flows

The governing equations of the model consist of continuity, kinematic and constitutive equations as follows:

Continuity equation of debris flows

\[
\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = i
\]  

Kinematic equation of debris flows

\[
S_x = S_m - \frac{\partial h}{\partial x} \frac{\partial u}{\partial x} - u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} + \frac{\partial u}{\partial x} \frac{\partial v}{\partial y}
\]  

\[
S_y = S_m - \frac{\partial h}{\partial y} \frac{\partial v}{\partial y} - u \frac{\partial v}{\partial y} - v \frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} \frac{\partial u}{\partial x}
\]
components along \( x \)- and \( y \)-coordinates; and \( g \) = gravity acceleration.

**Constitutive model of debris flows**

The total friction slope of debris flow can be expressed as:

\[
S_f = S_r + S_e + S_{wh} = \frac{\tau_y}{\gamma_w h} + \frac{K \rho \nu}{8 \gamma_w h^2} + n^2 \omega^2 h^{1/3}
\]

(4)

in which, \( S_r \) = yield slope; \( S_e \) = viscous slope; \( S_{wh} \) = turbulent-dispersive slope; \( \tau_y \) = yield stress; \( \gamma_w \) = unit weight of the sediment mixture; \( K \) = resistance parameter; \( \eta \) = viscosity; \( \omega \) = depth-averaged velocity; \( n \) = Manning’s coefficient.

Equation (4) is used to describe the rheological behavior (or shear stress vs. shear strain behavior of hyper-concentrated sediment flow during flow motion) of debris flow. Moreover, the most crucial rheological parameters, Bingham’s yield stress \( \tau_y \) and viscosity \( \eta \) can be straightforward expressed in terms of the volumetric concentrations \( C_v \) of debris flows as follows:

\[
\tau_y = \alpha_1 \times e^{\beta_1 C_v}
\]

(5)

\[
\eta = \alpha_2 \times e^{\beta_2 C_v}
\]

(6)

where, \( \alpha_1, \alpha_2, \beta_1 \) and \( \beta_2 \) = empirical coefficients determined by laboratory experiment or field tests.

**Selection of Model Parameters**

According to the above governing equations, the parameters required for the numerical simulation of debris flow are categorized into four types:

**Geomorphologic parameters**

1. DEM: high resolution 10 m \( \times \) 10 m (or 5 m \( \times \) 5 m) Digital Elevation Model was used.
2. Manning’s coefficient \((n)\): determined according to the HEC-1 manual and technical and design guide by U. S. Army Corps of Engineers (1990, 1997) or referred to the FLO-2D user’s manual (O’Brien et al., 2006)
3. Infiltration conditions: the abstraction of rainfall and hydraulic conductivity of soil can be determined according to the land use and soil conditions in watershed by FLO-2D model.
4. Boundary conditions: in the simulation of debris flow, source condition and sink condition need to be specified at the upstream boundary and downstream boundary respectively. The simulated area is exactly situated in between the two boundaries.

**Inflow parameters**

1. Flooding calculation: the calculation was carried out by the rainfall-runoff module of FLO-2D model to obtain the water flow (or inflow) hydrographs of daily rainfall intensity under specific return periods (10, 100 and 200 years). In which, the rainfall frequency analysis was performed using rainfall records of Hua-Lien region and the return periods can be used to define the hazard scale of debris flow event.

2. Bulking factor \( BF \): during the debris flow calculation (or when debris flow initiates), it needs to magnify the water flow hydrograph into debris flow hydrograph by multiplying a bulking factor \( BF \) as follow:

\[
BF = \frac{l}{1 - C_v}
\]

(7)

The volumetric concentration \( C_v \) (=\( V_{sf} / V_f \)) parameter is defined as the volume of sediment \( V_{sf} \) in debris flow mixture divided by the volume of debris flow mixture \( V_f \). Introducing the equilibrium concentration \( C_0 \), formulated by Takahashi (1991) as Equation (8), the \( C_v \) parameter can be determined by \( C_v/C_0 \) (=\( C_0 \)). In which, \( C_0 \) (=\( V_s/(V_s + V_w)/(1 - e) \)) is the volumetric concentration of solid fraction of deposition on channel bed and can be calculated by the porosity \( n \) of deposition on channel bed.

