

# Multiphysics and Multiscale Modeling of Bouldery Debris Flow Interactions with Baffles and Slit Dam

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## ABSTRACT

Debris flow is a channelized flow-type landslide that pose significant risks to infrastructures and human life due to its high-velocity slurry and impact forces from entrained boulders. Realistic numerical modeling of debris flow remains challenging, as it involves multiscale interactions between different phases (e.g., boulders, soil, slurry, and water) and multiphysics processes (e.g., fluid-particle and debris-structure interaction). This study introduces two advanced numerical frameworks to unravel the impact mechanism of bouldery debris flows on debris-resisting structures: 1) a fully resolved smoothed particle hydrodynamics-discrete element method (SPH-DEM) coupling model, and 2) a two-level discrete element method (2L-DEM). Both approaches explicitly resolve the multiphase nature of debris flows by treating boulders and fine-grained slurry as distinct interacting phases, enabling precise quantification of momentum transfer, energy dissipation, and structural responses. The SPH-DEM captures fluid-driven boulder dynamics and backflow effects around baffles, while the 2L-DEM captures granular jamming and force redistribution in the impact process on slit dam. The simulation results demonstrate that the formation of bouldery front and viscosity of slurry significantly alter the impact regimes on baffles, whereas the relative size of particle and slit dam aperture critically governs the debris retention efficiency. By bridging microscale particle interactions to macroscale flow-structure behavior, this work provides physics-based insights for optimizing debris-resisting structures, offering geotechnical engineers validated tools to enhanced hazard mitigation strategies on key infrastructure near mountainous region.

## 1 INTRODUCTION

Debris flow is a rapid, channelized landslide comprising boulders, soil, water, and organic matters that pose severe threats to infrastructure and human life due to its high mobility and destructive impact forces. This event is particularly devastating in urbanized regions, as exemplified by the 2008 Yu Tung Road debris flow in Hong Kong, which damaged critical infrastructure and necessitated a two-month closure of a major transportation artery, incurring substantial economic and social costs. Mitigating such hazards requires a robust understanding of debris flow dynamics and their interaction with protective structures, yet achieving realistic simulations remains a formidable challenge.

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Numerical modeling has emerged as a pivotal tool for studying debris flow mechanics. Existing approaches broadly fall into two categories: continuum methods, such as the material point method (MPM) (Li et al. 2020), smoothed particle hydrodynamics (SPH) (Han et al. 2019), and the arbitrary Lagrangian-Eulerian (ALE) method (Kwan et al. 2015), which treat debris flow as a homogenized fluid or solid; and discrete methods, like the discrete element method (DEM) (Choi et al. 2016; Gong et al. 2021), which resolve granular interactions through particle-scale friction and collision. While continuum methods excel at capturing bulk flow behavior, they often oversimplify the multiphase nature of debris. Conversely, DEM provides granular insights but struggles with computational efficiency for large-scale model. Most importantly, these models often neglect critical multiscale phenomena, such as the dynamic interplay between boulders and fine-grained slurry and structures, a gap that limits their predictive capability. Recent advances in computational power have spurred hybrid frameworks (Li & Zhao 2018; Leonardi et al. 2016), coupling continuum and discrete techniques to capture the multiphysics phenomena while balancing accuracy and scalability.

The inherent complexity of debris flows arises from their multiscale, multiphase composition. Debris materials span orders of magnitude in grain size, from clay particles to meter-scale boulders, which undergo rapid rearrangement during flow, creating spatially heterogeneous rheology (Iverson 2003). A key process is granular segregation (Figure 1), where larger boulders migrate to the flow front and surface of a debris flow (Hung et al. 2001), amplifying impact force on barriers compared to homogeneous flows (Ng et al. 2021). Conventional models, which homogenize debris into a single phase, fail to resolve this segregation-driven force concentration, leading to underestimations of structural loading. A paradigm shift toward explicit multiphase modeling is essential to advance hazard assessment and structural design.

To address these limitations, this study presents two novel numerical frameworks, 1) fully resolved SPH-DEM coupled model that integrates smoothed particle hydrodynamics (SPH) for fine-grained slurry with discrete element method (DEM) for boulder dynamics, enabling precise simulation of fluid-particle interactions and backflow effects around baffle structures, and 2) a two-level DEM (2L-DEM) approach that efficiently resolve boulder entrained dense granular flows impacting on a slit dam.

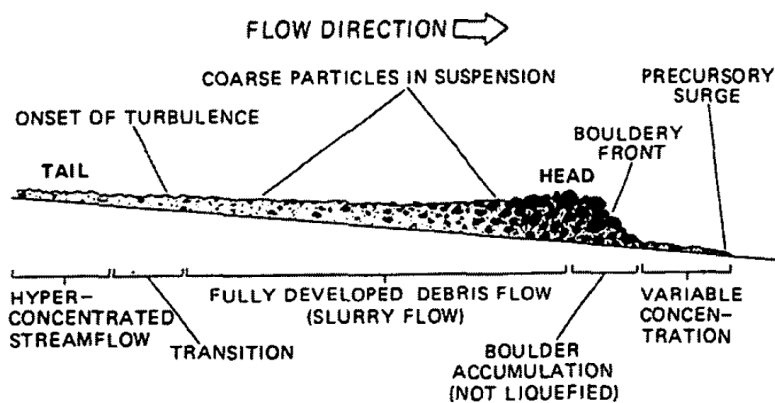


Figure 1 Bouldery front of a debris flow surge (Hung et al. 2001)

