New insights into the delayed initiation of a debris flow in southwest China

Taixin Peng¹² · Ningsheng Chen¹³ · Guisheng Hu¹³ · Shufeng Tian¹² · Zheng Han⁴ · Enlong Liu⁵

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Abstract

On 6 July 2020, 3 h 40 min after rainfall stopped, a delayed debris-flow disaster occurred due to colluvium deposits in a hollow region (CDH) in the Chenghuangmiao Gully, Sichuan Province, China, resulting in 4 deaths and 27 injuries. This study explores the initiation process of the delayed debris flow and the cause for the delay. Field investigations, catchment geometry interpretation, laboratory tests, theoretical calculations, and fluid–solid coupling numerical simulation were performed to obtain landslide parameters and understand the mechanisms of the event. Results show that (1) the event was a giant low-frequency viscous debris flow. (2) It was initiated by the delayed landslide process under the influence of back-end confluence. (3) The debris-flow discharge in the main gully increased over 19.5 min. (4) The seepage process inside the CDH continued for 3 h 20 min after the rainfall stopped before the pore pressure and reduction in strength were sufficient to initiate the debris flow. This research provides new insights on delayed debris-flow disasters and can be a reference for improving disaster management systems, especially monitoring and early warning systems, thereby avoiding future casualties.

Keywords Delayed debris flow · Hollow deposits · Landslide initiation · Fluid–solid coupling

Ningsheng Chen
chennsh@imde.ac.cn

¹ Key Lab of Mountain Hazards and Surface Process, Institute of Mountain Hazards and Environment (IMHE), Chinese Academy of Sciences (CAS), Chengdu 610041, China
² University of Chinese Academy of Sciences (UCAS), Beijing 100049, China
³ Academy of Plateau Science and Sustainability, Xining 810016, China
⁴ School of Civil Engineering, Central South University, Changsha 410075, China
⁵ State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resources and Hydropower, Sichuan University, Chengdu 610065, China
1 Introduction

Debris flows are triggered by high-intensity and short-duration, or low-intensity and long-duration rainfall (Iverson 1997; Iverson et al. 1997). When rainfall intensity and duration exceed the threshold, debris flow occurs (Cannon et al. 2008; Guzzetti et al. 2008; Baum and Godt 2010; Borga et al. 2014). Therefore, China’s Sichuan Province has established many rain gauges to monitor likely occurrences of debris flow in vulnerable areas and warn people about them. During 2019–2020, warnings for 14 debris flows were successfully issued, preventing 4932 casualties. However, this early warning mechanism is not perfect as delays make the warnings ineffective. The Chenghuangmiao Gully experienced heavy rainfall in Aba, Sichuan, on 5 July 2020. People were evacuated when the alarm sounded, and they returned when the rain stopped; however, the debris-flow disaster initiated by the colluvium deposits in a hollow region (CDH) occurred 3 h 40 min after the rainfall stopped, causing 4 deaths. Accordingly, the following questions must be addressed: How was this delayed debris flow initiated? What caused the delay?

The delay in the occurrence of landslides after rainfall is a common phenomenon, because they may take a long time to develop. The development of landslides has three stages: initial, secondary, and accelerated deformation. Statistical data on 20 large-scale landslides show that the three stages together take 21–2135 days (Deng et al. 2000; Qi et al. 2006; Qiang et al. 2008; Huang et al. 2012; Li et al. 2016). As the delay in the development of a landslide occurs, delay in the resultant debris flow is possible. Analyses through numerous cases studies and experiments have explained the initiation mechanism of debris flow triggered by landslides; high pore pressure causes softening or liquefaction of the soil to initiate debris flow (Iverson and Denlinger 2001; Iverson and Vallance 2001; Crosta and Dal Negro 2003; Feng et al. 2005). The debris-flow disasters initiated by the CDH landslide involve processes such as rainfall generation and the confluence of streams, landslide, and debris flow (Chen et al. 2007; Zhang et al. 2019). As these three processes occur over various durations, they should be studied individually. The following approaches are relevant:

(1) Rainfall generation and confluence: The US Soil Conservation Service (SCS) model and the rational formula model are universally recognised. They involve calculating the total surface runoff, the runoff generation time, and the peak flow of confluence (Mishra and Singh 2003; Hua et al. 2003; Alfieri et al. 2008; Yue et al. 2012).

(2) The CDH landslide: Seepage and deformation occurred in the CDH simultaneously under the influence of back-end confluence; their interaction (fluid–solid coupling) can be described by the finite-difference software (Kim et al. 2018; Zhou et al. 2019; Wang et al. 2020; Wei et al. 2009).

(3) Debris flow: Calculation of velocity and discharge of debris flow are based on cross-sectional investigation; this method is widely used for preliminary evaluation of debris flow and engineering treatment (Chen et al. 2015).