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

(8)

where, \( \theta \) = inclined angle of channel bed; \( \phi \) = internal friction angle of debris; \( \rho_w \) and \( \rho_s \) = densities of solids and water respectively.

**Material model parameters**

1. Rheological parameters: normally the Bingham’s yield stress \( \tau_y \) and viscosity \( \eta \) determined from laboratory test are lower than the actual values of field site due to lack of large particle of testing sample prepared in the laboratory. As a result, the parameters were back analyzed and calibrated by fitting the field observations to the numerical simulations of three historical debris flow events in Hua-Lien County.

2. Unit weight: the specific gravity \( G_s \) of sediment was determined according to the material type of deposition on channel bed. An estimated \( G_s \) value (=2.65) was adopted for the simulation simply due to the low sensitivity of numerical results to the \( G_s \) parameter.

3. Resistance parameter of laminar flow \((K)\): based on the values proposed by Woolhiser (1975) and field investigations data.
Simulation Procedures

The main goal of FLO-2D numerical simulation is to predict the hazard zone (or inundated zone), flow depth (or inundation depth) and flow velocity of debris flow at the downstream of debris-flow potential creeks where the land use commonly categorized as residential and agricultural lands. The simulation procedures of FLO-2D model in this study illustrated in Figure 2.

The numerical procedures of FLO-2D simulation can be summarized as follows:

1. Input data for simulation. For geometry: DEMs of watershed, channel geometry, Manning's roughness coefficient \( n \) of the flow channel and the floodplain; For hydrology: rainfall records and input data required for the FLO-2D rainfall-runoff module; For sediment: volumetric concentration \( C_v \), yield stress \( \tau_y \), viscosity \( \eta \), specific gravity \( G_s \), and resistance parameter \( K \) of laminar flow.

2. Perform the design rainfall and rainfall frequency analyses for Hua-Lien region to obtain the water flow hydrograph of simulated watershed using the rainfall-runoff module of FLO-2D model.

3. Determine the debris flow hydrograph which is equal to the water flow hydrograph multiplied by bulking factor \( BF \).

4. Specify the overflow point of debris flow. Normally, the point coincides with the apex of deposition fan of debris flow at the downstream of potential creek. In general, the apex is considered as the highest point of deposition zone such as the valley mouth or the topographic apex. Debris flows will lose confinements imposed by the bank of creek at the overflow point and spread out as sheet flow to form a deposition fan at hazard zone.

5. Assign a debris flow hydrograph at the overflow point and initiate the debris flow simulation. In addition, the debris flows were assumed to initiate at the peak value of water flow hydrograph (or at the occurrence of maximum rainfall) and last for one hour suggested by Shieh (1993) and Ikeya (1980). In this one hour duration, the water flow hydrograph was multiplied by bulking factor \( BF \) and magnified into debris flow hydrograph for debris flow simulation.

6. Eventually, the simulation results, namely, the inundation zone, maximum flow depth and maximum flow velocity distributions can be used for the hazard zone delineation and produce of hazard map.

ANALYSES OF CASE HISTORIES AND PARAMETER CALIBRATIONS

Cases Histories

Typhoon Toraji invaded Taiwan on July 30, 2001 and the rainfall induced debris flows caused serious damages: 150 houses were buried and claimed 27 deaths, 15 missing (presumed dead), 8 injuries in Da-Sing village, Hua-Lien County. The three debris-flow potential creeks situated at the watersheds of the three villages are numbered by SWCB as Hua-Lien 061 (Da-Sing village), Hua-Lien 069 (Jian-Cing village) and Hua-Lien A112 (Fong-Yi village) respectively. To calibrate the input parameters of FLO-2D, this study back analyzed the above three catastrophic debris flow using the field observations.

