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Effects of fluid conditions and particle size on the post-failure mobility of fluid–solid coupled landslides

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Fluid–solid interactions play an important role in the post-failure mobility of high-elevation, long-runout landslides; however, the respective effects of fluid conditions and particle size remain difficult to distinguish. Taking the Shuicheng landslide that occurred in Guizhou Province, China, on 23 July 2019 as a case study, this study employed the three-dimensional landslide post-failure numerical platform (LPF3D), incorporating an SPH–SDPH two-phase formulation, to investigate 13 cases with varying fluid volume fractions, fluid properties, and equivalent solid-particle sizes. The results indicate that landslide motion reflects the dynamic interaction between fluid-induced drag and solid-particle inertia, involving continuous spatiotemporal overlap, competition, and transformation between the two effects. Increasing the fluid volume fraction causes positive drag to develop earlier and over a wider area, thereby sustaining material transport even when the instantaneous peak drag is not the highest. Among the tested fluid-property combinations, water generates the highest short-duration velocity peak, low-viscosity mud provides more persistent driving effects, whereas high-viscosity mud induces stronger damping and promotes localized deposition. Smaller particles experience greater drag per unit mass, while larger particles retain stronger inertia under viscous conditions. These findings provide a reference for understanding and assessing the complex dynamic processes of similar fluidized landslides.

Keywords Fluid–solid coupled landslides, Post-failure mobility, Particle-size effect, Interphase drag, SPH-SDPH method

Introduction

Ongoing changes in the global climate and environmental conditions have led to considerable impacts on the geological environment, particularly through the alteration of rainfall patterns and the rising frequency of extreme weather events, which contribute to the frequent occurrence of fluid–solid coupled landslides. These high-elevation, long-runout fluid–solid coupled landslides pose significant threats to human life and property and occur frequently in the mountainous regions of southwest China^{1,2}. Representative events include the 2010 Dazhai landslide in Guanling, Guizhou^{3–5}, the 2013 Sanxi Village landslide in Sichuan^{6–8}, and the 2025 landslides of Dafang as well as the Sandu Monkey River Bridge in Guizhou. At 21:20 on July 23, 2019, a catastrophic long-runout landslide occurred in Jichang Town, Shuicheng County, Liupanshui City, Guizhou Province. The disaster resulted in 43 fatalities, left 9 people missing, and caused direct economic losses of approximately RMB 190 million, drawing widespread attention from researchers and the public alike^{9–14}.

Fluid–solid coupled landslides are typically triggered by the rapid infiltration of substantial surface runoff or water infiltrating into the deeper parts of the sliding mass, which significantly disturbs the original stress field and structural

integrity and transforms the failure mechanism from purely gravity-driven to a composite dynamic instability dominated by fluid–solid interactions. During runout, fragmentation and water mixing may transform an initially coherent slide into a fluidized multiphase mass, accompanied by expansion of the affected area^{15–18}, rapid acceleration^{16,17,19}, and intensified impact effects^{20–22}. The interphase mechanical interactions between solid particles and fluids can be classified into two fundamental modes: the seepage-dominated mechanism and the bypass-dominated mechanism. (1) In landslides that are primarily composed of fine-grained soils, seepage dominates the fluid–solid coupling process. Fluids influence the effective stress state of the soil matrix by regulating the pore water pressure, especially under conditions of rapid shear or transient loading, often leading to the generation of excess pore pressure, which weakens the shear strength and promotes sliding failure^{23,24}. (2) In debris flow systems dominated by coarse-grained materials, the primary mechanism is bypass flow. In such cases, the drag, lift, and pressure gradient forces generated by the fluid flow around the large particles serve as the key driving forces of the particle motion. These forces not only significantly reduce the overall shear resistance of the system but also promote fluidization of the sliding mass, eventually resulting in the high-speed, long-runout transport of a solid-liquid mixture^{25,26}.

Numerical simulation is widely used to analyze landslide runout and impact processes. Among the various simulation methods, equivalent fluid models (e.g., the Bingham fluid model and the Voellmy model) have been widely used to simulate the motion processes of regional landslides and debris flows due to their high computational efficiency and applicability to large-scale scenarios²⁷. However, these models cannot represent the inter-particle interactions within the landslide or capture its complex structural characteristics. To overcome the limitations of equivalent fluid models, in recent years, the coupled computational fluid dynamics-discrete element method (CFD-DEM) approach has been increasingly adopted to simulate fluid–solid interaction processes in landslides and debris flows^{28,29}. This method explicitly and discretely models solid particles and integrates CFD to continuously represent the pore fluid, thereby accurately capturing inter-particle contacts, fluid–solid drag forces, and pressure effects. However, this model is computationally intensive as it requires a fine particle resolution and small time steps, and it still faces significant limitations when applied to large-scale, real-world landslide simulations. Building on this model, the smoothed particle hydrodynamics-smoothed discrete particle hydrodynamics (SPH-SDPH) coupled model offers an alternative approach to efficiently simulating landslide flow behavior³⁰. It is particularly suitable for modeling fluid–solid interactions in highly saturated and fluidized landslides (e.g., debris flows and mudflows), and it has been demonstrated to have a high accuracy in capturing relative fluid–solid motions and shear-induced damage while significantly improving the computational efficiency.

In this study, we considered the Shuicheng landslide in Liupanshui City, Guizhou Province, as a case study and employed the three-dimensional landslide post-failure numerical platform (LPF3D) in conjunction with the SPH-SDPH coupled model to simulate the dynamic behavior and impact range of the landslide under various working conditions, including different fluid volume fractions, fluid material properties, and equivalent solid-particle sizes. We focused on the kinematic characteristics and fluid–solid interaction effects of fluid–solid coupled landslides. Specifically, the analysis compares runout geometry, solid-particle velocity, volume fraction, and drag-force evolution to clarify whether extended mobility is more closely associated with peak drag or with the timing, spatial extent, and persistence of interphase momentum exchange.

Geological setting

Geographic location and topography

The study area lies in Shuicheng County, northeastern Wumeng Mountains, between the eastern Yunnan Plateau and the Qianzhong Plateau–Guangxi Hills. Terrain is high in the northwest and low in the southeast, with a central mountain range dividing the Sancha River (Yangtze system) and Beipan River (Pearl River system). Elevations range from 1100–

2050 m (Fig. 1a). The landscape, dominated by karst landforms and erosion–tectonic features, shows steep slopes, deep valleys, and rugged relief, especially in the southeast (Fig. 1b). Tectonic activity has shaped the geomorphology, forming stepped erosion surfaces. A full view of the Shuicheng landslide is presented in Fig. 1c.

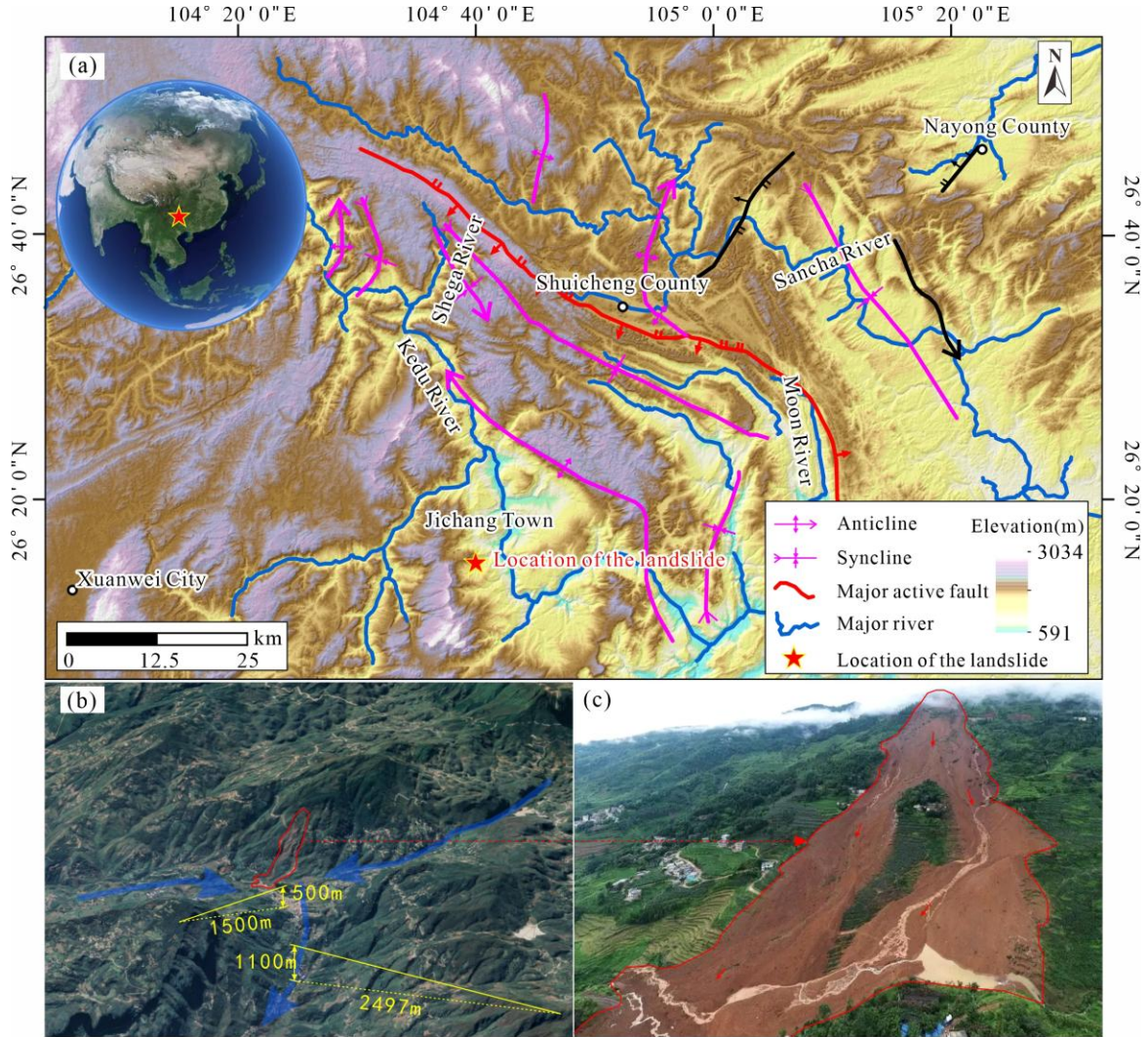


Fig. 1. Geomorphology and geologic map of the study area. (a) Geographic location of the study area. (b) Topography around the study area. (c) Full view of the landslide.

