Numerical simulation on post-earthquake debris flows: A case study of the Chutou gully in Wenchuan, China

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Abstract. Since the 2008 Wenchuan earthquake, post-earthquake debris flows have severely threatened people’s lives and the safety of public transit facilities, making particularly crucial to understand their formation mechanism. We focused on the Chutou gully debris flow and analyzed its formation mechanism based on field investigations and satellite images. The main inducing factor of this debris flow was a continuous heavy rainfall that exceeded the threshold of the study area: this, combined with the large amount of loose material created by the earthquake, dramatically promoted the volume and hazard degree of the debris flow. The three-dimensional debris flow simulation software RAMMS, based on an improved Voellmy–Salm fluid model, was used to simulate the movement process of the Chutou gully debris flow. The calibrated Coulomb friction ($\mu$) and viscous turbulent friction ($\xi$) coefficients in the study area were 0.225 and 180 m/s$^2$, respectively. The simulation results revealed the post-earthquake debris flow mechanism in terms of flow height, velocity, flow rate, and deposition area. The results of the numerical simulation were in good agreement with those of the field investigations. In particular, it was found that the peak flow of debris flow upstream of the Chutou gully was shorter in duration than the one upstream; however, due to the convergence of the branch gully, the downstream peak flow of debris flow increased significantly, while a large amount of solid material stranded downstream of the channel. Notably, this process is prone to occur again. This study proposes a new post-earthquake debris flow evaluation method, and its results are of reference value for the design of debris flow prevention engineering in meizoseismal areas.

1. Introduction

The term post-earthquake debris flow refers to debris flows induced by extreme rainstorms and formed under the joint effect of a steep terrain and slope and channel erosion; moreover, they are characterized by very large volumes, cluster occurrences, and a disaster chain effect$^{[1,2]}$. The rainfall threshold$^{[3,4]}$, channel runoff$^{[5,6]}$, initiation materials$^{[7,8]}$, and block-burst effect$^{[9,10]}$ of post-earthquake debris flows have been studied by a large number of researchers and obtained many practical results. The results of those studies have significantly strengthened the understanding of the mechanism of post-earthquake debris flows; however, there is still a lack of research on the entire occurrence process and the frequent occurrence of post-earthquake debris flows. In order to provide a solid decision basis for the identification of such flows, it is necessary to identify a method capable of reproducing their entire process. Conventional ground-based techniques have been considered the most effective means of revealing the characteristics of debris flows. $^{[1]}$. In order to overcome this issue, remote sensing techniques have applied in the last decades: they can efficiently superimpose high-resolution satellite
images or aerial images onto a high-resolution digital elevation model (DEM) for a numerical evaluation of debris flows. Conventional software (e.g., Dan-3D, Flo-2D, and Massflow) mostly use a discharge hydrograph to input the initial conditions, while the block release method is rarely used; therefore, the release point of the source materials cannot be considered \cite{11,12,13}. The Rapid Mass Movement Simulation (RAMMS) software provides two block release methods and an input hydrograph to set the initial debris flow conditions. Such setting is particularly suitable for areas affected by strong earthquakes. In addition, RAMMS is based on an improved Voellmy–Salin model, which considers the effect of turbulence and can thus more accurately evaluate the movement process of debris flows.

This paper presents a case study clarifying the movement and deposition processes of post-earthquake debris flows using RAMMS. The study site coincides with the Chutou gully, which is located in the area where the Wenchuan earthquake took place on July 10, 2013. The fluid height, flow velocity, discharge, and other characteristics of the debris flow were utilized to reveal its movement process and verified by field investigations. The results of this study strengthen our understanding of the initiation, movement, and deposition processes of rainstorm-induced post-earthquake debris flows, and provide a reference for the design of prevention projects in mezoseismal areas.