In general, from the onset of rainfall to the occurrence of debris flow, there were mature studies on back-end confluence, seepage and deformation of the landslide, and debris flow, respectively. However, the disaster’s physical process was not connected coherently on the timeline as real happened. The phenomenon of debris-flow delay is mentioned in references but has not been researched adequately. In this study, we use the SCS model and the rational formula to calculate the back-end confluence of the CDH; we then use a numerical method to simulate the debris flow initiated by the CDH landslide in the conditions of the back-end confluence. Through field investigation,
catchment geometry interpretation, and laboratory tests, the debris flow was characterised. Consequently, we identified the process of debris-flow initiation and the reasons for the delay on the time of occurrence.

2 Study area

2.1 Overview of geography, geology, and watershed of the catchment

The study area is located at the junction of Xiaojin County and Danba County in Sichuan Province, China, at a valley on the southeast edge of the Qinghai–Tibet Plateau. The region comprises middle mountain landforms that experienced rapid structural uplift, deep river cutting, and intense erosion and weathering (Fig. 1a). The study area is situated in the western wing of the Xiaojin Arc structure, which comprises two anticlines that sandwich a syncline; the three folds are aligned along the N–SW direction. The Chenghuangmiao Gully flows between the cores of the two anticlines (Fig. 1c). The lithology of the study area comprises slates, quartzites, and interbedded sandstones (Fig. 1c).

The watershed where the debris flow erupted belongs to a branch of the Xiaojinchuan River at the Chenghuangmiao Gully. The watershed area is 6.1 km², altitude is between 2168 and 4252 m, and relief of the basin is 2084 m. The Xiaojinchuan River and the Provincial Highway S303 pass through the mouth of the gully. Based on the longitudinal gradient and source distribution of the Chenghuangmiao Gully, the watershed is divided into the confluence area (Shimizu area) at the back end of the CDH, initiation and transition area, and accumulation area. The Shimizu area is located in the upper reaches of the

![Fig. 1 Chenghuangmiao Gully: a watershed; b altitude; c geological map](image-url)
Chenghuangmiao Gully above the altitude of 4060 m, with an area of 0.123 km² and a slope of 26–38°. The vegetation in the area is developed; the humus layer and colluvium deposits are 0.9–2.3 m thick. The concave terrain at the junction of the two slopes provides favourable conditions for runoff confluence. The altitudes of the initiation and transition areas are between 4060 and 2250 m, length is approximately 4.95 km, and area is approximately 5.930 km². Abundant loose materials and steep gradient channels provide favourable conditions for the initiation and transition of debris flows. The accumulation area is located from the mouth of the Chenghuangmiao Gully (2250 m in elevation) to the confluence point with the Xiaojinchuan River (2168 m in elevation), and the area is approximately 0.047 km². The relatively low slope provides good topographical conditions for the accumulation of debris (Fig. 1a and b).

2.2 Weather overview

The study area experienced sparse rainfall in spring and heavy rainfall in June; intermittent heavy rainfall occurred before the debris-flow event. According to statistics, the maximum monthly precipitation in the study area since 1952 was 233.9 mm, and the precipitation in June 2020 (222.6 mm) before the occurrence of the debris flow was close to the historical peak (Fig. 2a and b). The maximum daily rainfall intensity of 30 mm/d occurred on the day before the occurrence of the debris flow (5 July 2020); this value was close to the historical maximum daily rainfall of 37.8 mm/d (Fig. 2c). The maximum hourly rainfall

![Fig. 2 Rainfall trends in the study area: a monthly rainfall from 1952; b monthly rainfall from 2014 to 2020; c daily rainfall in the 12 days before the occurrence of debris flow; d hourly rainfall in the 12 days before the occurrence; f Hourly rainfall 30 h before the occurrence](image-url)
was 7.6 mm/h from 21:00 to 22:00 h on 5 July 2020 (Fig. 2d). The data show that rainfall occurred throughout the area during 01:00–08:00 h and 19:00–24:00 h on 5 July 2020. The effective rainfall was approximately 17.0 mm before the disaster (Fig. 2e).

3 Methodology

Field investigations, catchment geometry interpretation, and laboratory tests were conducted to obtain data on deposits and terrain parameters for the characterisation of the gully after the debris-flow disaster. Theoretical calculations and numerical simulation methods were performed to obtain the parameters regarding rainfall, runoff, CDH landslide at the debris-flow source, and debris flow (Fig. 3).

3.1 Field investigations, catchment geometry interpretation, and laboratory tests

Field investigations were performed to ascertain the following: (1) Terrain parameters of the debris-flow accumulation body were evaluated through sampling at the gully mouth and aerial photography using an unmanned aerial vehicle. (2) The geometric parameters of the gully section such as maximum mud-mark height (flow depth) and widths of the section at the top and bottom. (3) Terrain parameters and the composition of the CDH landslide at the source of debris flow.

Catchment geometry was interpreted to obtain its terrain parameters such as watershed area, gully length of debris flow, and hydraulic gradient. Laboratory tests, such as particle sieve analysis (Malvern), direct shear test, and permeability test, were conducted on the accumulated deposits of less than 60 mm; physical and mechanical parameters of the deposits were obtained.

