

Inverse Analysis of Initiation Process and Disaster Range Debris Flow Based on CDEM

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Received: September 5, 2025, Accepted: November 10, 2025

Abstract: The formation process of rainfall-type debris flow is a complex nonlinear process of hydraulic coupling. Based on on-site investigation and data collection, this article analyzes the formation conditions of the Wenjiagou debris flow. Based on the CDEM, the finite volume method of depth integration was used to conduct an inversion analysis of the initiation and deposition process of the "8-13" debris flow. The results show that when the friction angle is 8° and the cohesion is 50Pa, the sediment concentration reaches 15% and a debris flow initially forms one hour after the rainfall. The deposition area is basically consistent with that of the "8-13" debris flow when the comprehensive friction coefficient was 3°.

Keywords: Debris flow, Mechanical simulation, Initiation process, Deposition area, Wenjiagou.

Introduction

The initiation process and hazardous extent of rainfall-induced debris flows are of great significance for debris-flow forecasting and early warning. On August 12, 2010, at 18:00, an intense rainstorm occurred in Qingping Township, Mianzhu City, triggering a catastrophic debris-flow event (Tang et al. 2012; Huang, 2009; Xu, 2010). Among all affected gullies, the Wenjiagou debris flow exhibited the largest scale and caused the most severe damage, ranking as the largest single-gully debris flow ever recorded in China since the founding of the People's Republic.

Based on comprehensive field investigations, data collection, and geological condition analyses, this study employed the CDEM mechanical analysis software to investigate the formation conditions, rainfall-triggered initiation process, and affected range of the Wenjiagou debris flow. The findings provide valuable insights for future debris-flow prevention, mitigation, and monitoring in this region.

Methodology

The entire evolutionary process of debris-flow hazards was simulated using CDEM software. The core theoretical framework is a vertically integrated, multi-process coupling approach that simultaneously accounts for the interactions among rainfall, flooding, debris-flow motion, and erosion–deposition processes. During the initiation stage, the Mohr–Coulomb model

was applied to determine the shear failure of the accumulated materials. Once failure occurred, the loosened deposits entered the flowing water and were transported downstream with the flow. The Mohr–Coulomb failure criterion for the slope element of the accumulated material can be expressed as follows.

$$(\rho_b g h_s \cos \theta + \rho_w g h \cos \theta - p_{bed}) \tan \phi_b + h_s \frac{\partial}{\partial x_i} (\rho_s g h_s \cos \theta) + c_b = (\rho_b h_s + \rho_w h) g \sin \theta \quad (1)$$

where h and h_s denote the water depth and the thickness of the deposited material, respectively; ρ_s and ρ_w represent the densities of the sediment and water; g is the gravitational acceleration; θ is the slope angle; p_{bed} is the pore-water pressure at the bed; c_b and ϕ_b are the cohesion and internal friction angle of the deposited material; and x_i ($i = 1, 2$) are the coordinates in the x - and y -directions, respectively.

In simulating the propagation and disaster-forming processes of the debris flow, a mechanical model based on the Savage–Hutter theory, incorporating the entrainment effect, was adopted.

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = S_f + S_e \quad (2)$$

where $U = (h, hu, hv)^T$ denotes the vector of conserved variables.

$$F = \left(hu, hu^2 + \frac{1}{2} g_z h^2, huv \right)^T \text{ and}$$

$$G = \left(hv, hv^2 + \frac{1}{2} g_z h^2, huv \right)^T$$

are the flux vectors in the x - and y -directions, respectively.

$$S_f = \left(0, g_x h - g_z h \frac{\partial z_b}{\partial x} - \tau_{bx}, g_y h - g_z h \frac{\partial z_b}{\partial y} - \tau_{by} \right)^T$$

and $S_e = (E, uE, vE)^T$

represent the topographic–friction source term and the entrainment source term, respectively.

Here, E is the entrainment rate, defined as,

$$E = \frac{1}{\rho} \frac{\tau_f - \tau_b}{\sqrt{u^2 + v^2}} \quad (3)$$

where τ_f and τ_b denote the fluid-induced force and the basal resisting force, respectively.