### 2. Basic characteristics of the Chutou gully

The study area (103°29′08.43″E, 31°20′20.84″N), with a catchment area of approximately 21.7 km², is situated near the Wenchuan earthquake’s epicenter (Figure 1) and belongs to the Wenchuan County of the Sichuan province in China. The Chutou gully is situated on the right bank of the Min River, its main channel has a length of 8.9 km; moreover, the highest and lowest elevations of the gully are 4130 m and 1178 m, respectively (elevation difference = 2952 m), and the average longitudinal slope of the channel is 184‰.

#### 2.1. Debris flow events

The Chutou gully is characterized by an old debris flow gully whose topography and landforms were severely damaged by the Wenchuan earthquake: a large number of landslides developed, and the sources of loose solid materials increased significantly. On July 10, 2013, triggered by intense rainfall, a debris flow occurred in the Chutou gully: the corresponding runout of solid material was 38.5 × 10⁴ m³. As a result, the original and small storage dam of the hydropower station in the gully and the prevention and control project were washed away; additionally, more than 10 houses in the gully mouth were damaged, three people went missing, and ~ 200 m of the Dujiangyan–Wenchuan highway were buried under the fallen material. The solid materials squeezed out and occupied ~ 25 m of the length of the main Min River channel, causing it to drift.

#### 2.2. Geological setting

The study area is located in the central Longmenshan seismogenic fault zone, on the eastern edge of the Qinghai–Tibet Plateau, and belongs to the transition zone between the Sichuan Basin and the Qinghai–Tibet Plateau. The main fault structures in the area are the Wenchuan–Maoxian fault zone, the Yingxiu–Beichuan fault zone and Jiangyou–Guangxian fracture (Figure 1). The Wen–Mao fault is one of the main faults in the study area. The Chutou gully is located at ~ 30 km from the epicenter of the 5.12 Wenchuan earthquake (M_s 8.0) that occurred in 2008, and was hence greatly affected by it. The study area is underlain by the Proterozoic Huangshuihe Formation (P_m), the Silurian Maoxian Formation (S_m), granitic rocks (γ), diorite rocks (δ), and granodiorite rocks (γ_δ). Meanwhile, loose Quaternary deposits are distributed in the form of terraces and alluvial fans. The upper and middle Chutou gully is dominated by granodiorite, which is deeply fractured, highly weathered, and covered with a layer of weathered material, constituting the main source of material for the post-earthquake landslides.

The Chutou gully is a V-shaped deep-incised structure (an eroded landform). The correspondent catchment is leaf-shaped and its overall terrain is steep. Notably, the channel in the upstream section of the Chutou gully is relatively narrow (width = ~ 5–15 m) and has a large longitudinal slope, while the downstream section of the gully is wide (width = 50–120 m) and its longitudinal slope is gentle.
3. Causes and formation

3.1. Topographic features
The Chutou gully, located in a strong earthquake area, is characterized by a steep terrain and its main channel has a large longitudinal slope. Such topographic conditions are favorable to the development of debris flows. The bank slope of the Chutou gully is generally >35°; moreover, the gully valley has a ‘V’ shape, which is conducive to the convergence of material sources and water and the formation of debris flows. The Chutou gully catchment has 8 branch ditches, which generally have steep longitudinal slopes, narrow channels, and good hydrodynamic conditions. The angle of the valley slopes usually varies from 45° to 65°, but can locally reach 80°. The gully width varies between ~ 10–16 m, while the longitudinal slope of the channels between 371‰–737‰. After the earthquake with $M_s = 5.12$, the development of unfavorable geological phenomena caused the formation of abundant loose materials and, thus, increased the likelihood of debris flow occurrence. Notably, the occurrence of branch debris flows led to the Chutou gully debris flow by supplying abundant loose materials and leading to the development of favorable dynamic conditions.

