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Prediction of Debris-flow Danger Area by Combining Hydrological and Inundation Simulation Methods

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Abstract: Debris flows have caused serious human casualties and economic losses in the regions strongly affected by the Ms8.0 Wenchuan earthquake of 2008. Debris flow mitigation and risk assessment is a key issue for reconstruction. The existing methods of inundation simulation are based on historical disasters and have no power of prediction. The rain-flood method can not yield detailed flow hydrograph and does not meet the need of inundation simulation. In this paper, the process of water flow was studied by using the Arc-SCS model combined with hydraulic method, and then the debris flow runoff process was calculated using the empirical formula combining the result from Arc-SCS. The peak discharge and runoff duration served as input of inundation simulation. Then, the dangerous area is predicted using kinematic wave method and Manning equation. Taking the debris flow in Huashiban gully in Beichuan County, Sichuan Province, China on 24 Sep. 2008 as example, the peak discharge of water flow and debris flow were calculated as 35.52 $m^3 \cdot s^{-1}$ and 215.66 $m^3 \cdot s^{-}$, with error of 4.15% compared to the measured values. The simulated area of debris-flow deposition was 161,500 m^2, vs. the measured area of 144,097 m^2, in error of 81.75%. The simulated maximum depth was 12.3 m, consistent with the real maximum depth between 10 and 15 m according to the field survey. The minor error is mainly due to the flow impact on buildings and variations in cross-section configuration. The present methodology can be applied to predict debris flow magnitude and evaluate its risk in other watersheds inthe earthquake area.

Keywords: Debris flow; Arc-SCS model; Inundation simulation; Risk analysis; Wenchuan earthquake

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Introduction

Debris flow is a common surficial process in mountainous areas. It appears in over 70 countries in the world and often causes severe economic losses and human casualties, seriously retarding social and economic development. In the main area affected by the Wenchuan earthquake on May 12, 2008 (Ms8.0), a large number of unstable slopes and landslides were triggered, which resulted in abundant unconsolidated materials. Thus debris flows have evolved into a very active period which will last for a rather long time (Hu et al. 2010, Liu et al. 2010). The magnitude and frequency of debris-flow has increased, to the extent that it has become a major hazard in the area (Cui et al. 2009). In the last 3 years, over 800 debris flow events appeared and severely destroyed many residential areas. For instance, Qingping and Longchi towns were ruined by mass debris flows triggered by rainstorm on Aug. 13, 2010. On Sep. 24, 2008 Beichuan county and Qingchuan county suffered a rainstorm with a 20-year return period. That storm induced a large number of debris flows (Tang et al. 2009). Therefore, debris-flow prediction and disaster mitigation is a key issue during post-earthquake reconstruction and directly impacts local people's daily lives.

In general, fully comprehensive mitigation of debris flows may be quite difficult due to their complex process and origins, high frequency, wide distribution, and the high cost of treatment works. Debris flow prediction as an important and cost-effective mitigation measure has attracted widespread attention and become a leading issue (Aleotti 2004, Berti and Simoni 2005, Chen et al. 2007, Gregoretti and Fontana 2008).

A prediction should provide information about timing and magnitude of a debris-flow event, and the latter is more important for disaster mitigation planning. An ideal prediction of debris-flow magnitude should be able to provide the information of peak discharge, runoff and risk area, which are key parameters for the design of emergency measures and control engineering. The existing methods of debris flow inundation simulation are based on historical discharge data and thus are short of making ideal predictions, although it can generate information about the distribution of velocity, flow depth and momentum in high risk areas (Wei et al. 2003, Hu et al. 2003, Bisson et al. 2005, Yu et al. 2006). If these methods were to be used to predict the danger area, a method should be established for predicting the peak discharge and runoff process. So far, no effective method can predict those key parameters of flow magnitude. Even though the widely used method of rain-flood method can not yield detailed flow hydrograph which does not meet the need of inundation simulation. The next mission is to link the debris-flow runoff process with its formation background and to develop a prediction method for calculating debris-flow peak discharge and runoff process which can serve as input parameters in inundation simulation. This paper intends to approach runoff prediction by combining SCS model and hydraulic method. A prediction method of dangerous area may be generated by integrating the calculation of runoff process and numerical movement simulation. The recent advances in our knowledge of debris-flow formation mechanisms (Cui 1992, Iverson 1997) make this attempt possible. The numerical model adopts peak discharge as the key input parameter to simulate the deposition process of the debris flow and predict correctly the inundation area. Combing the two models, wise decisions can be made for hazard control and management.