3.2 Calculation of back-end confluence process

We obtained the surface-runoff at the confluence outlet through calculations using the SCS model, rational formula, and the pentagonal flow-process line method. First, the SCS model was used to calculate total surface runoff. The rational formula was used to calculate hourly
peak-flow rate and runoff-generation time. Based on these calculations, the pentagon-flow process line per hour was superimposed, and we obtained the surface-runoff process line (Clark 1945; Edward Kuiper 1965; Pegram and Parak 2004). Finally, we obtained the subsurface-runoff process line according to the empirical method and formed a complete-runoff process line for the confluence to the CDH.

The SCS model is composed of three relational equations: the equation for rainfall and runoff, the water balance equation, the linear equations of initial rainfall loss. The above three relational equations are combined to obtain the equations of the SCS model (Eqs. (1) and (2)).

\[
S = \frac{25400}{CN} - 254
\]

\[
\begin{align*}
Q &= (P - 0.2S)^2 / (P + 0.8S), P \geq 0.2S \\
Q &= 0, P < 0.2S
\end{align*}
\]

where \(P\) is the total amount of rainfall (mm); \(Q\) is the total surface runoff (mm); \(S\) is the possible detention in the basin at that time (mm); \(CN\) is the number of runoff curves (dimensionless). The common dataset of the University of Maryland for global soil cover and the simplified International Geosphere–Biosphere Programme soil cover classification system were used to determine the runoff curve coefficient \(CN\). Further, the hydrological soil groups of A, B, C, and D were determined according to the SCS soil classification.

The duration of runoff generation and the confluence and peak discharge were calculated by the rational formula of the Chinese Academy of Water Sciences (Eqs. 3–8):

\[
\tau_0 = \left[ \frac{0.278^{3/4}}{mR^{1/4}} \right]^{1/4} = \left[ \frac{0.383 \mu}{R^{1/4}} \right]^{1/4}
\]

\[
\psi = 1 - \frac{\mu}{R} \tau^n
\]

\[
\mu = 3.6F^{-0.19}
\]

\[
\tau_c = \left[ (1 - n) \frac{R}{\mu} \right]^{-1/4}
\]

\[
\tau = \tau_0 \psi^{-1/4}
\]

\[
Q_p = 0.278 \psi iF = 0.278 \psi \frac{R}{\tau^n} F
\]

where \(\psi\) is the coefficient of flood peak discharge (m³/s); \(i\) is the maximum average rainstorm intensity (mm/h); \(R\) is the hourly rainfall (mm/h); \(n\) is the rainstorm index; \(F\) is the confluence area (km²); \(L\) is the gully length (km); \(J\) is the gully-bed gradient; \(\tau\) is the watershed confluence time (h); \(\tau_0\) is the watershed confluence time (h) when \(\psi = 1\); \(\tau_c\) is the runoff generation process at time (h); \(\mu\) is the runoff generation parameter, i.e. the average infiltration intensity within the runoff generation process time (mm/h); \(m\) is the confluence
parameter; \( Q_p \) is the peak discharge (m\(^3\)/s). According to the survey, the rainstorm index \( n \) is 0.78, the confluence area \( F \) is 0.123 km\(^2\), the gully length of the confluence area \( L \) is 0.58 km, and the gully-bed gradient \( J \) is 591‰.

The rainstorm index was calculated using the rainstorm equation (Eqs. 9–11) and was considered when the confluence lasted for 1–6 h.

\[
H_{1p} = K_p \cdot \bar{H}_{1p} \tag{9}
\]

\[
H_{6p} = K_p \cdot \bar{H}_{6p} \tag{10}
\]

\[
n = 1 + 1.285 \lg \left( \frac{H_{1p}}{H_{6p}} \right) \tag{11}
\]

where \( K_p \) is a rainfall coefficient, which can be found in the Scale coefficient table of the Pearson type 3 curve; \( \bar{H}_{np} \) is \( n \) hours of average rainfall (mm), which can be found in the regional precipitation contour map; and \( H_{np} \) is \( n \) hours of maximum rainfall (mm).

### 3.3 Numerical simulation of the CDH landslide at the origin of debris flow

3D finite-difference software was used to calculate the dynamic response of the CDH under seepage flow at the source of the Chenghuangmiao Gully. Seepage and deformation were carried out simultaneously. The numerical model was established according to the field investigations and laboratory tests, and Table 1 shows the results obtained through density test, direct shear test under natural and saturated conditions, penetration test, laboratory confined compression test, and empirical formula for measuring porosity. The model consists of colluvium deposits, the bedrock, and the sliding surface, while comprising 7395 tetrahedral elements in total. The coupled deformation–seepage processes were formulated within the quasi-static Biot theory framework, which can be applied to problems involving single-phase Darcy flow in a porous medium. Darcy’s law describes fluid transport (Eq. (12)) (Polubarinova Kochina 1962):

\[
q_i = -k_i \hat{k}(s)[p - \rho_f x_j g_j] \tag{12}
\]

where \( q_i \) is the specific discharge vector, \( p \) is the pore pressure (Pa), \( k \) is the tensor of absolute mobility coefficients of the medium, \( \hat{k}(s) \) is the relative mobility coefficient, \( s \) is the fluid saturation, \( \rho_f \) is the fluid density (kg/m\(^3\)), \( g_j, j=1,3 \) is the three components of the gravity vector.