## 2 RESOLVED SMOOTHED PARTICLE HYDRODYNAMICS – DISCRETE ELEMENT METHOD (SPH-DEM) COUPLING MODEL

The resolved smoothed particle hydrodynamics-discrete element method (SPH-DEM) coupling model bridges fluid dynamics and granular mechanics to explicitly simulate interactions between boulders, slurry and protective baffle structures, with the following features: 1) Boulders are modeled as rigid clumps of SPH “solid particles” to resolve their rigid-body dynamics, collisions, and frictional contacts; 2) Debris slurry (a mixture of water, soil, and fine particles) is represented as a viscous fluid using SPH “fluid particles”, capturing its free-surface behavior, turbulence, and non-Newtonian rheology. The dual-resolution strategy enables precise analysis of momentum transfer between fluid-driven boulders and slurry, critical for evaluating impact forces on baffles.

### 2.1 Numerical scheme of SPH-DEM

The SPH-DEM framework integrates two open-source solvers: DualSPHysics (Domínguez et al. 2021), employing a weakly compressible smoothed particle hydrodynamics (WCSPH) formulation to simulate free-surface flows, and distributed contact discrete element method (DCDEM) (Canelas et al. 2016), which resolves multi-body interactions between boulders and their contacts with baffles. The surface resolved fluid-particle interaction forces are computed by applying dynamic boundary conditions on SPH “solid particles”. Furthermore, DualSPHysics supports GPU computation, enabling simulations with 786,352 SPH “fluid particles” to be completed within 2 hours.

The WCSPH solves the Navier-Stokes equations governing compressible flow, in terms of the continuity equation (1) and momentum equation (2) in Lagrangian form as follows,

$$\frac{D\rho}{Dt} = -\rho\nabla \cdot \mathbf{v} \quad (1)$$

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\nabla P + \Gamma + \mathbf{f} \quad (2)$$

where  $D/Dt$  denotes the material rate derivative,  $\mathbf{v}$  is the velocity vector,  $\rho$  is density,  $P$  is pressure,  $\Gamma$  is the dissipation or viscosity term, and  $\mathbf{f}$  is external acceleration (e.g. gravity).

In SPH, the fluid domain is discretized into particles that serve dual roles: i) Property carriers: each particle holds field properties such as density, velocity, and pressure; ii) Interpolation nodes: Particles act as discrete points for reconstructing continuous field quantities. The SPH interpolation of a flow field quantity  $A(\mathbf{r})$  at position  $\mathbf{r}$  is defined by the following integral approximation,

$$\langle A(\mathbf{r}) \rangle = \int_{\Omega} A(\mathbf{r}') W(\mathbf{r} - \mathbf{r}', h) d\mathbf{r}' \quad (3)$$

where  $\langle A(\mathbf{r}) \rangle$  is the smoothed estimate of  $A$ ,  $W$  is the kernel function,  $\Omega$  is the domain within the kernel support

radius  $h$ ,  $\mathbf{r}' \in \Omega$  denotes neighboring particle positions. This formulation approximates field quantities as weighted averages of neighboring particles, with the kernel  $W$  ensuring localized interactions with finite number of neighboring particles (see Figure 2). More details can be found in Domínguez et al. (2021).

As for solid phase representation, boulders and walls (including baffles) are modeled as rigid clumps of SPH “solid particles” (see Figure 2). These solid particles serve dual purposes. On one hand, they are applied with dynamic boundary conditions to resolve the fluid-solid interaction forces. On the other hand, each solid particle functions as a DEM particle to compute the solid-solid collisions using the DCDEM. The DCDEM employs a “soft sphere” contact model with 4 parameters: Young’s modulus  $E$ , Poisson’s ratio  $\nu$ , restitution coefficient  $e_0$  and friction coefficient  $\mu_f$ . More details can be found in Canelas et al. (2016).

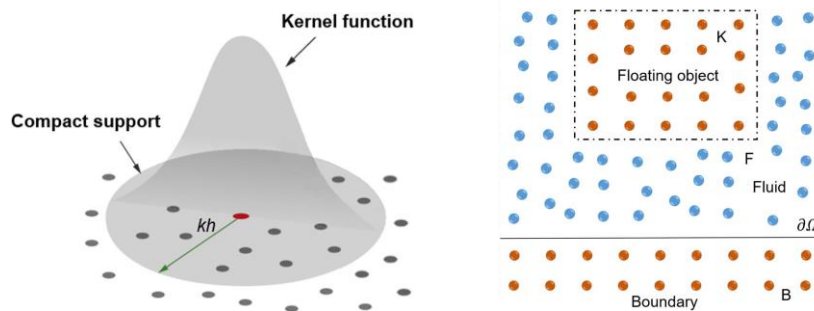


Figure 2 Schematic diagram of kernel function (left) and arrangement of solid/fluid SPH particles (right)

## 2.2 Numerical model setup

The SPH-DEM model simulates bouldery debris flow impacting staggered baffle arrays (Figure 3) with the following parameters: 102 m<sup>3</sup> of debris slurry modeled as viscous fluid, 5 boulders (1 m diameter) placed initially upstream on a 30° inclined channel of 6 m width and channel length of  $L_c = 23$  m; 3 staggered rows of baffles placed in front of the rigid barrier at the downstream deposition zone. No-slip walls and ground are assumed for the fluid and are prescribed with the same properties for DCDEM particles.