The debris flow at Huashiban gully was a typical case, resulting in more than 20 deaths and causing heavy losses, destroying and burying buildings for protection as earthquake relics. The investigation data were used to test the new method. The simulated result is close to the real debris flow deposit on Sept. 24, 2008, which indicates that this method can be used in the area affected by the earthquake.

1 Study Area Setting

Huashiban gully, with a catchment of 1.29 km², is a tributary of Weijia gully which joins the Tongkou river. It is located at 104°26'49"E and 31°49'5"N, about 1000 m southwest of Qushan town in Beichuan county. The total relief is 1011.7 m, and the main gully is 2.4 km in length (Figure 1). Beichuan county and other earthquake-affected areas suffered a heavy rainstorm on September 23-24, 2008. Between 0:00-5:00 in the morning of September 24, the rain gauge at Tangjiashan recorded precipitation of 57.9 mm. One-hour rain intensity reached 41 mm at 5:00~6:00 am, a value with a 20-year return period according to long-

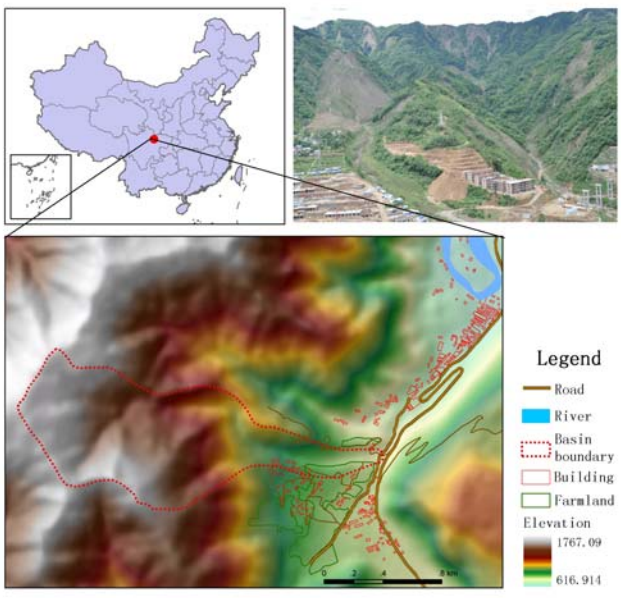


Figure 1 Location of Huashiban gully

term records of the Sichuan Provincial Meteorological Bureau. Local eyewitnesses recalled that loud noises of impacting rocks in the gully and the water level both increased at 5:00 am. A large flood mixed with rock and sand flowed along Huashiban gully into Qushan town and then flowed to the Tongkou River. The debris flow, with a peak discharge about 225 $m^3 \cdot s^{-1}$, lasted about 1 hour and deposited sediment in Qushan town, up to 4 m in average thickness and 12 m at a maximum. The event killed more than 20 people and buried many buildings.

2 Prediction Model for Debris Flow Discharge

Numbers of landslides and collapses were triggered by the earthquake, which generated up to $28\times10^8 m^3$ unconsolidated materials. Under the condition of abundance loose material, the debris flows occur very frequently and their formation are dominated by rainfall (Cui et al. 2010). Therefore, the frequency and magnitude of debris flow are mainly affected by precipitation and its runoff process is consistent with the water flow process which can be calculated using the hydrological model.