Geologic structure and stratigraphic lithology

The area where the Shuicheng landslide is located lies at the intersection of multiple structural deformation zones, and the rock mass structure is fragmented. The stratigraphic lithology of the study area comprises Quaternary gravel and clay, Triassic marl and mudstone, Permian sandstone and siltstone, and Late Permian Emeishan basalt. The Shuicheng landslide occurred within the Late Permian Emeishan basalt strata (Fig. 2a). Numerous structural surfaces are exposed, among which the two principal structural surfaces are as follows: (1) $102^{\circ}\angle 89^{\circ}$, steeply dipping toward the southeast; (2) $4^{\circ}\angle 36^{\circ}$, dipping toward the nearly north-south. Additionally, the bedding plane is oriented at $20^{\circ}\angle 41^{\circ}$, with an approximately east-west strike and a dip direction toward the northeast. These structural surfaces intersect and combine spatially, forming the primary controlling discontinuities within the sliding mass and along the slip surface (Fig. 2b–c).

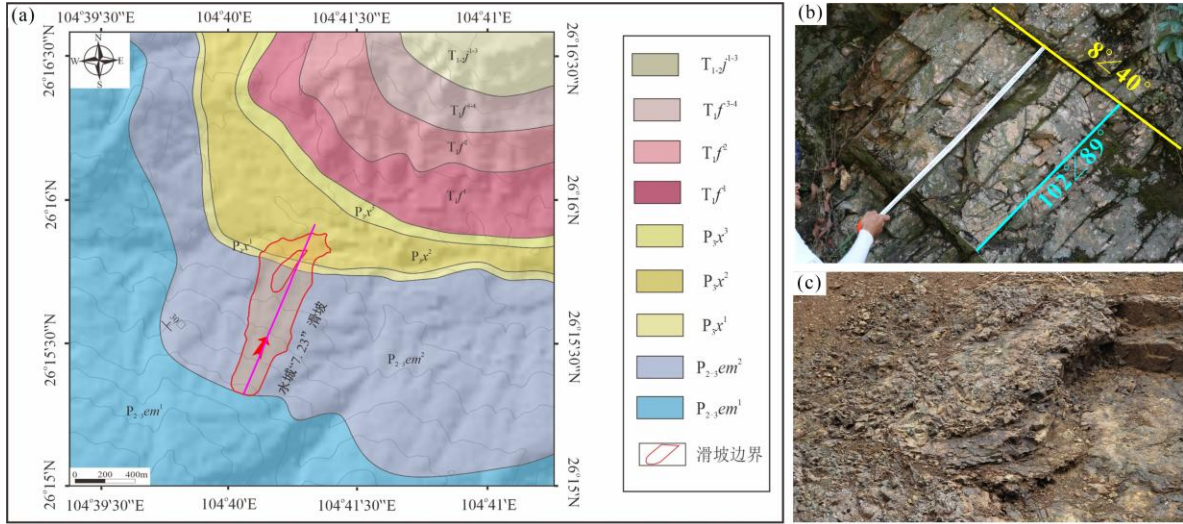


Fig. 2. Geological context and field observations at the landslide site. (a) Geological map of the study area. (b) Attitudes of the structural planes in the study area. (c) Intact bedrock prior to the landslide.

Rainfall and hydrological conditions

Landslides are closely related to heavy rainfall. June–August is the rainy season (Fig. 3a). From July 9–22, sustained rainfall greatly increased cumulative precipitation (Fig. 3b). On July 12, daily rainfall reached 83 mm, and from July 17–22, total rainfall was 153.7 mm, with a peak hourly intensity of 26.3 mm. This raised groundwater and pore pressures, weakening the rock mass. Although rainfall on July 23 was moderate, antecedent precipitation triggered the slide. Rain resumed on July 24, maintaining high surface water and secondary landslide risk. Long-term accumulation weakens rock strength, while short-term intense rainfall accelerates failure^{7,8,31}. Combined with the permeable basalt profile and slope deposits, these conditions favored failure.

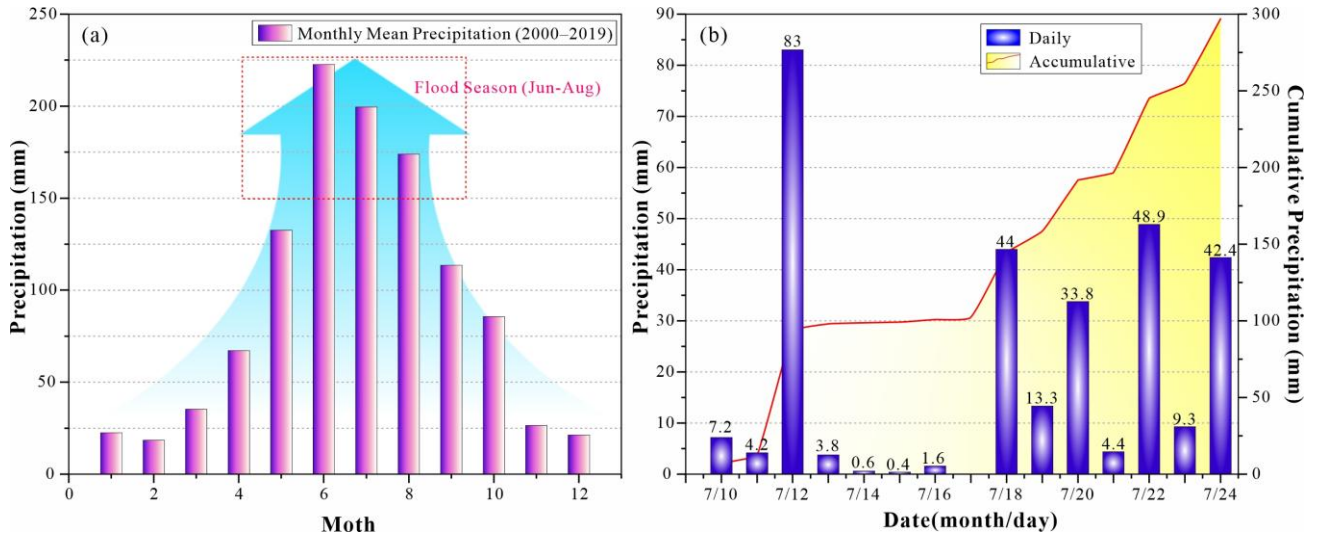


Fig. 3. Statistical diagram of the rainfall conditions in the study area. (a) Average monthly rainfall in the study area over the past two decades. (b) Antecedent rainfall during the two-week period immediately preceding the landslide disaster.

Landslide characterization

The average slope of the landslide is approximately 20°, and the slope surface generally dips gently from northwest to southeast, a configuration conducive to sliding. Columnar joints and layering of the Emeishan Basalt weakened rock integrity, facilitating transition from shear-dominated slide to fluidized movement under rainfall³². Field surveys and

drone images estimate the failed volume at $\sim 7.0 \times 10^5 \text{ m}^3$, showing high-elevation, long-runout features. Rainfall infiltration softened mudstone interlayers, initiating instability. About $5.0 \times 10^5 \text{ m}^3$ moved downslope N17°E with a 460 m drop, fragmenting and mixing with water into a two-phase flow. This scoured Quaternary deposits and weathered bedrock, splitting into two channels (N5°E and N34°E), and ultimately deposited a total volume of 2.0×10^6 cubic meters of material (Fig. 4a–f).