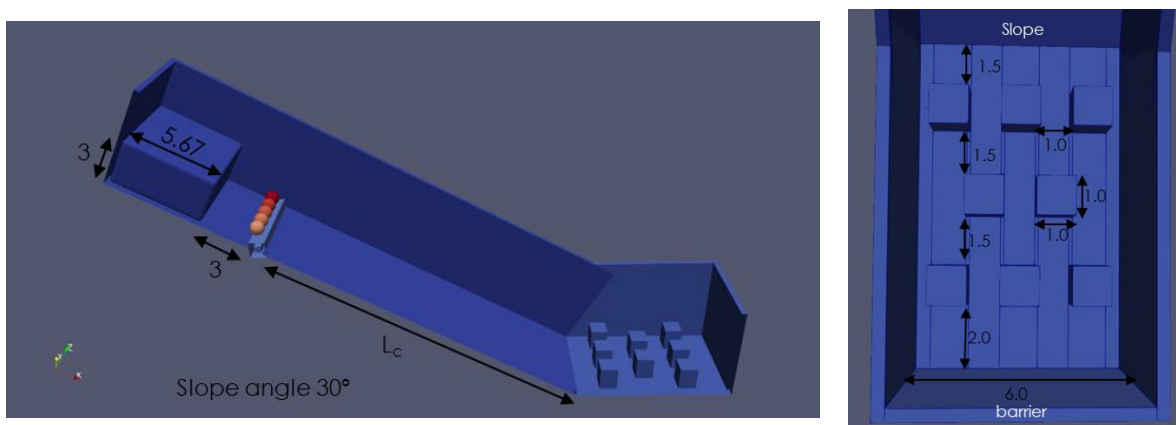


Figure 3 Geometry of SPH-DEM model (unit: m)

### 2.3 Simulation results

Three debris flow scenarios with different slurry kinematic viscosities ( $0.1 \text{ m}^2/\text{s}$ ,  $1 \text{ m}^2/\text{s}$ ,  $5 \text{ m}^2/\text{s}$ ) are simulated and compared in Figure 4. For the low viscosity case ( $0.1 \text{ m}^2/\text{s}$ ), the slurry overtops and precedes the boulders, forming a fluid-dominated front (Figure 4a). Jet-like run-up is observed during baffle impact with minimal energy dissipation (Figure 5). For the intermediate viscosity case ( $1 \text{ m}^2/\text{s}$ ), the balanced slurry-boulder coupling produces a coherent bouldery front flow case as shown in Figure 4b. The slurry pushes the boulders forward, showing an intermediate momentum transfer to the boulders. For the high viscosity case ( $5 \text{ m}^2/\text{s}$ ), slurry rigidity causes boulder detachment and flow stagnation behind motion of boulders (Figure 4c). When impacting baffles, the flow is dominated by pile-up mechanism, forming a hydrodynamic head zone upstream of the baffles (Figure 6).