The input parameters as shown in Table 1 were calibrated by comparing the hazard zones (or inundated zone) from FLO-2D simulations with those from observations. As shown in Figs. 3a and 3b, the hazard zone from FLO-2D simulations (dot shading) were in good agreement with those from aerial photo interpretation (solid pink line). In addition, the deviations of the simulations from the observations are listed in Table 2. In which, the difference percentages of hazard zone area \( P_{ahz} \) (=2.8~7.7%) and hazard zone overlapping area \( P_{ahz-overlap} \) (=19.0~23.9%) are used to inspect the validity of FLO-2D model.
Fig. 3 Comparisons of debris-flow hazard zone between aerial photos interpretation (pink solid line) and FLO-2D simulation (dot shading) at (a) Da-Sing (Hua-Lien 061) (b) Jian-Cing (Hua-Lien 069) and (c) Fong-Yi (Hua-Lien A112) villages based on different debris-flow potential creeks

Table 1 Input parameters for FLO-2D simulation back analyzed from the observations of three debris-flow potential creeks

<table>
<thead>
<tr>
<th>Item</th>
<th>Hua-Lien 061 (Da-Xing village)</th>
<th>Hua-Lien 069 (Jian-Cing village)</th>
<th>Hua-Lien A112 (Fong-Yi village)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topographic condition</td>
<td>10 m×10 m DEM</td>
<td>10 m×10 m DEM</td>
<td>10 m×10 m DEM</td>
</tr>
<tr>
<td>*Rainfall hydrograph</td>
<td>368 mm; 48 hrs</td>
<td>570 mm; 48 hrs</td>
<td>570 mm; 48 hrs</td>
</tr>
<tr>
<td>Flood hydrograph</td>
<td>FLO-2D modeling (Rainfall-Runoff module)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>**Manning’s coefficient</td>
<td>0.05/0.3/0.15</td>
<td>0.05/0.3/0.15</td>
<td>0.05/0.3/0.15</td>
</tr>
<tr>
<td>Specific gravity of debris</td>
<td>2.65</td>
<td>2.65</td>
<td>2.65</td>
</tr>
<tr>
<td>Resistance parameter of</td>
<td>2285</td>
<td>2285</td>
<td>2285</td>
</tr>
<tr>
<td>laminar flow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volumetric concentration</td>
<td>0.62</td>
<td>0.88</td>
<td>0.35</td>
</tr>
<tr>
<td>Bingham yield stress</td>
<td>1200 Pa</td>
<td>2500 Pa</td>
<td>800 Pa</td>
</tr>
<tr>
<td>Bingham viscosity coefficient</td>
<td>6 Pa-s</td>
<td>15 Pa-s</td>
<td>12 Pa-s</td>
</tr>
<tr>
<td>*Rainfall hydrograph: accumulative rainfall; rainfall duration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>**Manning’s coefficient: channel zone/watershed/deposition zone</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Comparisons and deviations of the hazard zone between simulations and observations

<table>
<thead>
<tr>
<th>Debris Flow No.</th>
<th>Area of hazard zone from aerial photos interpretation $A_{aerial}$ (m²)</th>
<th>Area of hazard zone from FLO-2D model $A_{model}$ (m²)</th>
<th>Difference percentage of hazard zone area $P_{ahz}$ (%)</th>
<th>Difference percentage of hazard zone overlapping area $P_{ahz-overlap}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hua-Lien 061 (Da-Sing )</td>
<td>476,292</td>
<td>489,600</td>
<td>2.8</td>
<td>19.0</td>
</tr>
<tr>
<td>Hua-Lien 069 (Jian-Cing)</td>
<td>72,446</td>
<td>75,200</td>
<td>3.8</td>
<td>23.9</td>
</tr>
<tr>
<td>Hua-Lien A112 (Fong-Yi)</td>
<td>127,303</td>
<td>137,100</td>
<td>7.7</td>
<td>19.7</td>
</tr>
</tbody>
</table>