Generally, debris-flow discharge is estimated by field survey or calculated by means of the modified flood discharge method. The flood discharge is calculated by the rational formula method. But the method cannot generate the information of flood hydrograph. Therefore, The SCS model is used for calculating the flood process. Thus the debris-flow runoff process can be calculated by combining the SCS model and the equation of peak discharge calculation.

2.1 Water flow discharge calculation

2.1.1 Rational formula

The standard formula for water discharge calculation in Sichuan Province is from the Sichuan Water and Power Department (Sichuan Water and Power Department 1984):

$$Q_p = 0.278\left(\frac{S_p}{\tau^n} - \mu\right)F \tag{1}$$

where, Q_p is the peak discharge of the water flow ($m^3 \cdot s^{-1}$), the subscript p is the precipitation frequency (%), τ is the flow concentration time (h), n is the rainstorm attenuation coefficient, S is the rainstorm intensity ($mm \cdot h^{-1}$), and F is the catchment area (km^2).

In the case of Huashiban gully, rainfall corresponded to a 20 year return period (p=5%) according to the temporary rain gauge at Tangjiashan dam, 1500m away. The water discharge under various precipitation frequencies can be calculated by relative parameters from the Sichuan Hydrology Record Handbook (Sichuan Water and Power Department 1984).

2.1.2 ARC-SCS model

The SCS model, devised by the US Soil Conservation Service (SCS 1972) in the 1950s, is a rainfall-runoff model based on the CN value. It is utilized widely for its convenience and its low requirement for observational data. The principle of the SCS model is as follows. During rainfall, runoff is the yield after plant interception, surface retention and soil infiltration, and the infiltration is regarded as the loss after the runoff yield. The ratio of actual water storage capacity and the maximum value is equal to the ratio of direct runoff and rainfall minus the initial infiltration. The expression is as follows:

$$\begin{aligned} &P = I_a + F + Q \\ &\frac{Q}{P - I_a} = \frac{F}{S} \\ &I_a = \lambda S \end{aligned} \tag{2}$$

$$Q = \frac{(P - I_a)^2}{P + S - I_a} \tag{3}$$

where P is the total amount of precipitation, I_a is the initial loss, F is the actual storage capacity after the runoff begins, Q is the water flow discharge, S is the maximum water storage capacity of the basin. λ is a coefficient and taken as 0.2 by experience. I_a= 0.2S, so the following formula can be obtained:

$$\begin{aligned} &Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad P \ge 0.2S \\ &Q = 0 \qquad P < 0.2S \end{aligned} \tag{4}$$

$$S = \frac{25400}{CN} - 254 \tag{5}$$

The amount of runoff can be calculated if the

CN value is identified. The *CN* value, ranging from 1 to 100, is influenced by land-use types, soil hydrological types, and antecedent soil moisture conditions in a basin. The *CN* value can be determined from the *CN* table provided by the SCS (SCS 1972).

2.1.3 Runoff concentration process

In order to analyze the runoff concentration process, Huashiban basin was divided into sub-hydrological basins based on a DEM. The flow direction of each grid cell was determined by the steepest gradient. The flow speed of each unit was calculated based on movement of a kinematic wave. Therefore, the time of water flowing through each grid was equal to the distance divided by the speed. The total concentration time from each grid cell to the basin outlet was obtained by routing flow along the concentration path in the flow direction from the basin outlet to each cell and summing up the concentration time of the whole concentration path. The runoff yield was the sum of flow volume in each cell which reaches the outlet at the same time.

To determine the concentration time from each grid cell to the basin outlet the slope flow velocity in each cell should first be calculated.