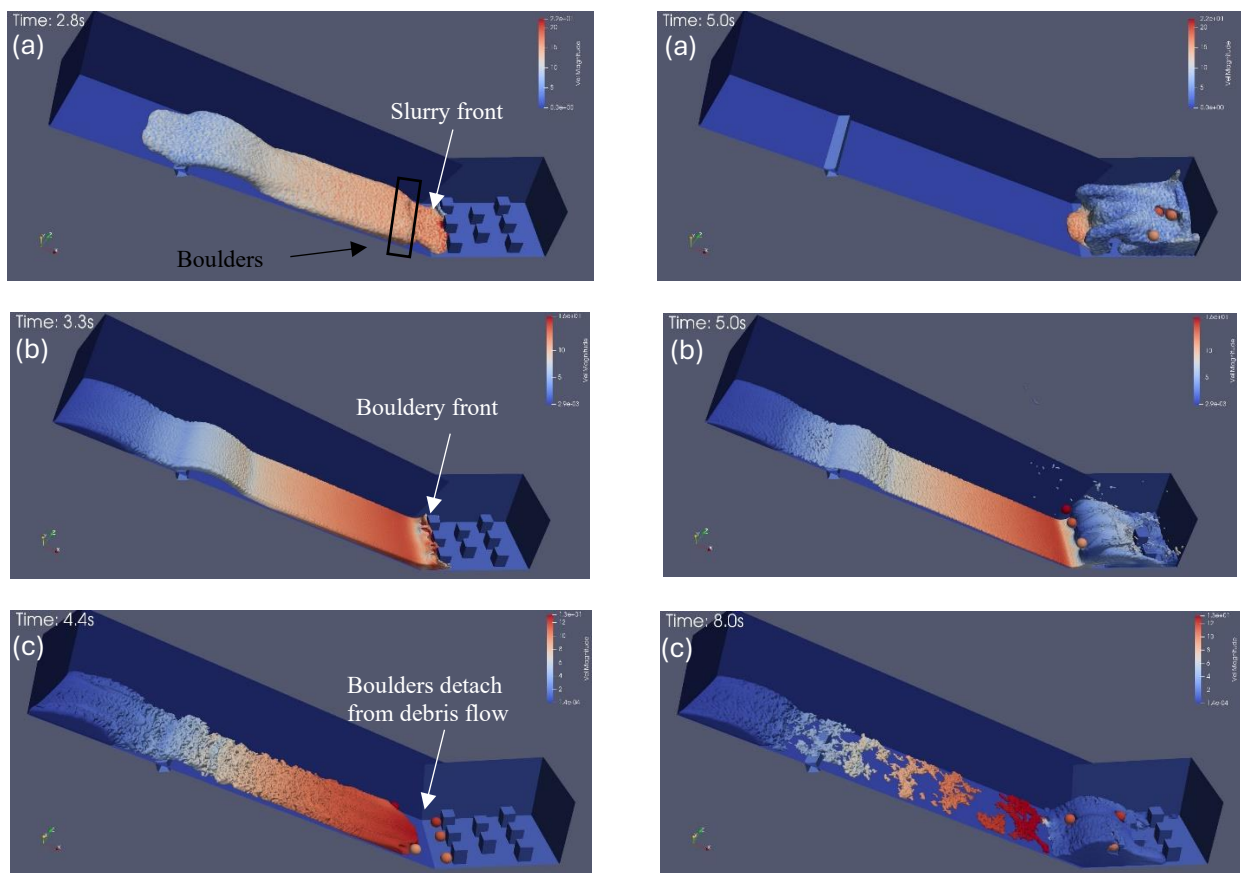


Figure 4 Snapshots of bouldery debris flow impact on baffles (left: impact of flow front; right: after impact) with different slurry viscosity (a)  $0.1 \text{ m}^2/\text{s}$  (b)  $1 \text{ m}^2/\text{s}$  (c)  $5 \text{ m}^2/\text{s}$

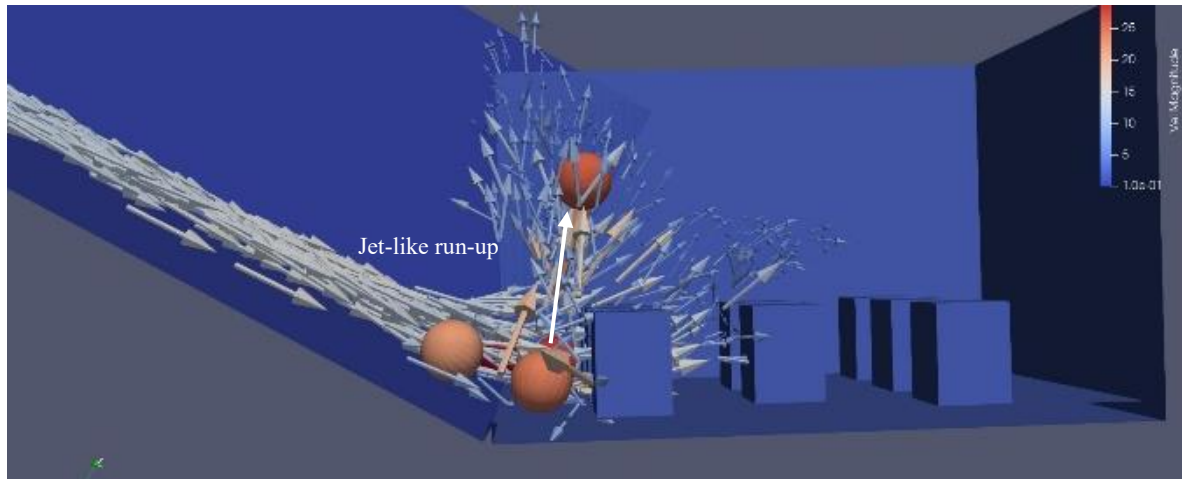


Figure 5 Jet-like run-up mechanism (slurry viscosity  $0.1 \text{ m}^2/\text{s}$ )