$P_{ahz}$ (%) = $A_{aerial}$ - $A_{model}$ × 100% / $A_{aerial}$ and $P_{ahz-overlap}$ (%) = $A_{aerial}$ - $A_{overlap}$ × 100% / $A_{aerial}$

$A_{overlap}$ = the area of hazard zone from FLO-2D modeling falling inside the area of hazard zone from aerial photo

Determination of Yield Stress

As shown in Eqs. (5) and (8), the yield stress $\tau_y$ can be expressed in term of volumetric concentration $C_v$ (= $C_s/C_d$) and related to the inclined angle of channel bed $\theta$ and engineering properties of solid debris in watershed. Table 3 displays the appropriate yield stress for each particular debris-flow potential creek. Considering the convenience and fast application of $\tau_y$ value to debris flow simulation for the entire watersheds in Hua-Lien region, the yield stresses straightforward related to the average slope of channel bed are summarized in Table 4.
Table 3 Appropriate yield stresses for debris-flow potential creeks back analyzed according to the observations of debris flow events

<table>
<thead>
<tr>
<th>Potential creeks No.</th>
<th>Main basin</th>
<th>Geological condition</th>
<th>Watershed area (ha)</th>
<th>Slope of Channel bed (deg)</th>
<th>Back analyzed yield stresses (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hua-Lien 061</td>
<td>Basin of Hua-Lien</td>
<td>Fragmented metamorphic</td>
<td>1429</td>
<td>15.6</td>
<td>1000~1200</td>
</tr>
<tr>
<td>Hua-Lien 069</td>
<td>River</td>
<td>rock</td>
<td>59</td>
<td>18.8</td>
<td>2000~2500</td>
</tr>
<tr>
<td>Hua-Lien A112</td>
<td></td>
<td></td>
<td>746</td>
<td>10.8</td>
<td>600~800</td>
</tr>
</tbody>
</table>

Table 4 Relations of yield stress and volumetric concentration with average slope of channel bed

<table>
<thead>
<tr>
<th>Average slope of channel bed (deg)</th>
<th>Yield stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;16</td>
<td>2500</td>
</tr>
<tr>
<td>12–16</td>
<td>1200</td>
</tr>
<tr>
<td>&lt;12</td>
<td>800</td>
</tr>
</tbody>
</table>

Debris Flow during Fong-Hung Typhoon

To verify the validity of the FLO-2D simulation procedures and the associated input parameters, the debris flow event of potential creeks Hua-Lien 072 (situated at the Shu-Hu village, Shou-Fong township, Hua-Lien County) triggered by Fong-Hung typhoon on July 28, 2008 which brought a torrential rainfall in Hua-Lien region was selected for verification. The FLO-2D simulation was performed using the actual rainfall data of Xi-Li rainfall monitoring station and a high precision DEM of 5 m × 5 m.

The debris-flow potential creek Hua-Lien 072 consists of several tributaries and a large scale debris flow occurred during Fong-Hung typhoon at the tributary situated near the upstream of Shu-Hu bridge No. 2. The debris flow caused severe damages of revetment, ground sill and road facilities and numerous sediments accompanied with large diameter debris were transported downstream and deposited on the channel bed as shown in Figs. 4a and 4b.

Numerical Results and Model Verification

Figure 4c illustrates the hazard zones determined by empirical method (SWCB) and numerical method (FLO-2D) and the deviation from the hazard zone interpreted by aerial photo. It indicates that the difference percentage of hazard zone area $P_{h,z}$ and hazard zone overlapping area $P_{h,overlap}$ are 9.12% and 28.27% respectively. The difference is mainly due to lacking of the DEM data immediate before debris flow event. The deviation of FLO-2D simulation from the aerial photo interpretation frequently occurs nearby the bank area of potential creek and this is due to the incapability of FLO-2D to capture the erosion of flow channel (or the variation of DEM of flow channel with time) during debris flow. Another factor which may influence the difference percentage is the error of aerial photo.
interpretation. Usually, the aerial photo would not be immediately taken at the occurrence of debris flow. Nevertheless, comparing with the hazard zone delineated using empirical method with field survey under the supervision of SWCB (yellow line), the hazard zone simulated by FLO-2D (orange line) is more rationale and accurate.