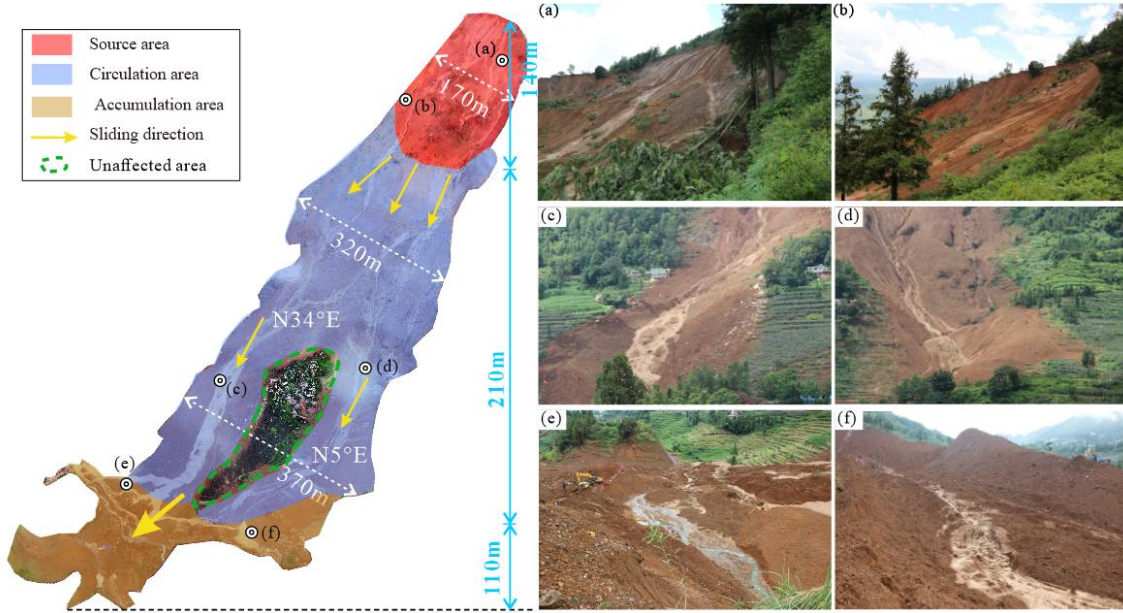


Fig. 4. Field characteristics of the landslide site. (a–b) Field photographs of the source zone. (c–d) Field photographs of the transport zone. (e–f) Field photographs of the accumulation zone.

The process involved three stages: rainfall-induced instability, fluid–solid coupled transport, and fluidized deposition (Fig. 5a–e).

(1) Rainfall-induced instability: The back edge at 1680 m and the shear outlet at 1540 m yielded a 140 m drop. The sliding mass was 10–30 m thick (avg. 15 m), $\sim 7.0 \times 10^5 \text{ m}^3$. Rainfall saturated the mass, raising pore pressure and triggering $\sim 5.0 \times 10^5 \text{ m}^3$ of movement, leaving $\sim 2.0 \times 10^5 \text{ m}^3$ in place.

(2) The outlet (1540 m) to toe (1220 m) gave a 320 m drop, avg. slope 24.5°. Intense rainfall and steep slopes caused disintegration, mixing with water, raising pore pressures, and enabling fluidization. Two-thirds of material moved N34°E, one-third N5°E, both showing fluidized transport.

(3) Ridge obstructions split flow into two paths. The main N34°E path extended 520 m (drop 110 m, slope $\sim 12^\circ$); the secondary N5°E path was 450 m (drop 180 m, slope $\sim 17^\circ$). Both converged into a fan-shaped zone, depositing coarse debris proximally and finer sediments distally. A composite deposit up to 18 m thick (avg. 10 m) covered $\sim 1.9 \times 10^5 \text{ m}^2$, forming a typical accumulation complex.

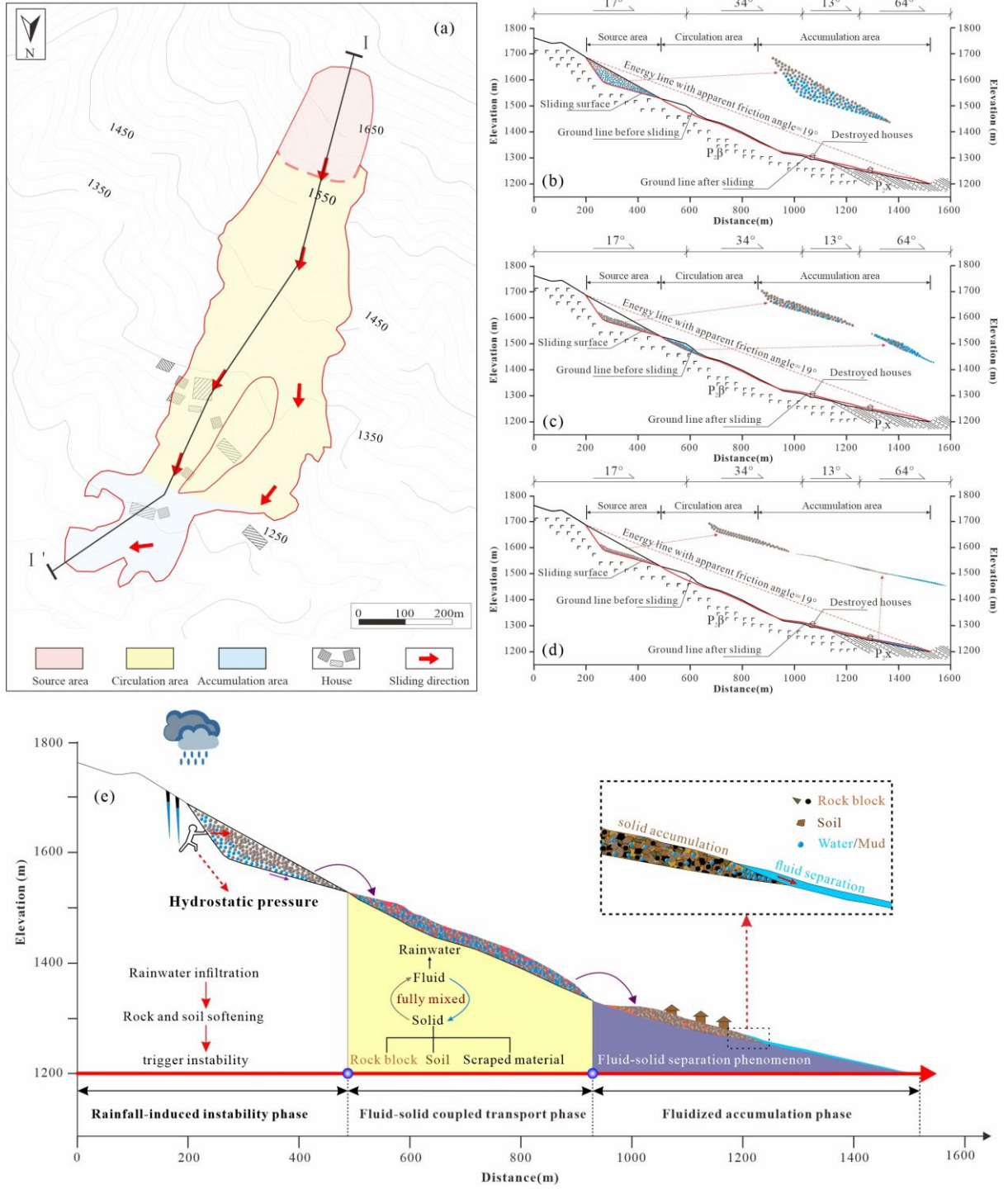


Fig. 5. Planar and profile maps of the study area. (a) Planimetric map of the study area. (b) Schematic profile of the sliding mass prior to failure. (c) Schematic profile of the sliding mass during downslope progression. (d) Schematic profile of the sliding mass in the rest state. (e) Schematic diagram of landslide failure initiation and kinematic evolution.

Numerical methodology

In this study, we employed the self-developed LPF3D platform, which integrates the smoothed particle hydrodynamics (SPH), smoothed discrete particle hydrodynamics (SDPH), and the discrete element method (DEM) to achieve fully coupled three-dimensional simulations of multiphase and multi-material landslide processes. Within the present formulation, the solid phase is represented using SDPH and the fluid phase using SPH. Interphase momentum

exchange is described using a Gidaspow-type drag treatment that combines the Ergun relation for dense conditions with the Wen–Yu relation for dilute conditions. To improve reproducibility, the essential governing equations and constitutive assumptions are summarized here, while the complete derivations and parameter definitions can be found in the relevant literature^{22,30}.

Governing equations and constitutive framework

Following the established LPF3D formulation, both phases satisfy mass and momentum conservation, and the total stress tensor is decomposed into isotropic pressure and deviatoric stress.

$$\frac{d\rho}{dt} = -\rho \frac{\partial v^\alpha}{\partial x^\alpha} \quad (1)$$

$$\frac{dv^\alpha}{dt} = \frac{1}{\rho} \frac{\partial \sigma^{\alpha\beta}}{\partial x^\beta} + f^\alpha \quad (2)$$

$$\sigma^{\alpha\beta} = -P\delta^{\alpha\beta} + \tau^{\alpha\beta} \quad (3)$$

$$P = P_0 \left[\left(\frac{\rho}{\rho_0} \right)^\gamma - 1 \right] \quad (4)$$

$$\tau^{\alpha\beta} = \mu \varepsilon^{\alpha\beta} \quad (5)$$

For the fluid phase, a weakly compressible equation of state [Eq. (4)] is used, and the Newtonian shear stress is related to the shear-strain rate by equation (5). The granular solid phase is described by a quasi-static elastic response together with an inertia-dependent frictional constitutive treatment.

In Eqs. (1)-(5), ρ is the phase mass density; t is time; d/dt is the material derivative; v^α is the α -direction velocity component; x^α and x^β are Cartesian coordinates; $\sigma^{\alpha\beta}$ is the total Cauchy stress tensor; f^α is the α -direction external body force per unit mass; P is the isotropic pressure; $\delta^{\alpha\beta}$ is the Kronecker delta; $\tau^{\alpha\beta}$ is the deviatoric shear-stress tensor; P_0 and ρ_0 are the reference pressure and reference density, respectively; γ is the weak-compressibility exponent; μ is the dynamic viscosity; and $\varepsilon^{\alpha\beta}$ is the deviatoric strain-rate tensor. Repeated Greek indices imply summation over the three spatial directions.