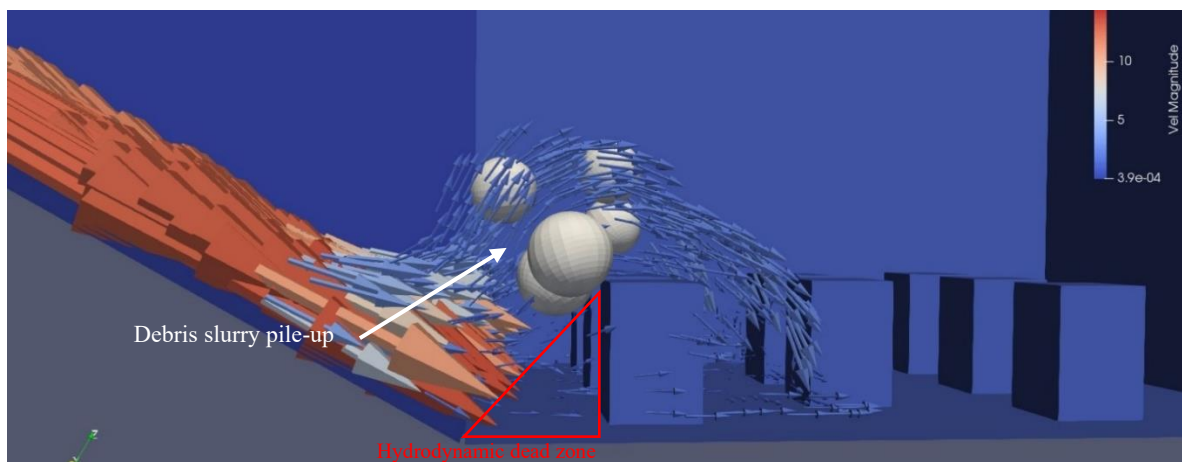


Figure 6 Formation of hydrodynamic dead zone and pile-up mechanism (slurry viscosity  $5 \text{ m}^2/\text{s}$ )

### 3 TWO-LEVEL DISCRETE ELEMENT METHOD (2L-DEM)

The Two-Level Discrete Element Method (2L-DEM) addresses the multiscale dynamics of bouldery granular flows interacting with slit dam by explicitly resolving two distinct phases: non-spherical boulders and monodisperse fine grains. This framework employs a dual-resolution strategy, where boulders are modeled as non-spherical bodies (constituted by triangular meshes) to capture their rotational and translational motion, while fine grains are represented as spherical particles using conventional DEM for efficient granular flow simulation. By coupling these phases into a co-simulation framework, the 2L-DEM enables detailed analysis of how boulder entrainment influences flow-structure interactions, particularly through slit dam apertures.

#### 3.1 Model framework of 2L-DEM

The 2L-DEM leverages the open-source physics engine Project Chrono (Mazhar et al. 2013), integrating two modules to balance accuracy and computational efficiency. The Chrono Core Module simulates boulder

dynamics using method tailored for non-spherical bodies, incorporating Hertzian-Mindlin contact model (for sphere-sphere and sphere-mesh contact) to resolve the force-displacement behavior. In parallel, the Chrono::GPU Module executes on graphics processing units (GPUs) to handle large-scale granular systems, optimizing monodisperse sphere interactions through parallel computing. For instance, a simulation case containing 6,256,544 particles completes in approximately 20 hours—a feat impractical for conventional CPU-based DEM solvers. A synchronization framework facilitates co-simulation between the two modules, enabling bidirectional exchange of contact data to capture coupled boulder-grain interactions.

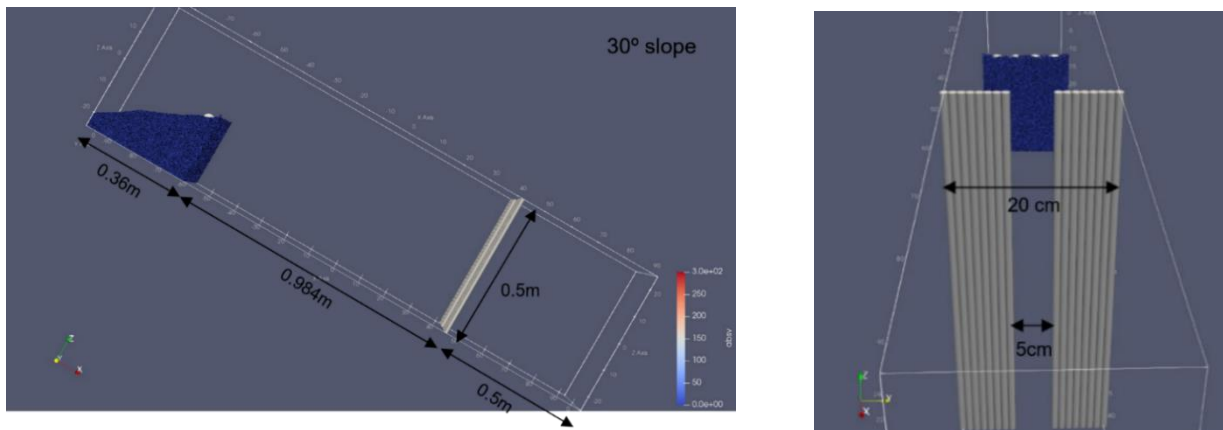


Figure 7 Geometry of 2L-DEM model

### 3.2 Numerical model setup

The 2L-DEM model replicates a flume experiment featuring a 30° inclined slope and a slit dam with a 5 cm aperture (Figure 7). Two groups of simulations are conducted: Type A, which models fine grains only, and Type B, which incorporates boulders (4 cm diameter) entrained within the granular flow. The slit width-to-particle diameter ratio ( $s/d$ ) is systematically varied across cases (Table 1), with case IDs such as *SD20* denoting a grain diameter  $d = 5 \text{ cm} / 20 = 0.25 \text{ cm}$ , which is one-twentieth of the slit width. This parameter is critical for understanding how geometric scaling governs discharge and clogging behavior.