HAZARD MAPPING OF DEBRIS FLOW

Hazard Zone Delineation

According to the simulation procedures of FLO-2D model calibrated by four debris flow events (Hua-Lien 061, 069, A112 and 072), one can exhibit the maximum flow depth and flow velocity of debris flow and delineate the hazard zone for each debris-flow potential creek under a specific hazard scale, as displayed in Figs. 5 (a) and (b). Meanwhile, the hazard scale can be designated by the daily rainfall intensity under a specific return period (10, 100 and 200 years). Figure 5 indicates that the hazard zone of potential creek Hua-Lien 069 mainly scatters at the two sides of Jian-Cing Bridge which is in good agreement with the observation from Toraji typhoon in 2001.

FLO-2D model evaluates the hazard level of debris flow according to the method proposed by Garcia et al. (2003, 2005) which considering the occurrence probability and hazard intensity. As shown in Fig. 6, the occurrence probability is related to the probability of exceedence of frequency rainfall under a specific return period (10, 100, 200, and >> 500 years). On the other hand, the intensity is determined by the maximum flow depth (inundation) and flow velocity (impact) as shown in Table 5. Incorporating the occurrence probability levels (High, Medium, Low and Very Low) with the intensity levels (High, Medium and Low) of hazard, one can evaluate the hazard levels (High Hazard: red; Medium Hazard: orange; Low Hazard: yellow) for a specific debris flow event. Although a higher intensity of hazard may occur due to a longer return period, the occurrence probability is low.

![Fig. 5 Debris flow simulation of Jian-Cing village based on the debris-flow potential creek Hua-Lien 069 under a daily rainfall intensity of 100-year return period (a) maximum flow depth (b) maximum flow velocity distributions](image)

![Fig. 6 Illustrative concept for various hazard levels (Garcia, 2003 & 2005)](image)

Table 5 Definition of various hazard intensities

<table>
<thead>
<tr>
<th>Hazard intensity</th>
<th>Hazard legend</th>
<th>$h$= Flow depth (m)</th>
<th>$v$= Flow velocity (m$^2$/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Red</td>
<td>$h$&gt;2.5 m or $h\times v$&gt;2.5 m$^2$/sec</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Orange</td>
<td>1.0 m&lt;$h$&lt;2.5 m or 1.0 m$^2$/sec&lt;$h\times v$&lt;2.5m$^2$/sec</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>Yellow</td>
<td>$h$&lt;1.0 m or $h\times v$&lt;1.0 m$^2$/sec</td>
<td></td>
</tr>
</tbody>
</table>

Produce Hazard Map

In this study, the daily rainfalls under return period of 10, 100 and 200 years were selected to define the hazard scale of debris flow and adopted for FLO-2D simulation. Using the distribution of maximum flow depth, $h$, and flow velocity, $v$, in the hazard zone delineated by FLO-2D simulation, one can assign and describe the hazard level for different areas within the hazard zone as: (1) High Hazard (red): structures can be damaged and humans both indoors or outdoors are endangered. (2) Medium
Hazard (orange): structures damage according to their structural type and humans outdoors are endangered. (3) Low Hazard (yellow): both structures and humans are not endangered but remain slightly affected. Eventually, incorporating with the geographic information system (GIS) technique, one can produce a hazard map for a hazard zone delineated under a specific hazard scale (for instance, medium scale with return period of 100 years), as exhibited in Fig. 7a. The figure indicates that the previous residents lived at the right hand side of the intersection of potential creek Hua-Lien 069 and Jian-Cing Bridge has moved out and a large amount of debris and sediment remains and blocks the residential building at the field site as shown in Figs. 7b and 7c.