The fluid mass balance is expressed as (Eq. (13)) (Biot 1956):

\[
-q_{ij} + q_v = \frac{\partial \zeta}{\partial t} \tag{13}
\]

where \( q_v \) is the volumetric fluid source intensity per second (m\(^3\)/s); \( \zeta \) is the variations in the fluid content or the fluid volume per unit volume of a porous material due to diffusive fluid transport as introduced by Biot (1956).

The changes in the variation in fluid content are related to the changes in pore pressure \( p \), saturation \( s \), mechanical volumetric strains \( \varepsilon \). The response equation for the pore fluid is formulated as (Eq. (14)) (Keith et al. 1982):
| Type   | Density (kg × m⁻³) | Natural cohesion (kPa) | Natural friction angle (°) | Saturated cohesion (kPa) | Saturated friction angle (°) | Shear modulus (Pa) | Permeability coefficient (m/s) | Porosity |
|--------|-------------------|------------------------|---------------------------|--------------------------|-----------------------------|---------------------|--------------------------------|----------|
| CDH    | 1980              | 35.7                   | 38.0                      | 6.7                      | 8.5                         | 1.5e6               | 3e−5                           | 0.32     |
| Bedrock| 2201              | 2000                   | 32                        |                          |                             | 2.3e10              | 5e−10                          | 0.24     |
where $M$ is the Biot modulus (N/m²), $n$ is the porosity, and $\alpha$ is the Biot coefficient.

After modifying the saturated fluid-flow equation, we obtain the unsaturated fluid-flow equation in coarse soils (constant air pressure and no capillary pressure). The nodal volumetric flow rates in a zone $Q_z$ are multiplied by relative mobility, $\hat{k}$ (see equation), which is a function ($\hat{k}(\hat{s}_{in}) = \hat{s}_{in}^2(3 - 2\hat{s}_{in})$) of the average saturation at the inflow nodes for the zone, $\hat{s}_{in}$. The gravity term $\rho_f x_i g_i$ is multiplied by the average zone saturation to account for partial zone filling. Nodal inflow rates are scaled according to local saturation. For unsaturated fluid flow, the nodal volumetric flow rates in a zone $\{Q_z\}$ are related to the nodal pore pressures $\{p\}$, which is expressed in matrix notation as (Eq. 15):

$$\{Q_z \hat{k}\} = [M]\{p - \rho_f x_i g_i \}$$

As some updated physical and mechanical properties of soil are not considered in this finite-difference software, the sliding surface is not affected by pore pressure (Schiliro et al. 2015; Li et al. 2020). In this simulation, we find the sliding surface strength parameters 'c' and 'φ' with saturation according to Yang et al. (2014) and Kabwe et al. (2020), which are updated every 100-time steps. During the simulation, saturation, pore water pressure, and displacement of different points in the CDH were monitored.

$$\lg c = k_1 s + k_2$$

$$\lg \phi = k_3 s + k_4$$

where $c$ is the cohesion (Pa), $k_n$ are the coefficients, $s$ is the saturation, $s > 0.2$.

### 3.4 Debris-flow mechanism and calculation of motion feature parameters

The density of debris flow was calculated based on the clay content obtained from the soil sieve analysis. We used the empirical correlation of viscous debris-flow velocity to calculate the flow velocity at different cross sections based on cross-sectional investigation (topographic surveys). We obtained debris-flow discharges at different cross sections by combining the cross-sectional features. According to the motion time of debris flow obtained from the survey, we used the corrected pentagon method to calculate the total volume and solid volume of debris flow.

The density calculation method based on clay content is used to determine debris-flow density (Li et al. 2018) (Eq. 18):

$$\gamma_c = -1.32 \times 10^3 x^3 - 5.13 \times 10^2 x^6 + 8.91 \times 10^2 x^5 - 55x^4 + 34.6x^3 - 67x^2 + 12.5x + 1.55$$

where $\gamma_c$ is the density of debris flow (g/cm³); $x$ is the percentage of clay particles (<0.05 mm) in the total content of particles (<60 mm) in the debris-flow deposits.

The flow velocity of debris flow was calculated by the cross-sectional investigation. During the investigation, many drop weirs, tortuous channels, and obstructions were observed, which were analysed as high resistance viscous debris flow, and hence, the calculation formula is Eq. (19) (The Geological and Mineral Industry Standard of the People’s Republic of China 2018).
where $n_c$ is the roughness coefficient, $H_c$ is the flow depth (m), and $I_c$ is the hydraulic gradient.

By combining the flow velocity with the cross-sectional area, we obtained the discharge (Eq. 20):

$$Q_c = A_{sc} \times V_c$$

(20)

where $A_{sc}$ is cross-sectional area (m$^2$) and $V_c$ is the velocity of debris flow of the section (m/s).