3.2. Material sources
Based on the data collected during the field investigations, a total of 58 source material points of different scales are developed in the Chutou gully. The source materials can be divided into three types, according to their origin and lithology. The first type corresponds mainly to granite and other magmatic rock masses, which are transformed into loose materials by avalanches of earthquake origin. This material is mainly distributed in the middle and lower slopes of the Chutou gully, as well as in the middle and lower reaches of the branch gullies (Figure 2a, c, f), and occupies a relatively large volume. The second type of source material corresponds to mixed soil and bedrock landslide deposits, which are mainly developed in the groove part of the bank slope and are locally thick, but leave the strongly weathered bedrock exposed (Figure 2d, e, j). The composition of these deposits is controlled by that of the terrace deposits. The third type of source material is mainly represented by soil and strongly weathered bedrock, has a fine granulometry, and is mainly located on the surface of overburden and avalanche deposits (Figure 2i). After the Wenchuan earthquake, some of the source material points (under the effect of slope erosion in the branch gullies) released material, leading to the occurrence of new debris flows under the action of rainstorms. The debris flow material was transported to different...
distances and deposited in the channels (both in the main channel of the Chutou gully and in the branch gullies) (Figure 2b, g, k, l).

Figure 2. Distribution of the source materials and typical source materials in the Chutou gully.

3.3. Rainfall and water sources

The study area belongs to a continental semi-arid monsoon climate zone: the overall climate is dry, the dry and rainy seasons are well distinct, and the rainy season is concentrated between July and September. The average precipitation over many years has been of 526.3 mm. According to the data records of the Yangdian Meteorological Observatory (located near the gully mouth), the following events were reconstructed. The ‘7.10’ Chutou gully debris flow was induced by rainfall that occurred in the Miansi area (Figure 3). This rainfall event started on July 8, 2013, but was particularly intense between July 9–10, 2013. The Chutou gully debris flow occurred instead at ~ 05:00 (in the morning) on July 10, 2013. The continuous rainfall time, from its start to the time of occurrence of the debris flow, was ~ 52 h; moreover, the cumulative rainfall was 148.1 mm, the excitation hourly rainfall intensity 18.6 mm/h, and the average rainfall 2.85 mm/h. Based on an established database [14], the accumulated rainfall of this debris flow exceeded the threshold of the study area.
Figure 3. Hourly rainfall and accumulated rainfall over the Chutou gully before and after the ‘7.10’ debris flow.

4. Methods and setup

The three-dimensional (3-D) numerical software RAMMS (based on an improved Voellmy–Salm fluid model) is typically used to analyze the behavior of debris flows after their initiation: their flow depths, velocities, discharge, and depositional areas are all calculated.

4.1. The Voellmy–Salm fluid model in RAMMS

The modified Voellmy–Salm fluid model was used in RAMMS and the friction resistance was divided into two parts: the static friction resistance (related to the dry-Coulomb friction coefficient ($\mu$)) and the motion resistance (related to velocity and the viscous turbulent friction coefficient ($\xi$)). The total resistance was calculated as follows:\textsuperscript{15}

$$S = \mu \rho H g \cos(\phi) + \frac{\rho g U^2}{\xi}$$ (1)

where $\rho$ is the density, $g$ the gravitational acceleration, $\phi$ the slope angle, $H$ the flow height, and $U$ the velocity ($U = (U_X + U_Y)^T$), which includes the flow velocity along the directions X and Y. The normal stress on the flow surface is expressed as $\rho H g \cos(\phi)$.

Since debris flows cannot be described by a simple linear relationship and $\mu$ is a constant in the model, the basic Voellmy–Salm model was modified to include the yield stress. In order to simulate the yield stress, the parameter $N_0$ was introduced. An ideal plastic material could be simulated through this method: $N_0$ was taken as the yield stress and $\mu$ as the ‘hardening’ parameter. The new equation for the friction resistance was:

$$S = \mu \rho H g \cos(\phi) + \frac{\rho g U^2}{\xi} + (1 - \mu)N_0 - (1 - \mu)N_0 e^{-\frac{N}{N_0}}$$ (2)

where $N_0$ is the yield stress of the fluid materials. Unlike a simple Mohr–Coulomb relationship, this formula ensures that $S$ is equal to 0 when $N_0$ and $U$ both tend to zero. Notably, the adoption of this relationship leads to a simulation in which the debris flows stop relatively early due to increasing shear stress.