### 3.3 Simulation results

In the Type A simulations, monodisperse granular flows impacting a slit dam are analyzed, with discharge rates (in kg/s) plotted with different particle sizes in Figure 8. All cases exhibited peak discharge at approximately  $t = 0.85 \text{ s}$ , with the slit width-to-particle diameter ratio ( $s/d$ ) exerting a dominant influence. Specifically, flows with 1 cm particles generated peak discharges 50% lower than those with 0.125 cm or 0.167 cm particles, underscoring the role of interparticle locking in coarser grains. Sensitivity tests on initial mass (e.g., cases A-SD5(1)&(2) and A-SD20(1)&(2)) reveal a marginal increase in discharge magnitude with larger masses, though this effect was secondary to  $s/d$ . After impact, a hydrodynamic dead zone forms behind the slit dam, stabilizing flows into quasi-steady regimes ( $t > 1.6 \text{ s}$ ) where discharge curves converge irrespective of particle size.

The trapping efficiency of slit dam is governed by distinct mechanisms for inviscid and frictional flows

(Goodwin & Choi, 2020; Armanini & Larcher, 2001). While inviscid flows rely on blockage ratios (barrier-to-channel width), frictional granular flows are sensitive to  $s/d$ . Prior numerical studies with limited particle counts (typically <100,000) have struggled to resolve  $s/d$ -dependent phenomena at scale. This study extends the  $s/d$  range significantly, demonstrating that at  $s/d \geq 30$  the particle size effects diminish as collisional and frictional forces homogenize within the dense granular packing.

Type B simulations evaluated boulder-laden flows, incorporating 4 cm diameter boulders into the granular matrix. Discharge rates for cases with 4, 16, or 32 boulders (Figure 9) exhibits temporal fluctuations due to transient blockages. Although boulder dimension (4 cm) approaches slit widths (5 cm), the low volumetric concentration ("dilute" distribution) of boulders within the granular packing preclude stable arch formation (Figure 10, 11), ensuring discharge rates never drop to zero.

The entrainment of boulders introduces dual engineering implications. Reduced peak discharge mitigates damage to downstream barriers, while transient boulder trapping could cause increase in both static and dynamic impact forces. In extreme clogging scenarios, the slit dam may behave as a rigid barrier, necessitating limit-state design considerations to account for complete blockage. These findings emphasize the need for balanced slit dam geometries that harmonize discharge reduction with structural integrity.

Table 1 Summary of simulation cases

	Case ID	Grain diameter (cm)	Number of fine grains	Total mass of fine grains (kg)	Number of boulders (4 cm diameter)
<b>Type A</b>	A-SD5(1)	1	12,393	17.20	-
	A-SD5(2)	1	10,697	14.84	-
	A-SD10	0.5	93,747	16.26	-
	A-SD20(1)	0.25	783,801	16.99	-
	A-SD20(2)	0.25	731,774	15.87	-
	A-SD30	0.16667	2,726,619	17.51	-
	A-SD40	0.125	6,256,544	16.96	-
<b>Type B</b>	B-SD10-4B	0.5	93,747	16.26	4
	B-SD20-4B	0.25	783,801	16.99	4
	B-SD10-16B	0.5	93,077	16.14	16
	B-SD20-16B	0.25	773,670	16.77	16
	B-SD30-16B	0.16667	2,608,752	16.67	16
	B-SD10-32B	0.5	93,077	16.14	32
	B-SD20-32B	0.25	773,670	16.77	32
	B-SD30-32B	0.16667	2,618,136	16.82	32