We calculated the total volume of this continuous debris flow, and the modified Pentagonal method was used for the calculation (The Geological and Mineral Industry Standard of the People’s Republic of China 2018). According to the process time $T$ and the maximum flow $Q_c$ of debris flow, a total volume of the debris flow $W_c$ is calculated by $W_c = KTQ_c$, $K=0.0378$. The solid volume of debris flow is calculated as follows (Eq. 21):

$$W_s = (\gamma_c - \gamma_w)W_c/ \left(\gamma_s - \gamma_w\right)$$

(21)

where $W_s$ is the solid volume of debris flow passed through the calculated section (m$^3$), $\gamma_w$ is the density of water (N/m$^3$), $\gamma_c$ is the density of debris flow (N/m$^3$), and $\gamma_s$ is the density of solid matter (N/m$^3$).

### 4 Features of debris flow in the Chenghuangmiao Gully

#### 4.1 Features of debris-flow disaster

The Chenghuangmiao Gully debris-flow disaster was a massive low-frequency viscous continuity delayed debris-flow event in a small watershed (Table 2).

The Chenghuangmiao Gully debris flow is recognised as a disaster resulting from geological process controlled by spatial distribution and temporal evolution features. The horizontal and longitudinal sections of the Chenghuangmiao Gully show that it can be divided into the CDH landslide at the gully source, initiation–transition area, and accumulation area (Fig. 4). After spatiotemporal analysis, we obtained the accumulation and motion features of debris flow and the dynamic features of landslides at the origin of the debris flow (the initiation process of debris flow).

#### 4.2 Accumulation features of debris flow

The debris flow experienced approximately 25 min of accumulation. After approximately 3200 m$^3$ of debris-flow solid material was washed into the Xiaojinchuan River, the debris-flow accumulation body of approximately 369.2 m in length, 198.3 m in width, 3222.8 m$^2$ in area, 1.4–6.7 m in thickness, 159% in longitudinal gradient, and 18,100 m$^3$ of solid volume (Fig. 5a–c) was formed. The deposits in the accumulation body were composed of slate and schist fragments and clay. The deposits were well sorted, with 2.35% clay content, and the maximum boulder size was 3.0×2.7×1.8 m (Figs. 5b and 6).
Table 2  Parameters of debris flow in the Chenghuangmiao Gully

| Features | Watershed (m³) | Peak discharge at mountain pass (m³/s) | Frequency (year/once) | Density (g/cm³) | Delay behind rainfall stop (h) | Death (person) |
|----------|----------------|----------------------------------------|-----------------------|-----------------|-------------------------------|----------------|
| Value    | 6.10           | 290.4                                  | 1%                    | 1.807           | 3.67                          | 4              |
| Property | Small          | Massive                                | Low frequency         | Viscosity       | Delayed                       | Disaster       |
Fig. 4 Plan and longitudinal section of the Chenghuangmiao Gully: a CDH landslide at the source of the Chenghuangmiao Gully; b transition area; c accumulation area

Fig. 5 Accumulation area: a accumulation area; b damaged houses; c altitude image

Fig. 6 Debris-flow accumulation particle curve
4.3 Motion features and process of debris flow

The debris in the Chenghuangmiao Gully had a high density. There was an increase in the initial velocity of debris flow with a subsequent decrease and a slow increase in its discharge. The motion feature parameters were obtained through cross-sectional investigations, laboratory tests, and theoretical model calculations. By incorporating 2.35% of clay content into the empirical correlation, we obtained a bulk density of 1.807 g/cm$^3$ for the debris flow. Based on maximum mud-mark height (flow depth) and gully-bed gradient obtained from the investigation of the debris-flow gully, the viscous debris-flow velocity calculation formula (Eq. 19) was used to obtain the debris-flow peak velocity of 3.39–5.20 m/s (Table 3). Based on the cross-sectional area obtained by the cross-sectional survey, the debris flow at different cross sections was calculated by (Eq. 20). The peak debris flow was 57.6–290.4 m$^3$/s, with the maximum occurring at the mountain pass (Fig. 7 and Table 3). Applying the modified Pentagon method $W_c = KTQ_c$ and (Eq. 21) to calculate the total volume of debris flow, the total volume of the debris flow $W_c$ was approximately 43,995.6 m$^3$, and the solid volume $W_s$ was approximately 21,260.2 m$^3$. According to the investigation results, the total process time of debris flow was 25 min, and the watershed

| Number | Section position | Hydraulic gradient | Flow depth (m) | Area (m$^2$) | Velocity $v_c$ (m/s) | Peak discharge (m$^3$/s) |
|--------|------------------|--------------------|----------------|-------------|---------------------|------------------------|
| 1      | 102°10′38.16″, 30°59′18.56″ | 0.68               | 2.1            | 17.0        | 3.39                | 57.6                   |
| 2      | 102°10′36.11″, 30°59′20.71″ | 0.68               | 2.3            | 18.5        | 3.69                | 68.3                   |
| 3      | 102°10′31.71″, 30°59′24.50″ | 0.82               | 2.5            | 18.0        | 4.06                | 77.2                   |
| 4      | 102°10′16.14″, 31°0′23.00″ | 0.34               | 4.6            | 29.1        | 4.15                | 120.5                  |
| 5      | 102°10′21.36″, 31°0′26.24″ | 0.29               | 5.2            | 34.2        | 4.15                | 141.9                  |
| 6      | 102°10′31.16″, 31°0′49.05″ | 0.21               | 7.2            | 53.5        | 4.39                | 234.9                  |
| 7      | 102°10′31.67″, 31°0′49.63″ | 0.55               | 4.5            | 49.2        | 5.20                | 255.6                  |
| 8      | 102°10′32.73″, 31°1′51.22″ | 0.27               | 6.2            | 58.0        | 4.68                | 270.9                  |
| 9      | 102°10′32.35″, 31°1′53.09″ | 0.36               | 4.3            | 66.2        | 4.39                | 290.4                  |
area was 6.1 km². The gully bed was rough, and its average gradient was 375‰; hence, $K = 0.0378$ and $1/n_c = 2.57$ in Eq. (19).