Fluid–solid drag and boundary conditions

The interphase drag force is calculated using the Gidaspow formulation, which combines the Ergun equation for dense phases and the Wen–Yu equation for dilute regimes, with a smooth transition between the two. The momentum exchange coefficient and the drag force per unit mass can be written in the general forms $\beta = (1 - \varphi_P)\beta_{\text{Ergun}} + \varphi_P\beta_{\text{Wen-Yu}}$ and $R_{\text{FP}} = \frac{\beta(v_f - v_P)}{\varphi_P \rho_P}$, respectively. Normal boundary interaction is treated using a penalty-function approach, whereas tangential resistance is represented by Coulomb friction for the solid phase and a laminar viscous law for the fluid phase. In these relations, β is the interphase momentum-exchange coefficient; β_{Ergun} and $\beta_{\text{Wen-Yu}}$ are its dense-regime and dilute-regime components, respectively; φ_P is the smooth blending function between the two regimes; v_f and v_P denote the fluid- and solid-phase velocity vectors; φ_P is the solid-phase volume fraction; ρ_P is the solid-phase density; and R_{FP} is the drag force per unit solid mass. Subscripts f and P denote the fluid and solid-particle phases, respectively.

Parameter selection and operating condition configuration

The physical and mechanical parameters of the landslide materials were derived from field-measured values. According to the field investigations, the landslide lithology is primarily Emeishan basalt, with a rock density (ρ) of 2100 kg/m³ and an average grain size of 0.3 m. For the fluid phase, the physical-mechanical parameters corresponding to the water and mud were applied, with densities ranging from 1000 to 1500 kg/m³ and dynamic viscosities between 0.001 and 1 Pa·s. The detailed parameter settings are summarized in Table 1.

Table 1. Parameterization scheme for numerical simulation of the Shuicheng landslide

Working conditions		Solid phase			Fluid phase	
		Particle size (m)	Coefficient of friction	Density (kg/m ³)	Fluid volume fraction (%)	Dynamic viscosity (Pa·s)
Different fluid volumes	I	0.3	0.35	-	-	-
	II	0.3	0.35	1000	10	0.001
	III	0.3	0.35	1000	30	0.001
	IV	0.3	0.35	1000	70	0.001
Different fluid material conditions	V	0.3	0.35	1000	50	0.001
	VI	0.3	0.35	1300	50	0.2
	VII	0.3	0.35	1500	50	1.0
	VIII	0.3	0.35	1020	50	0.002
Different solid particle sizes	IX	3.0	0.35	1020	50	0.002
	X	0.3	0.35	1200	50	0.1
	XI	3.0	0.35	1200	50	0.1
	XII	0.3	0.35	1480	50	0.9
	XIII	3.0	0.35	1480	50	0.9

To examine the impacts of the various parameters on the dynamic behavior of fluid–solid coupled landslides, 13 simulated cases were designed (Table 1). In all of the cases, the density of the solid phase was uniformly fixed to 2100 kg/m³, controlling the solid volume percentage of the mixed-phase mass. Case I simulates the downslope migration of pure solid particles without any fluid interaction effects. Case II involves a sliding mass containing 10% water by volume. Case III contains 30% water; and Case IV contains 70% water. The first four cases are designed to determine the effect of the fluid volume on the particle motion. To eliminate the confounding effect of varying fluid volumes in the subsequent cases, the remaining cases (Cases V–XIII) all have a uniform fluid volume fraction of 50%. Case V uses water as the fluid phase; Case VI uses low-viscosity mud; and Case VII employs high-viscosity mud. Case VIII considers low-concentration sediment-laden water as the fluid and small-diameter solid particles (0.3 m); and Case IX uses low-concentration sediment-laden water and large-diameter solid particles (3.0 m). Case X employs low-viscosity mud with small particles; and Case XI uses the same mud with large particles. Case XII combines high-viscosity mud with small particles, and Case XIII combines high-viscosity mud with large particles. These simulation configurations allow for a systematic investigation of how the fluid volume fraction, fluid properties (e.g., viscosity) and equivalent particle size affect the coupled flow-slide process and the resultant landslide dynamics.

Numerical simulation results

Model validation against field observations

Among the simulated cases, Case III showed the closest overall agreement with the observed runout characteristics of the Shuicheng landslide and was therefore selected for comparison with field observations. High-resolution UAV orthophotos and the reconstructed terrain were used to superimpose the simulated results on the observed landslide extent. The simulated maximum runout distance was 1437 m, close to the field-observed value of 1420 m, while the simulated accumulation area was 1.65×10^5 m² compared with the observed 1.90×10^5 m². The simulated flow path and overall spatial distribution were also generally consistent with the observed landslide boundary (Fig. 6). These results indicate that the model reasonably reproduces the large-scale runout distance and spatial extent of the Shuicheng landslide, providing a reference case for the subsequent comparative analysis under different fluid–solid conditions.

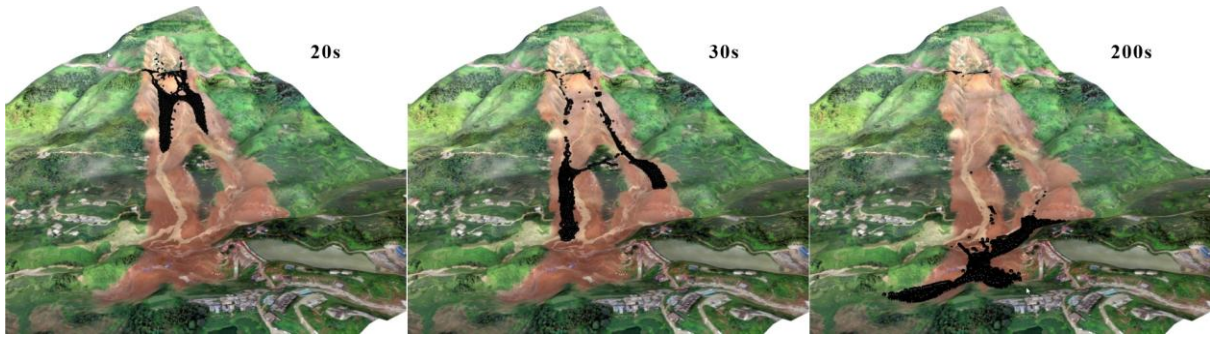


Fig. 6. Comparison of the simulated maximum landslide runout range with the observed runout range.

Effect of fluid volume fraction

Water is employed as the fluid phase in Cases I–IV to investigate the motion behavior of solid particles under varying water volumes by adjusting the water content in the model. The results indicate that as the water volume increases, the spatial extent and persistence of positive fluid drag generally increase, enhancing particle mobility. As a result, Case IV (70% water by volume), demonstrates the most extensive particle dispersion and the greatest travel distance, reflected by the widest accumulation area and farthest movement range (Fig. 7a–d).

Case I exhibits the smoothest velocity increase and primarily relies on gravity-driven sliding. Notably, both Case I and Case II display a two-stage acceleration pattern on the velocity profiles (Fig. 7e). Initially, the solid particles move primarily under the force of gravity. The particles slide rapidly under conditions approximating dry friction or weak lubrication as the fluid has yet to establish sustained lubrication or buoyancy between the particles. Consequently, the particles exhibit a state of free sliding with incidental collisions, and the velocity rapidly reaches a minor local peak. Following this initial acceleration, the particle mass enters a phase dominated by frictional dissipation, which is characterized by frictional contacts and inter-particle collisions. In particular, Case II has an insufficient fluid viscosity and buoyancy to maintain sustained particle support and lubrication. This leads to localized kinetic energy dissipation that exceeds the input and a consequent transient velocity drop. A second acceleration phase occurs once the combined fluid drag force and particle gravity component again surpass the frictional dissipation. Under high water content conditions, the fluid rapidly establishes continuous lubrication and buoyancy between the particles, significantly reducing the friction coefficients and exerting strong drag forces from the onset. Consequently, the free fall-frictional stalling-secondary acceleration pattern is nearly absent, and the velocity curve rises smoothly from zero to the peak value. The peak velocity of the solid particles increases with increasing water volume. In Case IV, the maximum velocity is 38.1 m/s. Under these conditions, the elevated fluid content promotes greater particle mobility and long-range transport capability.

Under low water content conditions (Case II), although the fluid drag force on the particles reaches the highest peak value (~ 8.38 Pa/g), it emerges relatively late, at ~ 29 s, and subsequently declines rapidly to about 1 Pa/g. This indicates that the fluid support and lubrication develop slowly, causing the particles to deposit and accumulate quickly once the drag force decreases. In Case III, the peak drag force is slightly lower (~ 7.29 Pa/g), but it occurs earlier (24 s) and then stabilizes, implying earlier and sustained fluid support, which facilitates longer particle transport distances. Under high water content conditions (Case IV), the drag force rapidly rises to 7.32 Pa/g within 12 s, then declines to a sustained plateau of approximately 3.5 Pa/g, and is maintained over an extended period (Fig. 7f). This continuous force allows the particles to remain suspended and to cause intense scouring within the high-energy fluid, resulting in the strongest long-range erosive and transport capabilities.