A: Hillslope flow velocity

The time of slope flow for a smooth flow (t_O) is expressed as the following kinematic wave equation (Xie et al. 2005):

$$t_0 = L^{0.6} n^{0.6} / i_c^{0.4} S^{0.3} \tag{6}$$

where, i_c is rainfall intensity (mm·s^{-1}), *L* is surface flow length (m), *n* is the roughness coefficient, *S* is slope gradient. The surface flow length *L* along the flow direction can be obtained as follows:

As shown in Figure 2, taking the grid size as 25×25 m^2, the surface flow length in the directions of 1, 4, 16, 64 is 25 m, that in the directions of 2, 8, 32, 128 is $25\sqrt{2}$ m, the $\sqrt{2}$ product of the former.

The flow velocity in each cell was obtained from the surface flow length *L* divided by flow time t_0. And then the flow velocity of the whole basin was obtained by merging the flow velocity in the river cells with that in slope cells. The flow length of each cell to the basin export point was calculated using the flow length module of ArcGIS. Therefore, the runoff time from each grid to the basin export point was reduced by the flow velocity in each cell divided by flow length from each cell to the basin export point.

32	64	128
16		1
8	4	2

Figure 2 The sketch of flow calculation

Table 1 The Manning roughness coefficient value for different land uses

Land use type	Manning roughness coefficient (*n*)
Forest	0.2
Wasteland	0.055
Agricultural land	0.04
Water	0.08
Construction land	0.015

B: Channel flow velocity

The channel flow velocity can be computed using Manning equation and the continuity equation (Xie et al. 2005):

$$V_c = S^{0.3} Q^{0.4} / n^{0.6} B^{0.4} \tag{7}$$

where, *B* is channel width (m), V_c is channel flow velocity (m·s^{-1}), other parameters are defined above.

C: Manning roughness coefficient

The Manning roughness coefficient is a key parameter for estimating the slope and channel flow velocities. The value for the Huashiban gully was obtained by referring to the relationship between land use and the Manning roughness coefficient (Table 1) (Brater 1976, Montes 1998).

According to the land use types in Huashiban gully and Table 1, we got the distribution of the Manning roughness coefficient.

2.2 Debris flow discharge calculation

The calculation of peak debris-flow discharge is based on water flow discharge. It assumes that debris flow and rain (water flow) occur simultaneously at the same recurrence interval. Firstly, peak water discharge with a 20-year return period (P=5%) of rainfall was calculated using equation (1). Then, considering the characteristics of the debris flow and the supply conditions of unconsolidated soil in source area, the debris flow discharge can be estimated from the following formula (Wu et al. 1993; Kang et al. 2004):

$$Q_c = (1+\phi)Q\ D_c \qquad (8)$$

Where Q_c is the debris-flow discharge (m³/s), Q is the water discharge (m³/s), D_c is the blocking coefficient, and Φ is the correction coefficient for the debris-flow bulk weight defined as:

$$\phi = (\gamma_c - \gamma_w)/(\gamma_H - \gamma_c) \qquad (9)$$

where γ_c is the debris flow density (kg·m^{-3}), γ_w is the density of water (10 Kn·m^{-3}), and γ_H is the density of solid matter in the debris flow (27 Kn·m^{-3}). According to experience, the empirical values of blocking coefficient D_c in formula (8) are listed in Table 2 (Wu et al. 1993, Kang et al. 2004).

The convergence process of debris flow can be deduced by merging the calculation of debris flow discharge into water discharge. Using Eq.1 to 8, debris flow discharge can be calculated. The water flow discharge process of the watershed outlet can be calculated by the Arc-SCS model, and then the debris flow discharge process can be calculated combined with Eq.8.

3 Application of Arc-SCS Model for Huashiban Gully

3.1 Water discharge for Huashiban gully

The water flow discharge of the Huashiban gully for a 20-year return period rainfall can be calculated using formula (1). The parameters for formula (1) were obtained from the Sichuan Hydrology Record Handbook in Table 3 (Sichuan Water and Power Department 1984). The calculated water discharge is 35.56 m^3·s^{-1}.

The parameters of the ArcGIS model were calculated and exported by ArcGIS using a DEM, land use and soil characteristics in Huashiban gully. Then, the water flow discharge between 3:00 and 6:30 am on 24 Sep. 2008 was generated by ArcGIS model (Figure 4).