The motion of debris flow in the main gully was a gradually increasing discharge process that required approximately 19.5 min. From section ① (approximately 0.01 km away from the CDH confluence outlet) (Fig. 8) to section ⑨ (at the mountain pass), the discharge slowly increased from 57.6 to 270.4 m³/s. Combined with the average velocity of 4.23 m/s and the gully length of 4.95 km, the time of the debris flow was calculated to be approximately 19.5 min.

Between section ④ (approximately 2 km away from the outlet of the CDH confluence) and section ⑦ (approximately 3 km away from the outlet of the CDH confluence), the discharge process line became steeper (discharge increased from 141.9 to 234.9 m³/s). By combining the increase in the hydraulic gradient observed by the two sections (increased from approximately 340% to approximately 550%), the expansion of the sectional area, and the rise in the thickness of the loose deposits, we found that the increase in discharge was due to an increase in the hydraulic gradient and material sources. The debris flow in the Chenghuangmiao Gully was not limited or blocked (Fig. 7).

4.4 Features of the CDH landslide at the origin of debris flow

The CDH landslide at the origin of debris flow was a small shallow soil landslide. The landslide was located at the outlet of the CDH confluence area (102°10′38.16″ and 30°59′18.56″) at an altitude of 4060 m (Fig. 8a). The slide body was composed of crushed rock and soil. The length, width, thickness, area, and volume of the slide body were 25.0 m, 12.3 m, 1.1–1.8 m, 296 m², and 362 m³, respectively. The angle between the sliding direction (337°) and bedrock inclination (3°) was 26°. The sliding surface was the interface between bedrock and deposits. The trailing edge was 7.7 m long, and the slope was 45° (Fig. 8b–g). The bedrock was located on the slide bed at an angle of 3° < 66°. Slate and
schist alternately appeared; the slate was bent, sericite was observed on the layer, scratches were developed, schist joints were broken, and the water flowed along with the schist layer towards the toe of the CDH (Fig. 8b–d). The hole of the CDH confluence outlet was located at the junction of the rear edge and the left boundary. The soil on the upper part of the outlet had not sunk owing to the development of moss. The outlet hole was 2.4 m wide; the highest was at 0.8 m, whereas the lowest was at 0.5 m and the cross-sectional area was 1.56 m² (Fig. 8c). With the downward sliding of the landslide, a bedrock block appeared on the landslide’s right boundary, which decreased by 4.8 m horizontally, and the left boundary of the landslide widened by 2.1 m southwest (Fig. 8e).

5 Initiation of delayed debris flow

The initiation of debris flow was delayed by the landslide process of the CDH at the back-end confluence. Rainfall primarily converged into the CDH in the form of surface and subsurface runoff. Under the effect of water infiltration, the saturation and pore pressure of the CDH increased, the intensity decreased, and instability occurred, resulting in the landslide and initiating the debris flow. The whole process required 9 h 20 min from 18:00 h on 5 July 2020 to 03:20 h on 6 July 2020.

The causes of the debris flow in the Chenghuangmiao Gully 3 h 40 min after the rainfall stopped are as follows: rainfall and confluence infiltrations during the rainfall could not sufficiently increase the pore pressure of the CDH, thereby weakening it to cause instability. The seepage process continued for 3 h 20 min inside the CDH after the rainfall stopped. That was sufficient to increase the pore pressure of the CDH and reduce its strength causing instability, thereby initiating the debris flow.

5.1 Surface runoff and subsurface flow mechanism at the back end of the CDH

The back-end confluence was the rainfall entering the CDH in the form of surface and subsurface runoff. The effective rainfall amount that was transformed into surface and subsurface runoff before the disaster was 32%. The confluence lasted approximately 5.76 h; the peak flow was 0.125 m³/s at 21:42 on 5 July 2020, and the rest of the rainfall was intercepted and evaporated by moss litter and others.