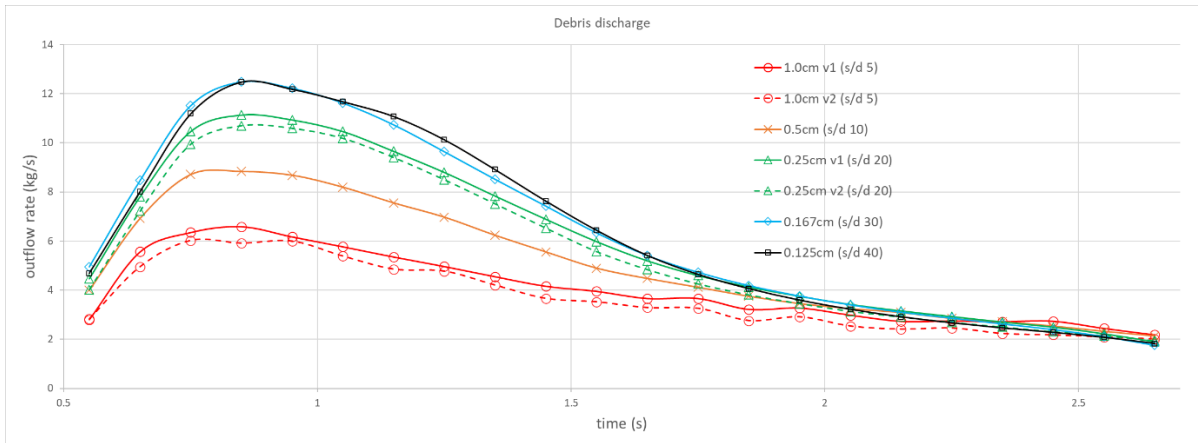


Figure 8 Evolution of granular mass discharge at slit dam for Type A test

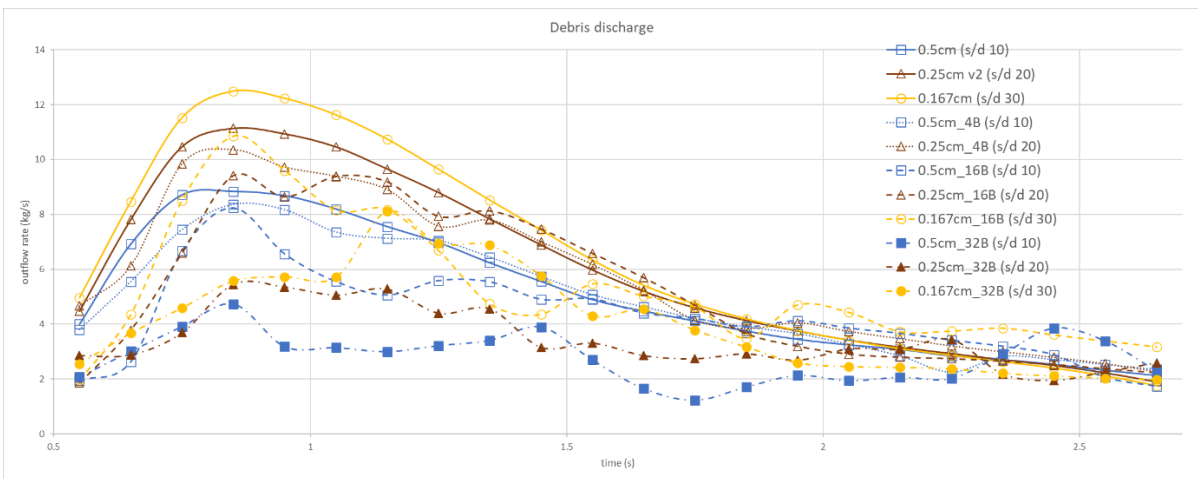
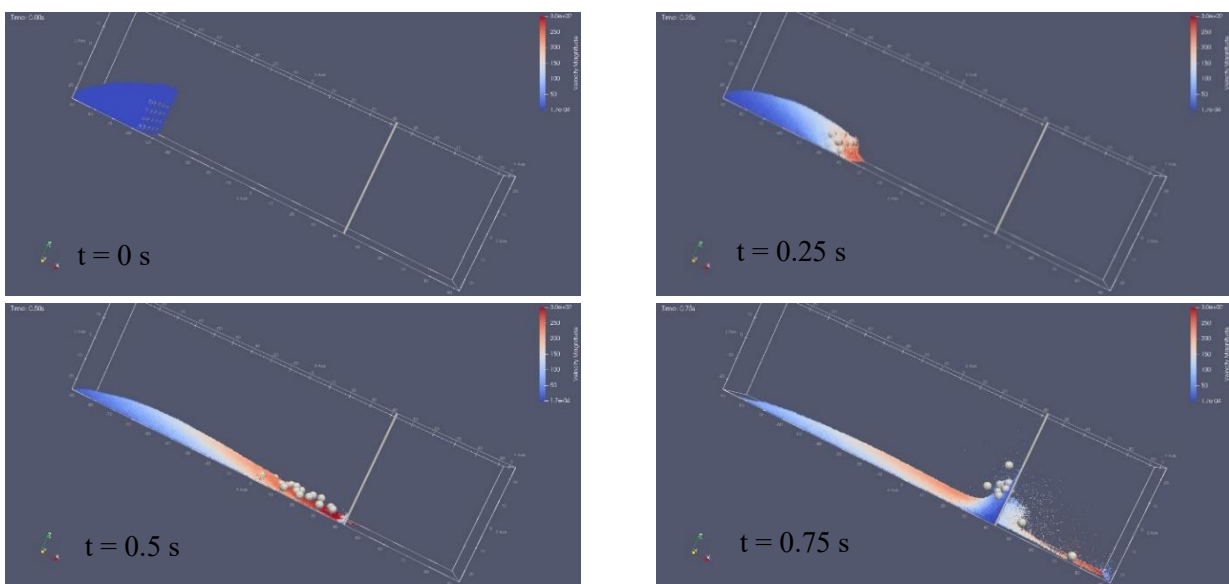