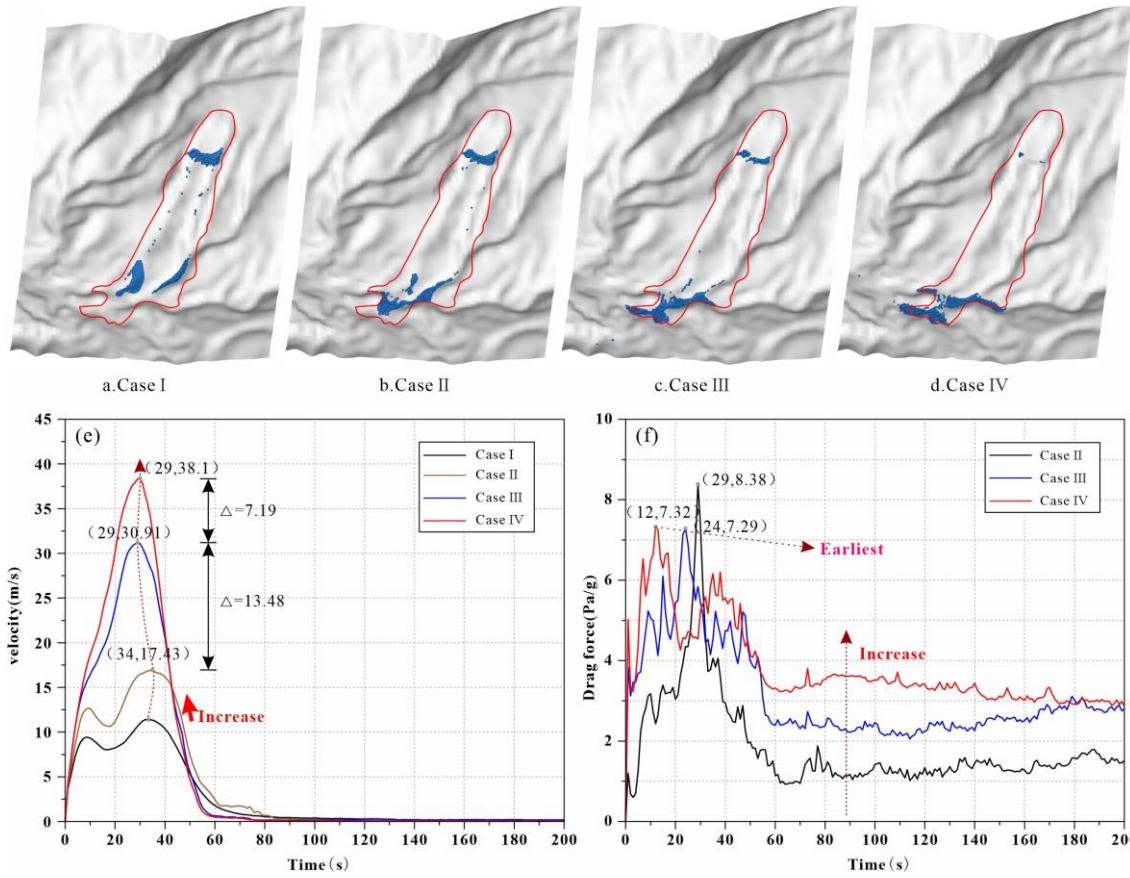


Fig. 7. Deposition patterns and dynamic responses of solid particles at different fluid volume fractions. (a–d) Deposition patterns of solid particles (Cases I–IV); the red line delineates the actual landslide impact zone. (e) Curves of the mean velocity of solid particles. (f) Curves of the mean drag force acting on solid particles.

Analysis of the velocity profiles reveals that three cases (i.e., cases II, III, and IV) all reach the peak velocity at ~ 30 s. Consequently, the 30th second is selected as the reference time to compare the solid particle distribution across the different scenarios (Fig. 8a–c). It is evident that with increasing fluid volume, the solid particle flow channel becomes wider, and the velocities increase and become more uniform, enabling high-speed propulsion over a larger area. Simultaneously, the solid volume fraction decreases as the fluid fills the interstitial spaces, facilitating particle suspension and enabling long-distance transport.

Comparison of the drag force distributions reveals that in Case II, the solid flow channel is narrow, the fluid shear is concentrated, and the overall drag force is low. Although localized high drag peaks (~ 8 Pa/g) occur, these peaks are confined to narrow channels surrounded by extensive regions of opposing drag forces that cause braking. In Case III, the overall positive drag peaks slightly increase, and the drag region becomes broader and predominantly positive, indicating sustained particle propulsion. Case IV exhibits the broadest region of sustained positive drag, reflecting enhanced interphase momentum transfer. Increasing the fluid volume not only enhances the acceleration rate and peak velocity of the solids but also alters the fluid–solid coupling mechanism.

The simulation results indicate that fluid volume is an important factor influencing the simulated landslide dynamics. As the fluid volume increases from low to high, the mixed flow transitions from a state of peak impact and rapid accumulation to a state of continuous suspension and long-distance transport. This transition reflects the change in the peak magnitude and fundamentally arises from the temporal and spatial variabilities of the drag forces. Furthermore, the simulations reveal that the early, rapid onset, and sustained energy input under high fluid content conditions allow debris flows to overcome topographic barriers and achieve extensive long-distance displacement. Conversely, under low fluid

content conditions, despite occasional strong impacts, the drag force rapidly dissipates, limiting the extent of the movement.

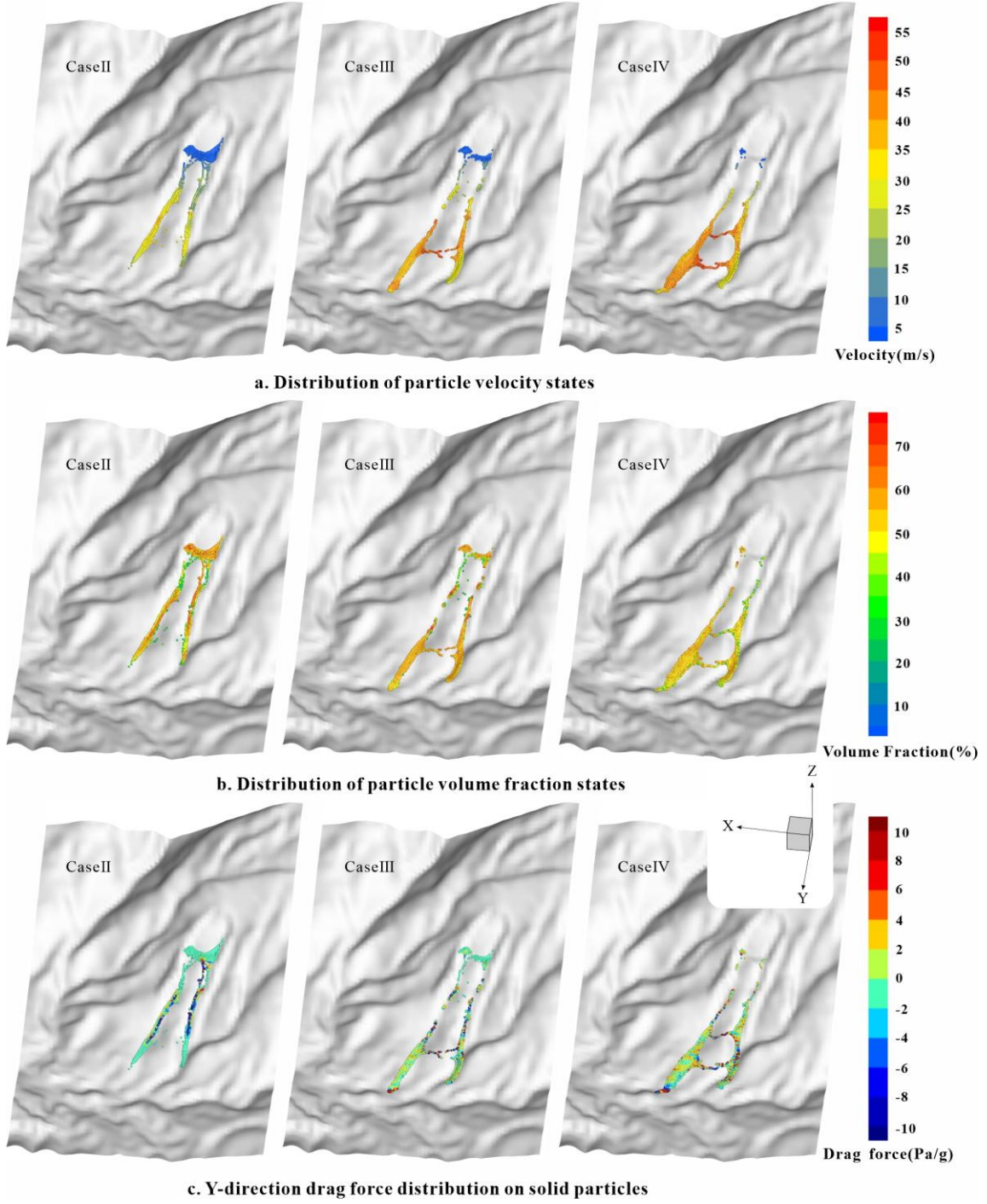


Fig. 8. Distributions of velocity, volume fraction, and drag force at $t = 30$ s for different fluid volume fractions. (a) Velocity. (b) Volume fraction. (c) Drag force in the y-direction.