The above data were obtained by the following calculation or empirical method: (1) Using the SCS model to calculate the effective rainfall (17 mm) from 18:00 to 24:00 h on 5 July 2020 produced a total surface runoff of 2.729 mm, that is, surface runoff accounted for 16.05% of the total rainfall (Eqs. 1 and 2); (2) Based on the rational formula (Eqs. 3–11), the 5 h peak flow and runoff time were obtained (Table 4); (3) By combining 16.05% runoff yield ratio, peak flow, and runoff time, the pentagon process line was used to generalise the surface-runoff process per hour, and then, the surface runoff flow process line was obtained; (4) According to the results of the experimental research on surface and subsurface runoff conducted by Li et al. (2010), the process of subsurface runoff was similar to the process of surface runoff, and the delay was 26.5 min in the study area (Li et al. 2010; Zhang et al. 2015); subsequently, we obtained the subsurface-runoff process line according to the surface-runoff process line; (5) By superimposing the surface-runoff process line and the subsurface-runoff process line, the runoff process of the confluence at the back end of the CDH was obtained (Fig. 9a); (6) Based on the research of Ye et al. (2004), the interception of the moss litter layer with a thickness of 9.8 cm in the study area accounted for
approximately 42% of the total rainfall (Ye et al. 2004; Wang et al. 2010). Finally, the pie chart of the rainfall distribution was prepared (Fig. 9b).

### 5.2 Initiation of debris flow induced by CDH landslide

The debris flow was initiated by an increase in the pore water pressure of the CDH and a decrease in its strength following the confluence and rainfall infiltration, and the CDH landslide entered the accelerated deformation stage. The rainfall from 18:00 to 24:00 h on 5 July 2020 caused surface and subsurface runoff to continuously converge into the CDH; on saturation, the CDH expanded rapidly along with the base interface to the leading edge, increasing the pore pressure of the soil near the base interface. The rain stopped from 00:00 to 03:20 h on 6 July 2020, and the expansion of the saturation range of the CDH became slower, and eventually, it saturated the soil near the leading edge and base interface, thereby decreasing the soil strength, causing the CDH landslide, and subsequently initiating the debris flow.

The changes in soil saturation, pore water pressure, and displacement reflected the changes in the soil’s state. Saturation at Point 1 in the trailing edge of CDH, Point 2 in the near-surface of the middle part of CDH, and Point 3 in the near base interface of the middle part of CDH increased first and then remained stable. Point 3 reached saturation first. Saturation at Point 4 is increasing throughout the process, and the range of saturation expanded, and at approximately 03:20 h the saturation at each point increased sharply (Figs. 10a, 11a–c). The changes in pore pressure and saturation were similar. Pore pressure at Point

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**Table 4** Results of the calculations of confluence parameters using the rational formula

| Time (h) | Peak discharge $Q_p$ (m$^3$·s$^{-1}$) | Surface runoff (m$^3$) | Runoff generation time $\tau_c$ (h) | Confluence time $\tau$ (h) |
|----------|--------------------------------------|-------------------------|------------------------------------|-------------------------|
| 19:00    | 0.0069                               | 33.56                   | 0.035                              | 2.029                   |
| 20:00    | 0.0000                               | 0.00                    | 0.000                              | 0.000                   |
| 21:00    | 0.0157                               | 51.33                   | 0.064                              | 1.651                   |
| 22:00    | 0.1141                               | 150.04                  | 0.236                              | 0.935                   |
| 23:00    | 0.0538                               | 96.73                   | 0.162                              | 1.210                   |
| 24:00    | 0.0001                               | 0.98                    | 0.002                              | 5.864                   |
increased the fastest, from 0.0 kPa to 7.2 kPa, whereas that at the other points increased slowly and decreased sharply at approximately 03:20 h. Throughout the process, the value of pore pressure increased and the range of positive pore pressure increased (Figs. 10b, 11e–g). These changes in saturation and pore pressure caused the near base interface part of the CDH to become the main seepage channel. The seepage channel caused the continuous infiltration in the leading edge of the CDH. The strength at the leading edge and the soil near the base interface of the CDH reduced resulting in the landslide. The displacement of the monitoring points shows the landslide instability and deformation that initiated the debris flow. The displacement of each point of the CDH exhibited an increasing trend during and after the rain stopped and increased by 0.03, 0.25, 0.26, 0.26 m, respectively, at the four points at 02:00 h on 6 July 2020. After 02:00 h on 6 July 2020, the displacement at each point increased sharply. The rate of displacement at each point from 02:18 to 02:50 h decreased slightly, and the displacement curve exhibited a stable and rapid increase from
02:50 to 03:20 h (Figs. 10c, 11g–i). According to (Tavenas and Leroueil 1981; Azimi et al. 1988), we divided the stages of slope deformation and failure. Evidently, the initial deformation stage occurred from 02:00 to 02:18 h, the secondary deformation stage occurred from 02:18 to 02:50 h, and the accelerated deformation stage occurred from 02:50 to 03:20 h.

The debris flow reached the gully mouth at 03:40 h during filed investigation, and the debris flow required 19.5 min by calculation; hence, the debris flow was initiated at approximately 03:20 h. Therefore, the accuracy of the simulation was verified.