In addition, the residential area located at the left hand side of the potential creek is categorized into Medium Hazard and an inundation may occur during the torrential rainfall. As a consequence, to the residents in the hazard zone, it is necessary to draw an appropriate prevention/rescue plan and emergent evacuation plan against debris flow and a frequent maneuver for the plans is also needed.

Fig. 7 (a) Hazard map of Jian-Cing village based on the debris-flow potential creek Hua-Lien 069 under a daily rainfall intensity of 100-year return period (c) bird view and (d) short view of inundation of Jian-Cing village during Toraji typhoon in 2001
DAMAGE LOSS ASSESSMENT OF DEBRIS FLOW (Debris-Flow Potential Creek: Hua-Lien 069)

The damage loss caused by debris flows can be categorized into direct damage loss (or direct loss) and indirect damage loss (or indirect loss). The direct loss is the loss immediately induced from debris flows such as: casualty of human life, destruction of residential building, break down of main road and damage of public facilities. On the other hand, the indirect loss is the loss excluded from the direct loss such as: the subsidy from government to compensate the living cost or the expense of medical care for those residents suffering from debris flow. The direct loss is an essential reference index to the relevant authorities which can immediately reflect the hazard scale in advance. Particularly, the evaluation of direct loss is extremely important to the public agencies in charge of the emergent rescue and countermeasure during the debris flow.

Damage Elements and Damage Loss Assessment

In this study, the damage loss assessment was emphasized on the direct loss includes: land loss and ground object loss. The land loss is resulted from the inundation or erosion of land which causes the land completely lost its utilization value. The ground object loss is categorized into two types: the building loss (mainly resulted from the damage of residential building) and the non-building loss such as rice field, orchard, tea farm and bamboo forest (mainly resulted from the damage of crops). The building loss was evaluated according to the flow depth (or inundation depth) of debris flows whereas the non-building loss is directly estimated by the economic value of object and considered to be totally destroyed due to debris flow inundation. The evaluation of damage loss for different damage elements (land use and ground objects: building or non-building) can be given as follows:

**Land loss**

\[ LL = \sum_{i=1}^{i=N} LV_i \times LL_A_i \]  (9)

in which, \( LL \)=land loss (NT$), \( LV_i \)=land value (NT$/m$^2$), \( LL_A_i \)=inundation area of land (m$^2$) and \( i \)=land number considering the classification of land use for different purposes. The land value \( LV_i \) can be referred to the land value proclaimed by the land administration of local government.

**Building loss**

\[ BL = \sum_{i=1}^{i=N} \sum_{j=1}^{j=M} BC_{ij} \times BA_{ij} \]  (10)

in which, \( BL \)=building loss (NT$), \( BC_{ij} \)=construction cost of \( j^{th}\)-floor of \( i\)-type building (NT$/m^2$), \( BA_{ij} \)=floor area of \( j^{th}\)-floor of \( i\)-type building (m$^2$). The construction cost \( BC_{ij} \) can be calculated according to the classification of housing utilization for different purpose and the standard unit price of house proclaimed by local government.

**Non-building loss**

The damage loss of this type is resulted from the inundation or erosion of cultivation land, forestry land, and ground objects for transportation and hydraulic purposes. The damage loss was evaluated by multiplying the unit price of ground object (NT$/counting unit) by damage quantity (counting unit such as m$^2$). The unit price of various non-building objects can be referred to the proclaiming value from local government. For the non-building loss on cultivation land can be given by:

\[ CL = \sum_{i=1}^{i=N} CO_i \times CP_i \times CLA_i \]  (11)

in which, \( CL \)=crop loss (NT$), \( CO_i \)=crop production (kg/hectare); \( CP_i \)=unit price of crop (NT$/kg) and \( CLA_i \)=inundation area of crop field (hectare). The unit price of crop can be referred to the annual statistic report of agriculture from the Agriculture and Food Agency of Taiwan.