Effect of fluid properties

Here we compare the effects of different fluids on the kinematic behavior of landslides, highlighting that the kinematic behavior and accumulation characteristics of the solid particles are significantly influenced by the tested fluid-property combinations (Fig. 9a–c).

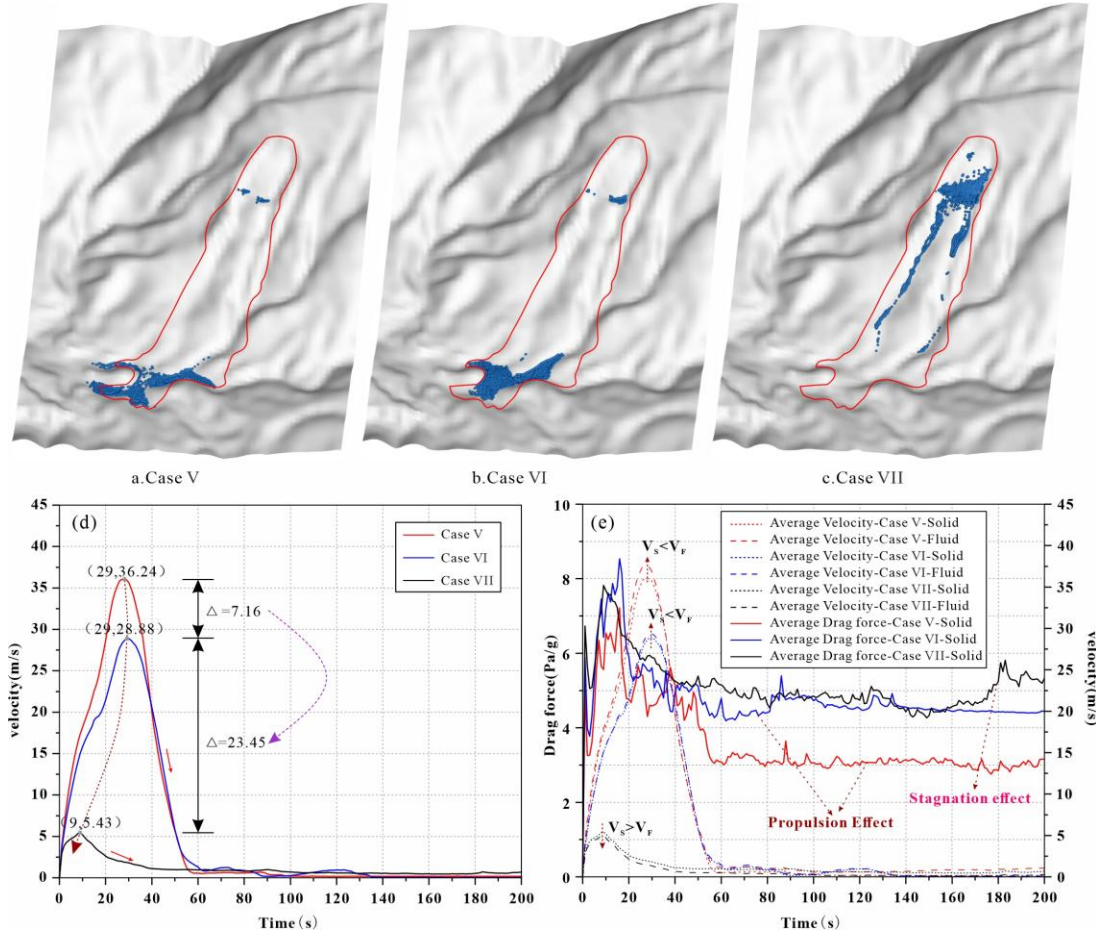


Fig. 9. Deposition patterns and dynamic responses of solid particles under different fluid properties. (a–c) Deposition patterns of solid particles (Cases V–VII); the red line delineates the actual landslide impact zone. (d) Curves of the mean velocity of solid particles. (e) Curves of the mean drag force acting on solid particles.

The velocity profiles of the solid particles vary depending on the fluid. In Case V, in which the fluid is water, the solid particle velocity increases most rapidly and reaches the highest peak (36.24 m/s at 27 s). Following this peak, the velocity sharply decreases due to fluid–solid separation and kinetic energy dissipation, resulting in a movement process that concludes over a short time period. In Case VI, in which the fluid is low-viscosity mud, the solid particle velocity peaks at 28.88 m/s at ~29 s. This case exhibits a more gradual acceleration and decay compared to the water case (Case V). Conversely, in Case VII, in which the fluid has a high viscosity, the drag force acts early, but significant viscous dissipation results in this case having the lowest average acceleration and peak velocity (Fig. 9d). Despite the low peak velocity, the decay is extremely slow, indicating gradual settling of the solid particles under the sustained drag force of the viscous fluid. Across the three fluid-property conditions, the acceleration, peak, and decay phases of the solid particle velocity exhibit coherent progression from instantaneous peak impact to moderate sustained propulsion to slow compaction and deposition. Water-driven flows are characterized by explosive motions with high peaks, short durations, and rapid decays. Low-viscosity mud facilitates steady-state propulsion of the solid particles over medium to long durations through balanced acceleration and damping. High-viscosity mud exhibits high damping. Although the initial acceleration is rapid, the solid particles subsequently settle gradually, and the decrease in velocity is uniform, resulting in localized accumulation.

The three fluid environments also differ in terms of the relative fluid and solid velocities. When the fluid velocity exceeds that of the solids, fluid drag propels the solid particles; conversely, when the fluid velocity is lower, it impedes

solid particle movement. Across the tested fluid-property combinations, the fluid drag force on the solids shifts from a predominantly propulsive to a predominantly resisting role (Fig. 9e). Low-viscosity mud provides a balance between propulsion and sustained support, enabling rapid initiation and persistent drag over tens of seconds and thereby supporting long-range transport within the tested cases. Water produces the strongest instantaneous thrust but does not provide prolonged support. High-viscosity mud initially exerts a force on the particles, but this force rapidly decays due to excessive internal dissipation, leading to swift particle settlement and accumulation. Within the tested parameter combinations, low-viscosity mud produces the most persistent transport; this result should not be generalized independently of fluid density, solid concentration, and terrain. Hazard assessment should therefore consider both the initial velocity peak and the duration and spatial continuity of transport.