3.2 Debris flow discharge for Huashiban gully

From field investigations, it was apparent that large landslides in the upstream reaches of the debris-flow source area (Figure 3) had blocked the gulley before debris-flow initiation. Therefore, the blocking coefficient D_c was chosen as a maximum value of 2.5. Then, debris-flow discharge can be deduced from formula 8. Using the rational formula and the Arc-SCS model, water flow discharge and debris-flow discharge were calculated. The results are listed at Table 4.

The table 4 shows that the calculated results from rational formula (215.9 m^3·s^{-1}) and from the Arc-SCS model (215.66 m^3·s^{-1}) are close to that obtained from the field investigation (225.00 m^3·s^{-1} [1)]). This indicates that the Arc-SCS model established in this paper has an error of 4.15%. Therefore, it is feasible to use the distributed hydrological model (Arc-SCS model) for simulating debris-flow discharges (Figure 4).

Table 2 Empirical value of blocking coefficient

Block coefficient	No block	Milt	Moderate	Serious
D_c	1	1.5	2	2.5

Table 3 Values for formula 1 for Huashiban gully

Parameters of formula 1	Value
Area F (km²)	1.54
Gully length L (km)	2.4
Watershed coefficient of feature θ	2.87
Confluence parameter m	0.27
Runoff generation parameter μ	3.32
Design precipitation frequency P (%)	5
Rainstorm parameter n (n1)	0.28
Rainstorm force Sp (mm·h^{-1})	94.04
Runoff coefficient ψ	0.95
Flow concentration time τ (h)	1.31
Peak discharge Q_B (m^3·s^{-1})	35.56

1) The report of debris flow emergency exploration in Xishanpo, Beichuan County, Sichuan Institute of Geological Engineering Investigation, 2008

Figure 3 Landslides in debris-flow source area

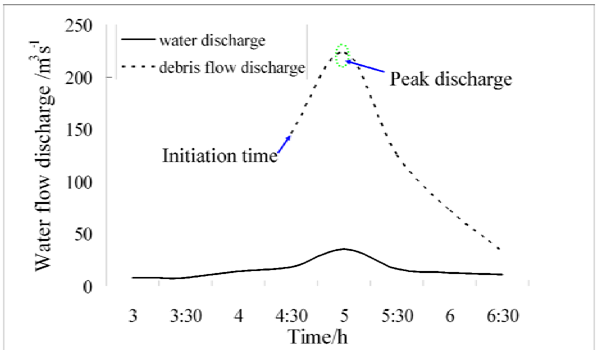


Figure 4 The discharge process of debris flow

Table 4 Comparison of calculated results and results from field-investigation

Calculation method	Rational formula	Arc-SCS	Field investigation
Water-flow peak discharge ($m^3 \cdot s^{-1}$)	35.56	35.52	-
Debris-flow peak discharge ($m^3 \cdot s^{-1}$)	215.90	215.66	225
Error	4.04%	4.15%	-

Table 5 Simulation parameters for debris flow deposition

The name of debris flow gully	Peak discharge ($m^3 \cdot s^{-1}$)	Density ($g \cdot cm^{-3}$)	Time of flow duration (h)
Huashiban gully	215.66	2.0	1.5

4 Debris Flow Deposits Simulation

4.1 Numerical approach

Most debris-flow motion equations are derived from the Saint-Venant equation (Wang et al. 1998). Concerning the research of debris flow deposits, the equation includes three important variables, mud depth, the X-velocity component and the Y-velocity component.

$$\frac{\partial u}{\partial t}+(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y})=gS_{sx}-gS_{fx} \tag{10}$$

$$\frac{\partial v}{\partial t}+(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y})=gS_{sy}-gS_{fy} \tag{11}$$

where u and v are x and y-component velocities, g is acceleration of gravity, S_{sx} is the bottom slope of the deposition area in the X direction, S_{sy} is the bottom slope of the deposition area in the Y direction, S_{fx} is the friction gradient of debris flow in the X direction and S_{fy} is the friction gradient of debris flow in the Y direction.