Figure 9 Evolution of granular mass discharge for type B test



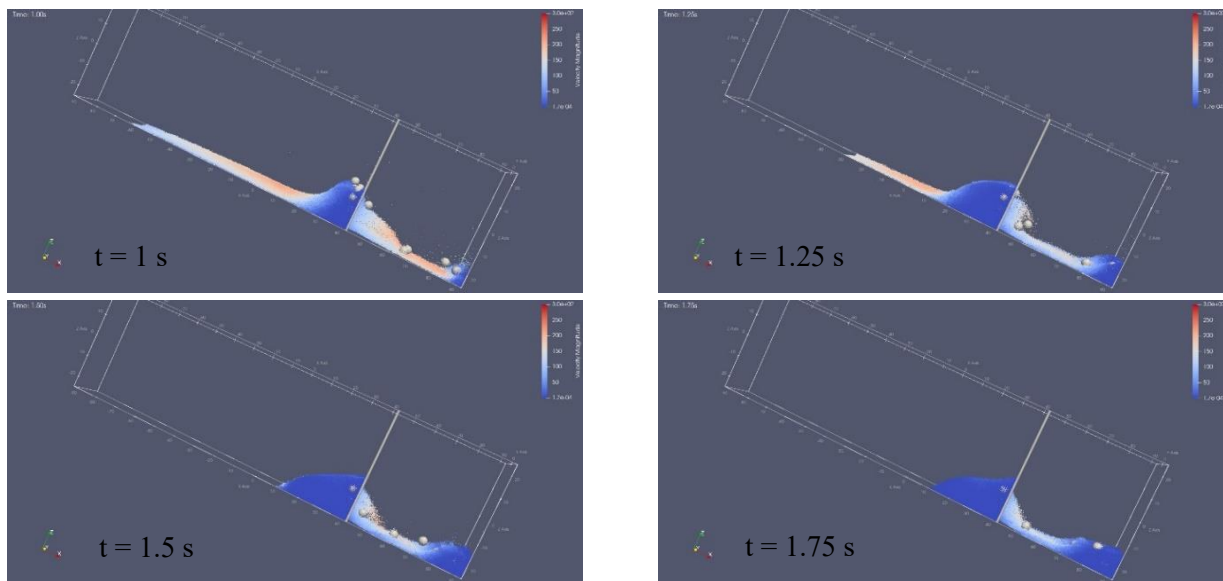


Figure 10 Snapshots of bouldery granular flow of case B-SD10-16B

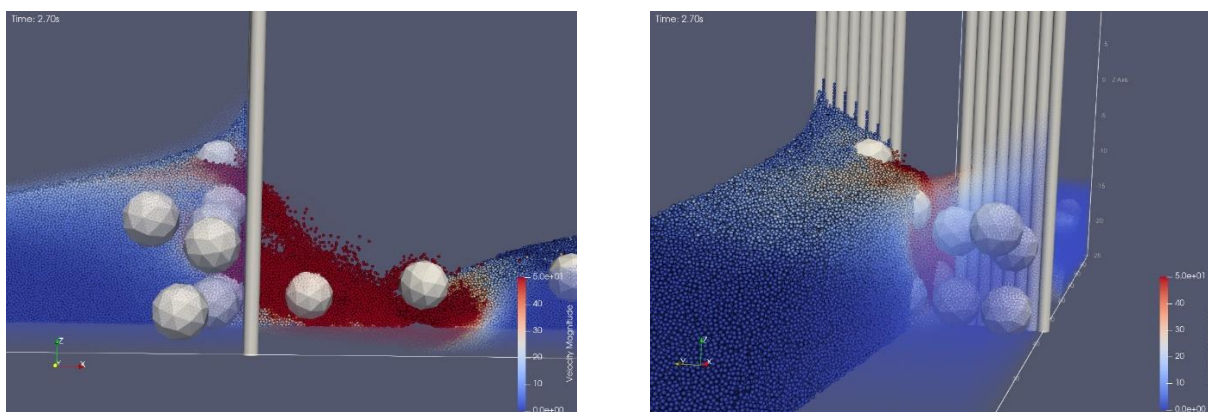


Figure 11 Snapshots of case B-SD20-32B (fine grains at front portion are transparent to reveal the boulders)

#### 4 DISCUSSION AND CONCLUSIONS

This study demonstrates the efficacy of two advanced numerical frameworks, the resolved SPH-DEM coupling and the 2L-DEM for simulating bouldery debris flows and their interactions with debris-resisting structures. By explicitly resolving the multiphase nature of debris flows, these models provide critical insights into the distinct behaviors of boulders and fine-grained phases, which are often homogenized in conventional single-phase approaches. The SPH-DEM model reveals that slurry viscosity plays a pivotal role in governing flow coherence and impact mechanisms. It also underscores the importance of tailoring debris-resisting structures, such as baffle arrays to regional debris flow rheology.

The 2L-DEM framework which leveraged GPU-accelerated computing advances granular flow modeling by resolving the interplay between non-spherical boulders and monodisperse grains. For slit dam, the slit width-to-particle diameter ratio ( $s/d$ ) emerges as a dominant factor in discharge dynamics. At  $s/d \geq 30$ , particle size effects diminish, homogenizing collisional and frictional forces within the flow. Boulder entrainment introduces

temporal discharge fluctuations due to transient blockages, though permanent clogging is absent under tested conditions. This behavior highlights a critical design trade-off: while boulders reduce peak discharge (protecting downstream barriers), they amplify dynamic loading on slit dams that would require a robust limit-state design to account for potential clogging.

By advancing multiphysics and multiscale modeling capabilities, this study equips geotechnical engineers with predictive tools to enhance the resilience of debris-resisting structure, ultimately safeguarding communities in hazard-prone regions.

## ACKNOWLEDGEMENTS

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