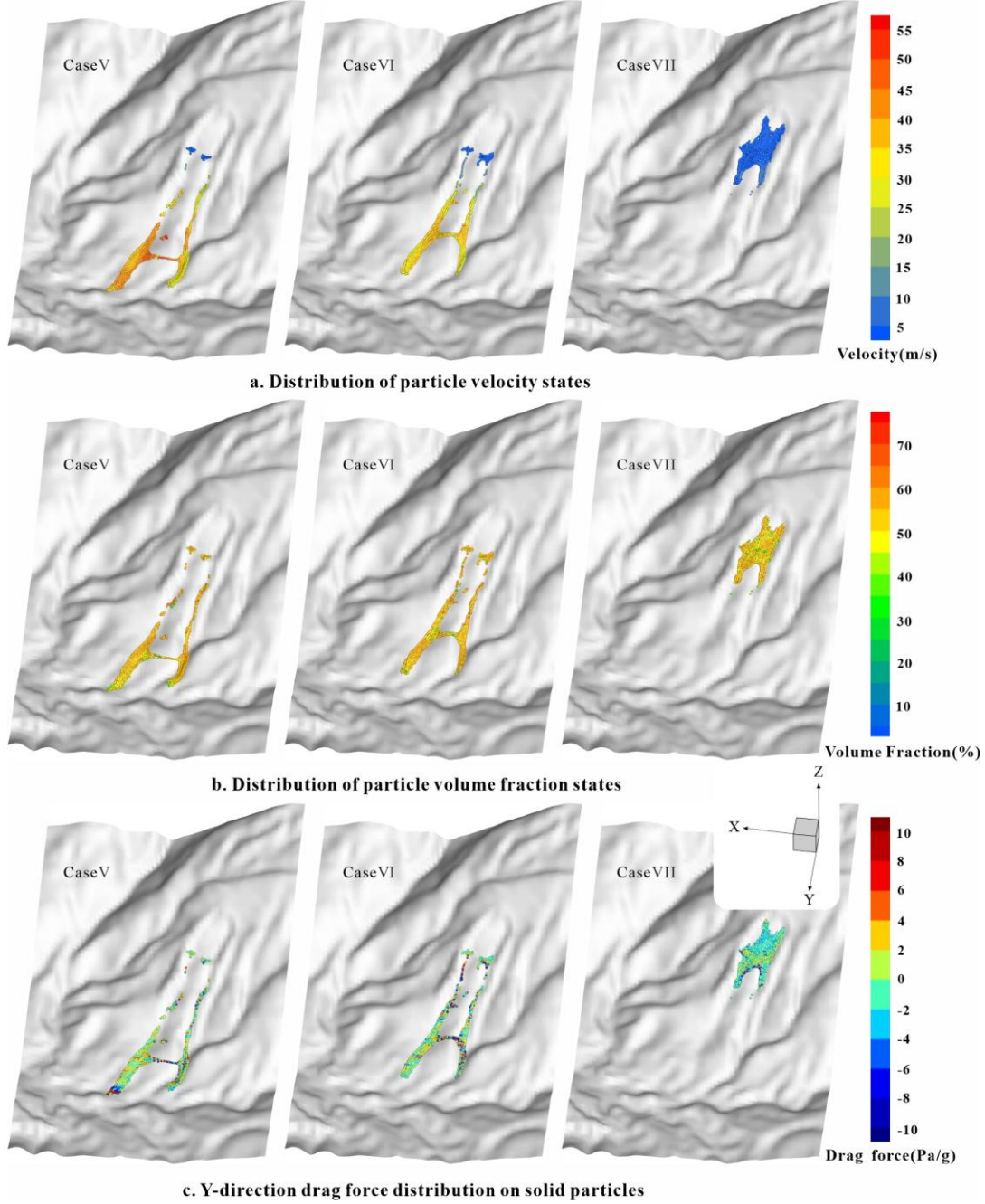
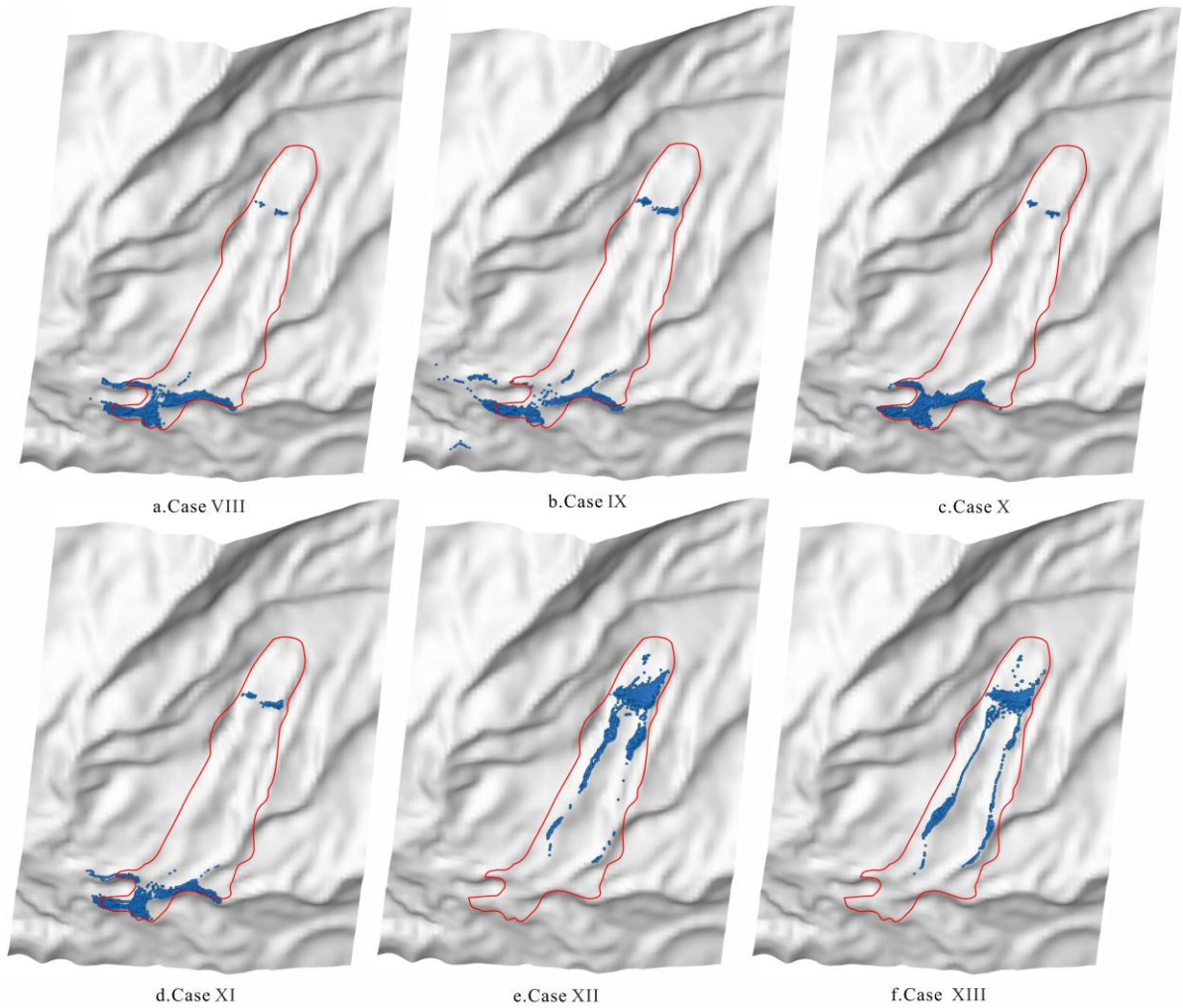


Fig. 10. Distributions of velocity, volume fraction, and drag force at $t = 30$ s for different fluids. (a) Velocity. (b) Volume fraction. (c) Drag force in the y-direction.

Similarly, analysis of the state distribution of the solid particles at 30 s under different types of fluids revealed that under the influence of water (Case V), the solid particles form two narrow, high-speed jets with velocities concentrated within the range of 20–50 m/s and a generally low volume fraction. In Case VI, the mainstream flow channel is slightly wider than in Case V, with velocities concentrated within the range of 10–35 m/s. In addition, this case exhibits attenuated velocity towards the jet terminus, a larger volume fraction, and more aggregated solid particles. Moreover, on one side of the jet, the drag force shifts to negative values due to topographic and fluid effects, hindering solid particle transport. In the high-viscosity mud case (Case VII), the main flow expands into a broad, umbrella-shaped pattern, and the velocities are uniformly distributed within the range of 5–15 m/s. The solid particles exhibit mudflow-like behavior due to bonding by the highly viscous fluid, and the drag force is predominantly negative across most areas, resulting in nearly continuous accumulation in the slip source zone and just below the shear exit (Fig. 10a–c).

Effect of solid particle size

Previous studies have extensively investigated the effects of the fluid volume and fluid properties; however, the characteristics of the solid particles are equally critical to the dynamics of real landslides. In this section, we investigate the kinematic behavior of landslides with various solid particle sizes. The simulation results indicate that compared to the cases with small particles, the cases with large particles yield more dispersed deposit morphologies, longer travel distances, and a wider influence range (Fig. 11a–f).



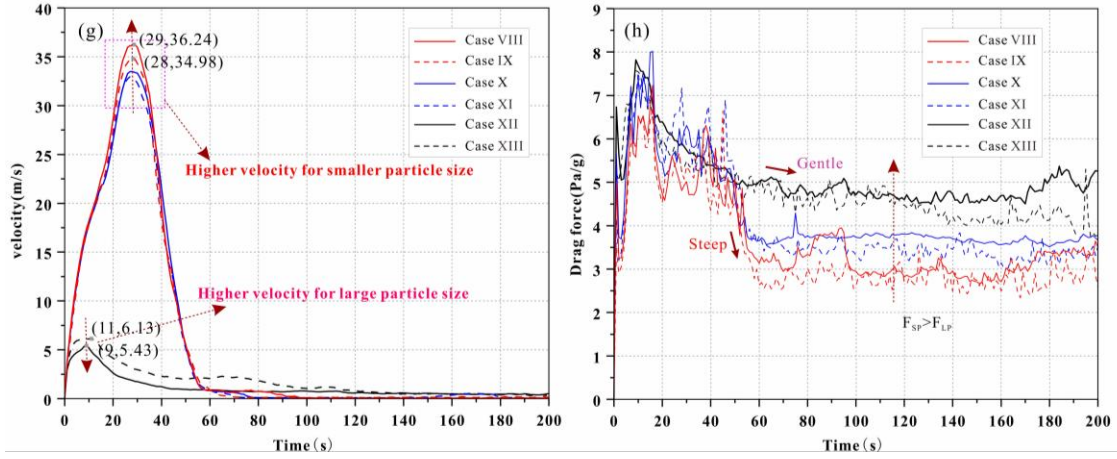


Fig. 11. Deposition patterns and dynamic responses of solid particles for different solid-particle sizes. (a–f) Deposition patterns of solid particles (Cases VIII–XIII); the red line delineates the actual landslide impact zone. (g) Curves of the mean velocity of solid particles. (h) Curves of the mean drag force acting on solid particles (SP = small particles; LP = large particles).

In low-viscosity fluid environments (e.g., low-concentration sediment-laden water and low-viscosity mud), the movement velocity of smaller particles is slightly higher than that of larger particles. However, as the fluid viscosity increases, the influence of the particle size on the velocity of the solid particle decreases. In high-viscosity fluid environments, the larger particles exhibit higher velocities than the smaller particles due to their relatively lower resistance per unit mass and their greater inertia, enabling them to better overcome viscous damping (Fig. 11g). Regarding the drag force, in all three fluid environments, the smaller particles experience greater drag forces compared to the larger particles. This is attributed to the higher surface-area-to-mass ratio of smaller particles and their stronger fluid coupling per unit mass, which results in generally higher peak drag forces on smaller particles (Fig. 11h). However, it should not be presumed that landslides composed of smaller particles necessarily possess higher kinetic energy than those composed of larger particles. A comprehensive assessment must consider the inertia of larger particles, terrain influences, and other factors.

Cases VIII, IX, X, and XI were designed to represent the state distribution of the landslide at 30 s under different solid particle sizes (Fig. 12a–c). The velocity distributions in the main flow channel are generally slightly higher for the large particle size cases compared to the small particle size cases. At 30 s, the large particles exhibit a sparser distribution. As the fluid viscosity increases, the variation in the volume fraction caused by the particle size differences gradually decreases, yielding a more continuous volume fraction field. Smaller particles tend to concentrate in narrow, high-velocity channels characterized by focused impacts due to the interplay of fluid shear and inertia. In contrast, benefiting from greater inertia, larger particles disperse into broader, more continuous transport zones within the landslide.