6 Conclusions and discussions

Since 18:00 h on 5 July 2020, rainfall converged into the CDH in the form of surface and subsurface runoff. The pore pressure of the CDH increased and its strength decreased (Fig. 12a). At 02:00 h on 6 July 2020, the CDH exhibited conspicuous deformation signs and entered the initial deformation stage of the landslide (Fig. 12b). At 03:20 h on 6 July 2020, the displacement of each point of the CDH increased sharply, the CDH landslide entered the accelerated deformation stage, and the debris flow was initiated. At 03:40 h on 6 July 2020, viscous debris flow experienced a gradual increase in its discharge motion for approximately 19.5 min, reaching Yuanying Village, Xiaojin County (Fig. 12c). At 04:05 on 6 July 2020, the debris flow that lasted for 25 min ended, causing 4 deaths and 27 injuries (Fig. 12c).

We studied the delayed debris flow that occurred recently in the Chenghuangmiao Gully at Aba Prefecture of Sichuan Province. Through field investigations, laboratory tests, theoretical calculations, and fluid–solid coupling numerical simulation based on Biot theory, the motion features and the initiation of the debris flow were analysed based on surface and subsurface runoff (at the back end), and the instability and landslide process of the CDH. The following conclusions were drawn.

(1) The Chenghuangmiao Gully debris-flow disaster was a giant viscous continuous delayed low-frequency debris-flow disaster in a small watershed. The density of the debris flow was 1.807 g/cm$^3$, which analytically occurs only once in a century. The maximum velocity of the debris flow was 5.2 m/s, max discharge at the mountain pass was 290.4 m$^3$/s, and debris-flow volume was approximately 44,000 m$^3$.

(2) The CDH landslide at the source of the Chenghuangmiao Gully was a small shallow soil landslide. The sliding direction of the landslide was 337°, and its sliding surface was the base interface; it had an area of 296 m$^2$, with the sliding volume being 362 m$^3$.

(3) The initiation of debris flow was represented by the delayed landslide process of the CDH under the influence of back-end confluence. Rainfall flowed into the CDH in the form of surface and subsurface runoff. The pore pressure of the CDH increased, whereas its strength decreased. The CDH landslide entered the accelerated deformation stage to initiate debris flow. The whole process required 9 h and 20 min.

(4) The motion of debris flow in the main gully represented a process that slowly increased discharge, which required approximately 19.5 min.

(5) Rainfall and confluence infiltration were insufficient to reduce the pore pressure and increase the instability of the CDH, thereby causing the delay in debris flow. After the rainfall stopped, the seepage process continued for 3 h 20 min inside the soil, and it
Fig. 12 Evolutionary process of the delayed initiation of Chenghuangmiao debris flow: a rainfall and runoff process; b seepage and deformation of the CDH landslide, the initiation of the debris flow; c transition and accumulation of the debris flow.
increased the pore pressure of the soil sufficiently and reduced the strength of the CDH to initiate the debris flow.

We changed the cohesion and internal friction angle in the numerical model, monitored the time when the maximum displacement of CDH reaches 120 mm, and compared the time consumed under different cohesion and internal friction angle. The maximum displacement of 120 mm is selected as the judgement index because when the maximum CDH displacement reached 120 mm under the original parameters, the soil displacement suddenly changed and entered the accelerated deformation stage. As Fig. 13 shows, with the increase in internal friction angle or cohesion, the time consumed for the CDH landslide in the accelerated deformation stage increased.

The evacuation of personnel from vulnerable areas should be the focus of the prevention and mitigation process of a debris-flow disaster event. There is a need to perform a comprehensive disaster investigation, provide measures for active prevention, identify and control hidden danger points, achieve passive relocation, and continuously monitor debris-flow confluence area (Shimizu area), which can effectively reduce the losses caused by delayed debris flow. Debris-flow gully in the confluence area (Shimizu area) should be studied. After identifying the hidden dangers of geological disasters and assessing the disaster risks, timely, preventive, and passive avoidance measures must be undertaken. When rainfall occurs at the hidden point and disappears for a few hours, it is necessary to continuously monitor the debris-flow source area and confluence area (Shimizu area) afterward, and issue early warnings in time. Finally, the management and control of evacuation measures should be strengthened to ensure the cessation of human activity within the danger zone before the disaster occurs.

There are some limitations and uncertainty associated with the methodology and results, and these are also our prospects for future work. In terms of methodology, there are some empirical coefficients in the empirical correlations and rational formulas for calculating rainfall runoff. These empirical coefficients are calculated based on the monitoring data of rainfall runoff in Sichuan Province, which has geographical limitations and cannot

![Parameter sensitivity analysis of the numerical simulation](image)

Fig. 13 Parameter sensitivity analysis of the numerical simulation
be applied to areas except Sichuan. A (fluid–solid coupled) model for the decrease in soil strength parameters with the increase in saturation is used in the numerical simulation. However, in the actual process, under the influence of seepage force and pore pressure, the change in soil strength with saturation will be more complex. In terms of results, the results emphasised the delay mechanism of debris flow induced by the CDH landslide (shallow landslide). Combined with specific cases, the whole process of the delayed disaster was reconstructed, and many quantitative data and explanations regarding the whole process were provided. However, the lack of support from more cases enabled us to quantitatively determine the duration of occurrence of disaster after the rainfall.

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**Data availability** The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

**Code availability** The codes used during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Conflict of 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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