The particle model first developed by Wang et al. (1997) and then improved by Hu et al. (2003) was used to solve eq. (10) and (11) numerically. The model treats debris-flow masses as aggregates of many small particles, each of which has its own mass and velocity and moves under gravity with resistance. Movement can be approximated by using the forward difference for each particle. The difference equations can be expressed as follows:

$$\frac{u_k^{n+1}-u_k^n}{\Delta t}=gS_{sx}^{n,k}-gS_{fx}^{n,k} \tag{12}$$

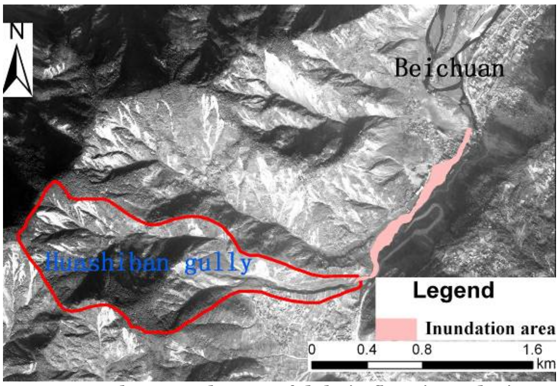
$$\frac{v_k^{n+1}-v_k^n}{\Delta t}=gS_{sy}^{n,k}-gS_{fy}^{n,k} \tag{13}$$

Moreover, the MAC (Marker-And-Cell) computational technique (Wei et al. 2003) was used to trace particle movements. The real topography of Huashiban gully was converted into a DEM (digital elevation model) grid by the GIS technique. That is, the whole computational region is divided into square cells. Each intersection (the corner of the cell) has a value for flow depth, velocity and elevation.

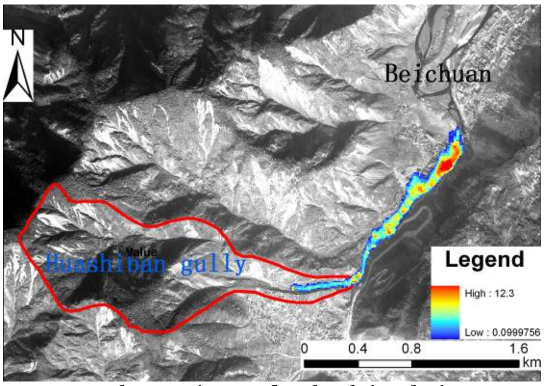
4.2 Simulation result

According to the debris flow convergence process deduced by the Arc-SCS model, the parameters used in this calculation are shown in table 5.

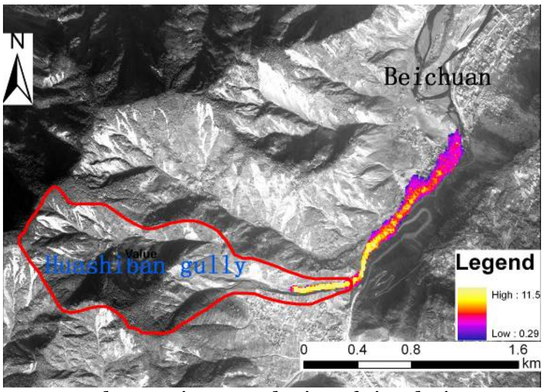
The debris-flow movement process on alluvial fan of Huashiban gully can be simulated based on the DEM of the fan. Each intersection has a value for flow depth, velocity and elevation. The