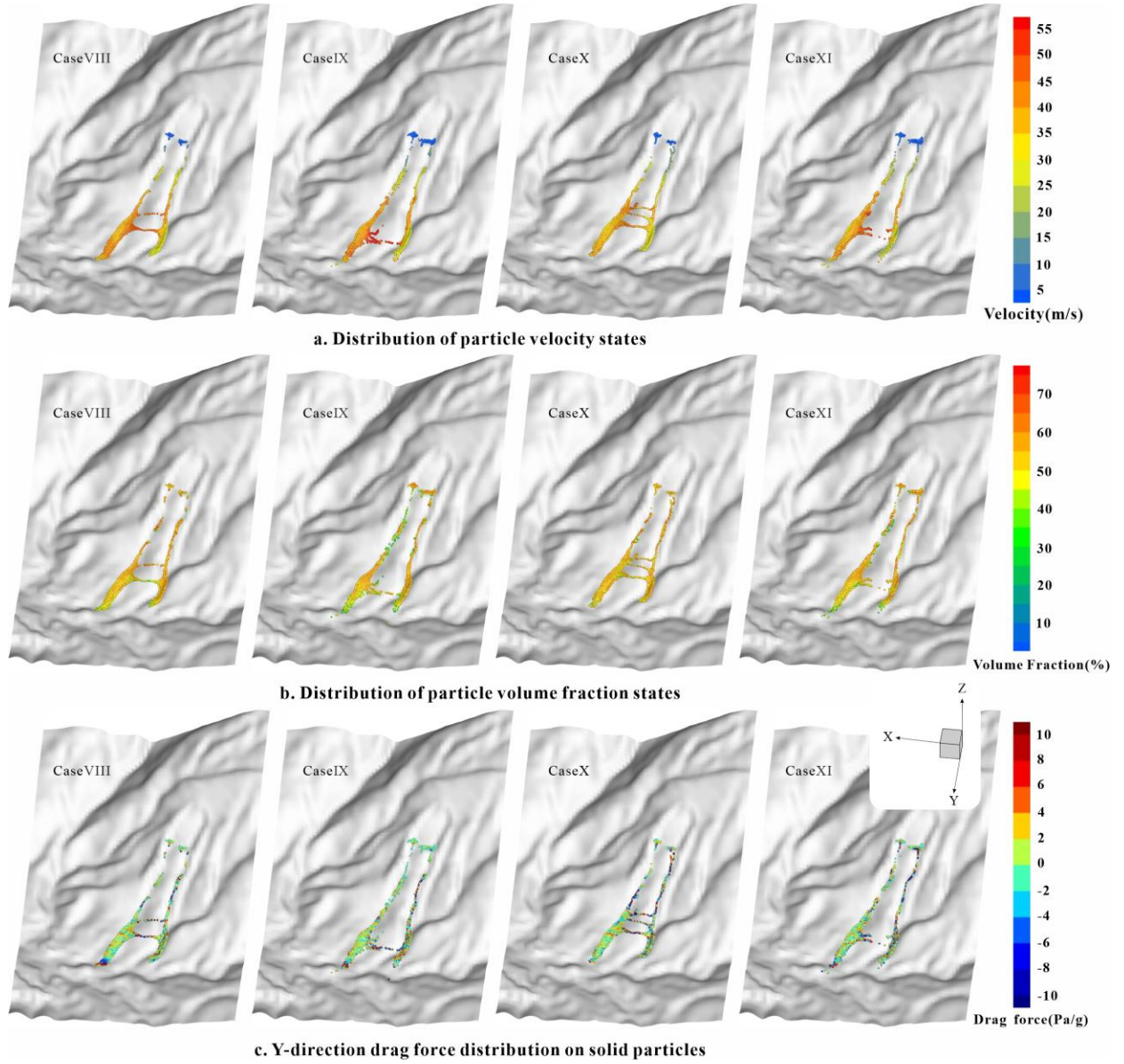


Fig. 12. Distributions of velocity, volume fraction, and drag force at $t = 30$ s for different particle sizes. (a) Velocity. (b) Volume fraction. (c) Drag force in the y-direction.

Discussion

The 13-case matrix reveals a scale-linked interpretation of the simulated mobility. At the particle scale, the relative fluid-solid velocity controls the direction and magnitude of interphase drag. At the mixture scale, fluid volume fraction and rheological properties regulate whether particle contacts remain frictional, become lubricated, or evolve toward collision-dominated transport. At the slope scale, topographic confinement converts these local interactions into channelized acceleration, flow branching, and fan-shaped deposition. This interpretation is consistent with two-phase debris-flow theories that explicitly couple solid and fluid momentum balances³³ and with SPH formulations in which the interaction term governs phase-relative motion³⁴.

The fluid-volume cases further show that long-runout capacity is not controlled by the largest instantaneous drag peak alone. Gao et al.³⁵ demonstrated that fluid drag depends jointly on liquid volume fraction, solid-fluid velocity difference, and fluid viscosity. In the present simulations, Case II reaches the largest local peak relatively late and the

drag then decays rapidly, whereas Cases III and IV develop positive drag earlier, across wider regions, and for longer durations. The sustained momentum exchange helps the moving mass remain mobile through flow branching and terrain-induced changes in direction, while a short-lived peak is more readily dissipated by friction and particle collisions. Experimental work likewise shows that pore fluid can increase granular-flow mobility by modifying grain-scale interactions, although the magnitude of the effect depends on flow volume and boundary conditions³⁶.

The fluid-property and particle-size results indicate a regime-dependent balance among momentum transfer, viscous dissipation, and particle inertia. Water produces the highest velocity peak but undergoes rapid phase separation and decay; low-viscosity mud provides lower peak velocity but more persistent propulsion; and high-viscosity mud strongly damps motion and favors localized accumulation. This pattern agrees qualitatively with the view that debris-flow resistance reflects coupled viscous and collisional contributions³⁷ and that yield strength and plastic viscosity directly influence post-failure velocity and runout³⁸. Particle-size effects are also conditional: smaller particles have a higher surface-area-to-mass ratio and thus respond more strongly to fluid drag per unit mass, whereas larger particles retain greater inertia under the more viscous conditions. Laboratory studies show that grain-size distribution and fine-particle content can modify pore-pressure response and shear behavior³⁹, while differences in grain-size distribution can alter phase separation, runout, and fan morphology⁴⁰.

The numerical analysis focuses on the post-failure motion of the Shuicheng landslide and therefore does not explicitly reproduce the preceding rainfall infiltration, transient pore-pressure evolution, progressive slope failure, or the associated transformation of the initial sliding mass. In addition, the natural landslide material exhibits a broad and spatially heterogeneous grain-size distribution, whereas equivalent particle sizes and idealized fluid properties are adopted here to isolate the respective effects of particle size, fluid volume fraction, and fluid properties. Moreover, because the present analysis is based on a single landslide and a prescribed range of numerical conditions, the identified relationships should be interpreted as mechanistic trends within the investigated parameter space rather than as universally applicable laws for all fluid–solid coupled landslides. Future studies should incorporate more realistic grain-size distributions and independent landslide cases to further evaluate the applicability of the proposed framework.

Conclusions

In this study, numerical simulations of the Shuicheng landslide in Guizhou Province were conducted using the self-developed LPF3D platform. A total of 13 cases with different fluid volume fractions, fluid properties, and equivalent particle sizes were analyzed to investigate their effects on post-failure mobility and fluid–solid interaction. The main conclusions are as follows.

(1) Based on simulation and analysis of 13 working conditions for the Shuicheng landslide, the results indicate that the landslide process is neither a purely granular slide nor a simple fluid flow. Instead, it represents a dynamic interaction between fluid-induced drag forces and the inertial forces of solid particles, characterized by continuous spatial and temporal overlap and transformation. The early stage of motion is dominated by high-intensity impacts, while the later stage is sustained by persistent shear forces. Variations in fluid volume, fluid viscosity, and solid particle size result in markedly different simulated landslide behaviors. These results highlight the importance of considering the coupled effects of the fluid and solid phases when interpreting the mobility of fluidized landslides.

(2) Fluid volume fraction influences mobility mainly by changing when, where, and how long positive drag acts. Higher fluid fractions produce earlier and broader sustained momentum transfer, whereas lower fluid fractions can generate large but localized and short-lived drag peaks. Within the investigated conditions, extended runout is more closely associated with the spatiotemporal persistence of interphase momentum exchange than with a single peak drag value.

(3) Within the investigated parameter ranges, fluid properties and particle size exert coupled, regime-dependent

effects. Among the tested fluid-property combinations, water produces the highest short-duration velocity peak, low-viscosity mud provides the most persistent propulsion, and high-viscosity mud produces stronger damping and localized deposition. Smaller particles experience greater drag per unit mass, whereas larger particles retain greater inertia under viscous conditions.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

All authors contributed extensively to the present paper. J.L.: Conceptualization and writing. Y.G.: methodology and writing. L.W.: software and investigation. Y.L.: formal analysis and validation. H.Z.: data curation. Y.Y.: conceptualization. All authors have read and agreed to the published version of the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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