Results

Based on the back-analysis results, when the internal friction angle of the loose source material was set to 8° and the cohesion to 50 Pa, a large-scale debris flow occurred in the Wenjiagou catchment. Under this parameter combination, the simulated distributions of debris-flow concentration, flow velocity, and flow depth after 1 hour of rainfall are shown in Figure 1. After one hour of rainfall, most areas within Wenjiagou exhibited sediment concentrations exceeding 15%, indicating the formation of a relatively stable debris flow. The overall transport velocity of the debris mixture exceeded 3 m/s, with the local flow depth reaching more than 5 m.

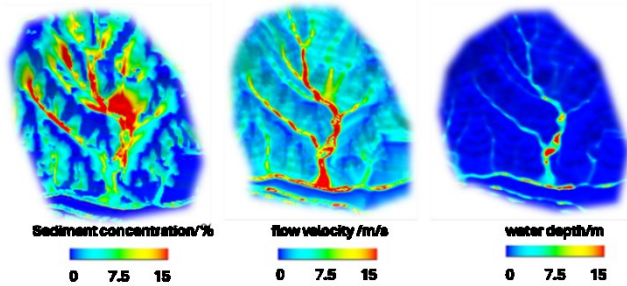


Figure 1, Sediment concentration, water velocity and water depth in Wenjiagou after one hour of rainfall.

After approximately 1500s of rainfall, the soil mass became saturated, and surface runoff gradually developed along the slope. When the rainfall reached 3600s, at this stage, the flow velocity ranged between 2 and 5 m/s. Considering the frictional interaction between the debris-flow fluid and the bed surface during motion, the simulation results show that when the comprehensive friction angle is set to 3° , the predicted affected area closely matches the actual disaster extent of the “8-13” Wenjiagou debris flow (Figure 2). After approximately 104 s of rainfall, a depositional fan had formed at the gully outlet, and the Mianyuan River was nearly blocked, with a small portion of the debris flow moving toward the opposite bank. When the elapsed time reached 173 s, the debris-flow movement had largely ceased (Figure 3).

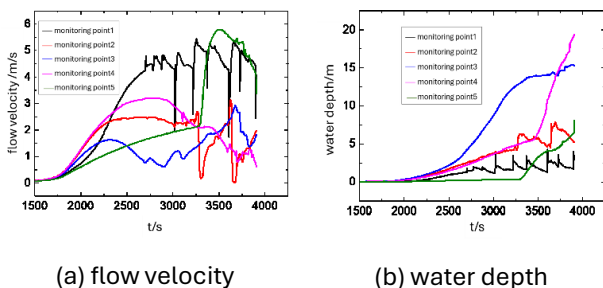
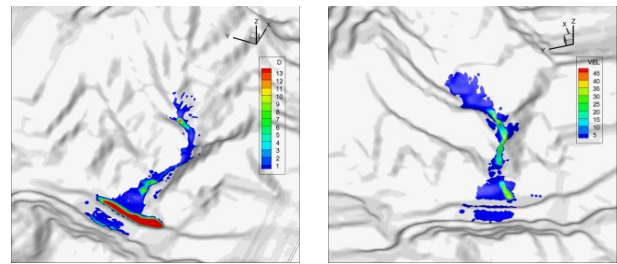


Figure 2, Flow velocity and flow depth in Wenjiagou during continuous rainfall.

Conclusion

(1) When the internal friction angle of the loose source material was set to 8° and the cohesion to 50 Pa, a large-scale debris flow occurred in the Wenjiagou catchment.

Under this parameter configuration, after one hour of rainfall, the sediment concentration reached 15%, the overall transport velocity of the debris mixture exceeded 3 m/s, and the local flow depth was greater than 5 m, indicating that the debris flow had been largely formed.



(a) deposition depth (unit: m) at 173s (b) movement velocity at 173s (unit: m/s)

Figure 3, Deposition depth and movement velocity of debris flow under 3° comprehensive friction angles.

(2) Among five different friction angles, the simulation with a comprehensive friction angle of 3° produced a disaster range that closely matched the actual affected area of the “8-13” Wenjiagou debris flow. At 52 s, the debris flow front reached the outlet, attaining a maximum velocity of approximately 45 m/s. By 100 s, the depositional fan at the outlet was nearly formed, and by 173 s, the movement of the debris flow had essentially ceased, completely blocking the Mianyuan River.

Acknowledgement

This research was supported by National Key Research and Development Program Project grant: 2023YFC3007200.

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