According to the cumulative records of field investigation and historical information of debris flow events in the past, one can draft a diagnostic criterion for determining the damage levels of various ground objects as shown in Table 6. The working procedures of damage loss assessment of debris flow adopted in this study are demonstrated in Fig. 8.

**Table 6**  Criterion for damage level evaluation

<table>
<thead>
<tr>
<th>Buried depth of debris flow</th>
<th>Ground objects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Building damage</td>
</tr>
<tr>
<td>more than 2.5 m</td>
<td>completely destroyed</td>
</tr>
<tr>
<td>1 m ~ 2.5 m</td>
<td>semi-destroyed</td>
</tr>
<tr>
<td>lower than 1 m</td>
<td>slight damage</td>
</tr>
</tbody>
</table>
Results of Damage Loss Assessment

Using Jian-Cing village (debris-flow potential creek Hua-Lien 069) for instance, one can obtain the flow depth distribution map under three return periods (10, 100 and 200 years) according to the FLO-2D simulation procedures. Subsequently, various damage elements such as cultivation land, forestry, crops, building, road and bridge etc. were superimposed onto the distribution map to come out with a damage loss evaluation map as displayed in Fig. 9. Eventually, the damage loss of the three return periods can be evaluated using the damage loss assessment module of FLO-2D model as listed in Table 7.

In Table 7, the damage loss of 100-year return period approximates two times higher than that of 10-year. This is due to the residential building at the left bank of flow channel was buried by debris flow under the rainfall intensity of 100-year return period.

Fig. 8 Flowchart for the damage loss assessment of debris flows

(a) (b) (c)

Fig. 9 Distributions of hazard zone and maximum flow depth for various damage elements (roads, buildings) under a daily rainfall intensity of (a)50-year (b)100-year(c) 200-year return periods
Table 7 Illustrative example of the total damage loss of Jian-Cing village (debris-flow potential creek Hua-Lien 069)

<table>
<thead>
<tr>
<th>Debris-flow potential creek No.</th>
<th>Return period of rainfall</th>
<th>Land Cost (NT$)</th>
<th>Building Cost (NT$)</th>
<th>Road Cost (NT$)</th>
<th>Woodland Cost (NT$)</th>
<th>Total Cost (NT$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hua-Lien 069</td>
<td>10 years</td>
<td>0</td>
<td>0</td>
<td>2,815,650</td>
<td>60,483</td>
<td>2,876,133</td>
</tr>
<tr>
<td></td>
<td>100 years</td>
<td>240,000</td>
<td>1,677,357</td>
<td>4,235,940</td>
<td>75,538</td>
<td>6,228,835</td>
</tr>
<tr>
<td></td>
<td>200 years</td>
<td>315,000</td>
<td>2,574,608</td>
<td>4,235,940</td>
<td>102,479</td>
<td>7,228,027</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Based on the simulation results, several conclusions can be drawn:

1. FLO-2D model can capture the flow motion and deposition behavior of debris flows in Hua-Lien region and give a more objective and accurate prediction of hazard zone than empirical method used by SWCB.

2. The most crucial rheological parameter, yield stress of debris flow, was calibrated by three historical debris flow events in 2001 (Da-Sing village, Hua-Lien 061; Jian-Cing village, Hua-Lien 069; Fong-Yi village, Hua-Lien A112) and verified by a recent debris flow events in 2008 (Shu-Hu village, Hua-Lien 072). The yield stress in the range of 2500~800 Pa is appropriate for FLO-2D simulation in Hua-Lien region.

3. A systematic operation procedure has been set up for the hazard zone delineation and hazard damage loss assessment of debris flows in Hua-Lien region. These simulation results can provide useful information to the government agencies for making a prevention/rescue plan and emergent evacuation plan in advance of debris flow disaster.

ACKNOWLEDGEMENTS

This research was granted by the Soil and Water Conservation Bureau, Council of Agriculture, Executive Yuan. The authors appreciate the financial support from the SWCB for the research project entitled “2008, Hazard Zone Delineation and Damage Loss Assessment of Debris Flow in Hua-Lien Region”.

REFERENCES