4.2. Setup for the numerical simulation

The adoption of a reasonable set of basic conditions can significantly enhance the accuracy of the simulation results. RAMMS was used to calculate the motion of the movement from its initiation to its runout over a 3-D terrain. Our model used depth-averaged equations to predict the slope-parallel velocities and flow heights. This information is sufficient for most engineering applications. Such model requires however an accurate digital representation of the terrain. As a matter of fact, engineers can specify the initial conditions (e.g., location and size of the release mass) and friction parameters, which depend on the terrain (e.g., roughness, vegetation) and material properties.

4.2.1 DEM and satellite images

To successfully start a new RAMMS project, a few preparations are necessary. Topographic input data (i.e., DEM), project boundary coordinates, and georeferenced maps or remote sensing images should be prepared in advance. The 12.5-m DEM of the study area obtained from the ALOS satellite was processed using a 10-m simulation grid, which was then employed as a basis for the numerical analyses. A data management system was used to convert the DEM into recognizable formats (e.g., ASCII-, XYZ-, and GEOTIFF) in RAMMS. Notably, the georeferenced datasets needed to be in the same Cartesian coordinate system as the DEM; in fact, polar coordinate systems in degrees (e.g., WGS84 Longitude–Latitude) are not supported. The satellite images were mainly obtained through Google Earth (from historical Keyhole aerial photography and an extended database) and their spatial resolution reached 0.5 m.

4.2.2 Material source settings
In RAMMS there are two options to define the starting conditions (i.e., the release information) of a simulation: the block release and the input hydrograph. For debris flows creating a clear destruction area, it is useful to use a release area with a given initial depth, which will be released as a block. Through the interpretation of satellite images collected before and after the ‘7.10’ debris flow in the Chutou gully, it was found that, despite the signs of many old debris flows in the Chutou gully, the new deposits created by the ‘5.12’ Wenchuan earthquake still occupied a dominant position in the study area. The last debris flow did not induce new landslides or collapses. Therefore, according to the satellite images collected before the ‘7.10’ debris flow, it was possible to determine the distribution characteristics of the debris sources: 58 of them were identified in the Chutou gully. Based on the influence area of the Chutou gully and through in-site investigations, the depth of each solid material area was also determined \cite{1}. The average sedimentary depth of the clastic source material was \( \sim 1.5 \) m, the maximum deposition depth 5.5 m, and the total volume of the material 124.41 \( \times 10^4 \) m\(^3\). The impact area obtained from this information and the images of the debris flow led to very similar estimations.

### 4.2.3 Calculation parameters

According to the results of the field density test for the upstream, middle, and lower reaches of the Chutou gully, we obtained an average of 1672 kg/m\(^3\). This value was taken as the density of the debris flow in the gully. Before performing any calculations, we set their range based on the scope file: the larger the range, the higher would have been the performance requirements of the computer and, hence, the slower the calculations. According to the field investigation results and the results of the back calculation, we set the total simulation time to 1800 s and the dump-step to 20 s. Notably, the dump-step interval defines the resolution of the simulation’s animation, but has no effect on the simulation results. In addition, for every dump-step, RAMMS summed up the momenta of all grid cells, and compared it with the maximum momentum sum. If this percentage was \(<5\%\), RAMMS aborted the simulation and the debris flow was regarded as stopped. The value of the earth pressure coefficient Lambda was 1.0.