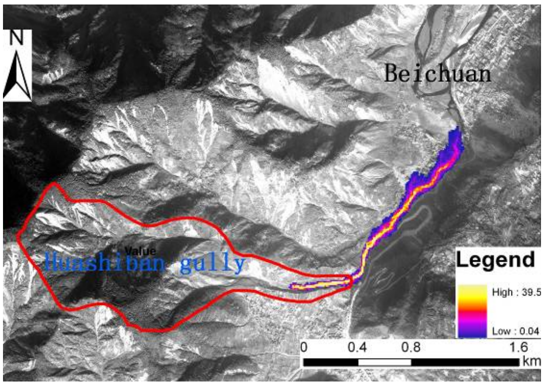
A. The actual area of debris flow inundation



B. The maximum depth of simulation



C.The maximum velocity of simulation



D. The maximum momentum of simulation

Figure 5 The simulation results of debris flow movement in Huashiban gully

Beichuan township after the quake before debris flow occurrence

Beichuan township after debris flow on 24th September, 2008

Figure 6 The destroyed scenes after earthquake (left) and after debris flow on 24 September 2008 (right, photo from cnsphoto)

distributions of velocity and flow depth at each intersection during the movement process on the alluvial fan can be obtained. The distribution of maximum velocity, maximum flow depth and maximum momentum can be obtained consequently (Figure 5). The simulated deposit area is similar to the actual one. In the view of the distribution of momentum and velocity, simulation shows that the major risk area for debris flow expands along the channel, and that the submerged area includes most of the former county town of Beichuan county.

The simulated value for the accumulation area is 161,500 m^2, while the measured area of the real debris flow is 144,097 m^2. Comparing the simulation value with the measured value, the simulation accuracy is 81.75%. The simulated value of maximum debris flow depth is 12.3 m. According to field investigation results (Figure 6), the actual debris flow fills up 4 m on the average and up to 12 m near original flow path, which is consistent with the simulated result. The debris flow made the situation worse by burying a large part of Beichuan town in place where the damaged buildings were supposed to be reserved as earthquake relics. The error is mainly induced by the impacts of buildings and variation in cross section configuration. The results indicate that the methodology established in this paper can be applied to other debris-flow watersheds for magnitude and risk area prediction.

5 Conclusions

Strong earthquakes often induce a large number of collapses, landslides and unstable slopes and generate abundant unconsolidated materials for debris flows. Debris flows will be a major hazard in the Wenchuan earthquake area for many years. Therefore, developing a method to predict debris-flow magnitude and inundation area is a critical element for post-earthquake reconstruction and for disaster mitigation. It is difficult to predict debris-flow runoff process quantitatively. Debris flow in the area is mainly controlled by rainfall and thus the runoff process is consistent with flood process. Based on this hypothesis, the debris-flow process was predicted by combining the Arc-SCS method for flood hydrograph and peak discharge equation for debris flow. The results were used as input parameters for inundation simulation. The following are the main results:

1. The Arc-SCS model was applied to calculate the flow-hydrograph, and then the debris-flow discharge process was obtained by combining the results from SCS model and equation of debris-flow discharge. The calculated results show that the maximum water-flow discharge was 35.52 $m^3 \cdot s^{-1}$ and the corresponding maximum debris-flow discharge was 215.66 $m^3 \cdot s^{-1}$. The error between the calculated value and the field-measured value is 4.15%, indicating that the result generated by Arc-SCS model is acceptable.

2. Taking the motion equation and setting up grids on the alluvial fan based on a DEM, the process was simulated using the parameters from Arc-SCS. The simulation shows flow depth, inundated area and the high risk area. The simulation results indicate that the area of the planned earthquake museum is at significant risk of future recurrent debris flow. The simulated results are consistent with the values determined in the field. Therefore, this method can be applied to other debris-flow basins for risk assessment in Wenchuan earthquake affected-area.

By combining the Arc-SCS method and the equation of discharge, the hydrograph was yielded which served as input parameters for simulation. Then, the prediction of debris-flow dangerous area can be predicted. This method considers only the hydrological processes in debris flow formation, which may be utilized in the condition of rainfall-triggerred debris flow. In the future, the prediction method should be developed by coupling the flood process and the soil supply process together which may yield more accurate result of magnitude for inundation simulation.

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Reference

Aleotti P (2004) A warning system for rainfall-induced shallow failures. Engineering Geology 73:247-265.

Berti M, Simoni A (2005) Experimental evidences and numerical modelling of debris flow initiated by channel runoff. Landslide 2: 171-182.

Bisson M, Favalli M, Fornaciai A et al. (2005) rapid method to assess fire-related debris flow hazard in the Mediterranean region: An example from Sicily (southern Italy). International Journal of Applied Earth Observation and Geoinformation 7: 217–231.

Brater EF, King HW (1976) Handbook of hydraulics for the solution of hydraulic engineering problems. New York: McGraw Hill Book Company.

Cui P (1992) Study on condition and mechanisms of debris flow initiation by means of experiment. Chinese Science Bulletin 37(9): 759-763.

Cui P, Chen XQ, Zhu YY et al. (2009) The Wenchuan Earthquake (May 12, 2008), Sichuan Province, China, and resulting geohazards. Natural Hazards doi:10.1007/s11069 - 009-9392-1.
Cui P, Zhuang JQ, Chen XZ et al. (2010) Characteristics and countermeasures of debris flow in Wenchuan area after the Earthquake. Journal of Sichuan University (Engineering Science Edition) 42(5): 10–19. (In Chinese).
Hu KH, Cui P, Wang CC et al. (2010) Characteristic rainfall for warning of debris flows. Journal of Mountain Science 3:207-214.
Hu KH, Wei FQ, He YP et al. (2003) Application of particle model in risk zoning of debris flows. Journal of Mountain Sciences 21(6): 726-730. (In Chinese).
Iverson RM (1997) The physics of debris flow. Reviews of Geophysics 35(3): 245-296
Kang ZC, Li ZF, Ma AN et al. (2004) Study on debris flows in China. Beijing: Science press 54-55. (In Chinese).
Liu JF, You Y, Chen XZ et al. (2010) Identification of potential sites of debris flows in the upper Min River drainage, following environmental changes caused by the Wenchuan earthquake. Journal of Mountain Science 3:255-263.
Montes S (1998) Hydraulics of open channel flows. Reston: ASCE Press, pp 1-697.
SCS (Soil Conservation Service) (1972) SCS National Engineering Handbook, Section 4. Hydrology, Soil Conservation Service. US Department of Agriculture,Washington, DC.
Sichuan Water and Power Department (1984) Sichuan Hydrology Record Handbook, pp 2-36.
Tang C, Zhu J, Li WL et al. (2009) Rainfall-triggered debris flows following the Wenchuan earthquake. Bulletin of Engineer Geology Environment 68:187-194 doi:10.1007/s10064-009-0201-6.
Wang G, Shao S, Fei X (1997) Particle model for alluvial fan formation. In: Chen, CL (ed.), Debris flows Hazard Mitigation: Mechanics, Prediction, and Assessment, Proceeding of the First International DFHM Conference, San Francisco, CA, USA, August 7-9. New York: ASCE, pp 143-152.
Wang GQ, Song SD, Fei XJ (1998) Debris flow simulation:I-model. Journal of Sediment Research 43(3): 7-131. (In Chinese).
Wei FQ, Hu KH, Lopez JL et al. (2003) Method and its application of the momentum model for debris flow risk zoning. Chinese Science 48(3): 298-301.
Wu JS, Tian LQ, Kang ZC et al. (1993) Debris flow and its comprehensive control. Beijing: Science Press pp 17-191. (In Chinese).
Xie H, Du J K, Hu Y J et al. (2005). Study on sSpatially distributed hydrological model based on routing time method. Journal of Wwuhan Uuniversity of Ttechnology 27: 75-78. (In Chinese).
Yu FC, Chen CY, Chen TC etal. (2006) A GIS process for delimitating areas potentially endangered by debris flow. Natural Hazards 37:169-189.