The flow of the material source was mainly controlled by the static friction coefficient \( (\mu) \) and the viscous turbulent friction coefficient \( (\xi) \). The friction parameters could be adjusted to match the observed flow characteristics: larger friction coefficients would have caused the debris flow to stop earlier. The debris flow in the Chutou gully was then calibrated based on the field survey results (Table 1).

| Table 1. Parameters used for the calibration of the debris flow in the Chutou gully. |
|-------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| **Field investigations**      |                                                                                                                                  |
| Cross-sectional analysis      | Heights of levees or heights of marks on constructions, estimation of velocity (through splashing and super elevation)          |
| Flow paths                    | Tracks of boulders, rocks, and mud                                                                                               |
| Deposition of material         | Lobes, levees, and debris flow heads                                                                                             |
| Estimation of the total volume| Retention basin in the runout zone plus deposited material in torrents and in the receiving river                               |
| **Photographs**               |                                                                                                                                  |
| Release area                  | Geometry of the release area                                                                                                    |
| Flow Paths                    | Deposited material analyzed by aerial photographs                                                                              |

Based on the in-site investigations, and in particular by comparing the velocity and flow height, it was possible to calibrate the model. In the case of a given total solid material volume, and by matching the simulation results with the in-site investigations of the mud height and velocity at a given location, we obtained the most suitable Voellmy–Salm friction parameters for the Chutou gully: \( \mu = 0.225 \) and \( \xi = 180 \text{ m/s}^2 \).
5. Simulation results

5.1. Flow height
As shown in Figure 4, after the debris flow started, the solid material of the branch channel continuously converged into the main channel. After ~ 500 s, all the solid material of the branch channel had gathered into the main channel. With the development of the debris flow, the sediment in the gully moved down and accumulated on both sides of the channel. The flow height of the debris flow in the main channel increased considerably, and the debris flow began to deposit. After ~ 1800 s, the deposition was almost complete: most of the solid materials were deposited in the middle and lower section of the Chutou gully’s channel, while others were washed out of the gully mouth. The highest accumulation height in the downstream section reached 18 m, and the average height in the accumulation area was ~ 3–4 m. The simulation results showed that the total runout volume of the Chutou gully debris flow was $3.5 \times 10^4$ m$^3$, a value which is consistent with that deduced from the in-site investigations ($\sim 3.8 \times 10^4$ m$^3$).

![Figure 4. Flow height characteristics during the development of the debris flow](image)

5.2. Flow velocity
The debris flow velocity results showed that this parameter was related to the terrain’s characteristics at the time of initiation of the debris flow: the initiation speed was higher for steeper slopes. When $T = 100$ s, the starting speed of the solid material reached 14.96 m/s; however, when $T = 500$ s (as in the middle reaches of the gully, where the channel width varied between 80 m and 40 m), the maximum velocity was 7.05 m/s (Figure 5). According to the in-site investigations, the flow velocities in sections 1 and 2 were ~ 3.8 m/s and 2.5 m/s, respectively (in good agreement with the simulation results). These simulation results are of important reference value for the design of debris flow prevention projects.
5.3. Discharge
As shown in Figure 6, since the initiation of the debris flow, the discharge in section 1 increased significantly at ~ 160 s, reaching its maximum at 400 s (~ 362 m$^3$/s) and then decreasing continuously. From ~ 600 s, the debris flow began depositing. This process had a total duration of ~ 440 s. In section 2, the discharge increased significantly at ~ 500 s and reached its maximum at ~ 800 s. Due to the presence of abundant solid materials between section 1 and section 2 of the Chutou gully, the peak discharge of profile 2 was much greater than that of profile 1, and the peak discharge was ~ 448 m$^3$/s (consistent with the in-site investigations). Since the debris flow in the branch channel was still converging into the main gully, the peak flow lasted for ~ 700 s. Notably, the average annual discharge of the Min River is ~ 448 m$^3$/s\cite{1}, possibly explaining why the debris flow partially blocked the Min River.

![Figure 5. Velocity characteristics of the Chutou gully debris flow at various times.](image)

5.4. Deposition area
The distribution of the affected areas was largely affected by the location of the solid materials and the runoff characteristics. For practical applications, engineers and technicians often focus on the deposition area (where serious damages can occur). As shown in Figure 7, the national highway and the expressway at the mouth of the gully were partially buried under the deposits that reached the mouth of the Chutou gully. We infer that a large amount of solid material should have flowed into the Min River, reducing the amplitude of the Min River channel, rising the water level in the upstream and downstream sections, and causing the flooding of the Miansi service area. This process would have also caused the flooding of towns located along the upstream section of the river.

![Figure 6. Hydrograph of section 1 and section 2 of the Chutou gully debris flow. The corresponding location is shown in Figure 5.](image)
6. Discussion
A good-quality DEM and a high-resolution grid are crucial for delineating areas potentially affected by debris flows and, thus, for hazard assessment and mapping\(^{[16]}\). In this study, considering the large area of the Chutou gully, we decided to apply a simulation grid with a resolution of 10 × 10 m. This setup was also reasonable for our computer configuration. Notably, a smaller grid resolution would have led to a more accurate simulation of the affected area, but also compromised the computer performances. According to the classification of debris flow intensity proposed by Chang et al., the debris flow intensity is defined by the maximum unit width discharge (\(Q\)) used in hydraulics\(^{[17]}\). As shown in Table 2, here \(Q\) was defined as the maximum simulated flow depth (H) multiplied by the maximum simulated flow velocity (V), and it was expressed in m\(^2\)/s. At the same time, H was an important reference factor. The depth and velocity data obtained from RAMMS were exported in the ASCII format and finally processed by a geographic data management software. After processing, these data were combined with the information obtained from the field investigations, leading to the classification of high, medium, and low flow intensities (Table 2).

### Table 2 Levels of debris flow intensity.

| Debris flow intensity | Maximum simulated flow height H (m) | Relation | Maximum simulated flow height and velocity Q (m\(^2\)/s) |
|----------------------|------------------------------------|----------|----------------------------------------------------------|
| High                 | \(H > 2.0\)                        | or       | \(VH > 4.0\)                                             |
| Medium               | \(0.5 < H \leq 2.0\)               | and      | \(1.0 < VH \leq 4.0\)                                    |
| Low                  | \(H < 0.5\)                        | and      | \(VH < 1.0\)                                             |

7. Result
According to the results of in-site investigations, remote sensing, and numerical simulations, we can conclude the following.

1. The Chutou gully was a typical post-earthquake debris flow and its main trigger was an extreme rainstorm; additionally, the Wenchuan earthquake provided a large amount of solid material, increasing the scale and harmfulness of the debris flow.
2. In the Chutou gully, the flow depth of the debris flow was smaller in the narrower steep section and larger in the wider slow section, while the opposite was true for the flow velocity. Besides, the upstream peak discharge of the Chutou gully was minimum and its duration short, while the downstream peak discharge obviously increased and its duration was longer due to the supplement of material from the branch ditches.
(3) RAMMS is an efficient and accurate 3-D debris flow simulation software based on the Voellmy–Salm model. The calibrated Coulomb friction coefficient ($\mu$) and the viscous turbulent friction coefficient ($\xi$), obtained from in-site investigations in the Chutou gully, were 0.225 and 180 m/s$^2$, respectively, and can be applied to the study of debris flows occurring under similar geological conditions.

(4) The simulation results showed that there are a large amount of solid material persisted in the Chutou gully after the ‘7.10’ debris flow, and that the risk of new debris flows occurring in the future in the same location is high. The systematic analyses of the whole process of debris flow movement conducted in this study was helpful for clarifying the initiation, migration, and deposition mechanism of the debris flow; moreover, it can support the design of effective protection projects. Finally, the proposed classification standard of debris flow intensity can be used as a reference for debris flow hazard predictions.

8. Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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