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PARTICLE MORPHOLOGICAL EFFECTS ON THE BEHAVIOUR OF DRY GRANULAR FLOW AGAINST RIGID OBSTACLES

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Abstract: Geohazards such as rockfall, catastrophic landslides, and debris flow pose a significant risk due to the rapid movement of the vast amount of granular material carrying tremendous destructive potential and energy. Experimental and numerical studies on channelized flumes have been prevalent in analyzing the kinematics and dynamics of the flow and their interaction with various mitigation measures along the projected flow path. Continuum, discontinuum, and hybrid numerical methods have been successfully employed in the past to comprehend the complex material behaviour of granular mass flows. Although the numerical schemes within a continuum setting offer some insights into critical factors like flow velocity, flow depth, runout distance, etc., the granular interaction within the particle ensemble and the impact force on the barrier system for a better estimate of the force-transmission paths cannot be accounted for. The present study employs the Discrete Element Method to investigate the underlying physics of the micromechanical interaction of the granular assembly with the rigid barrier. Although past studies have explored granular flow-like events within a discrete setting, such studies did not incorporate particle morphology. This paper explores the effect of particle shape on kinematics and impact dynamics against a rigid obstacle. First, the numerical results have been benchmarked against the experimental studies for conventional spherical particles, and then we explore the effect of particle morphology. The present findings indicate that the particle shape significantly influences the flow kinematics and leads to a reduction in impact force on the barrier due to the higher angularity of particles with different morphological features than spherical particles, generally considered in the existing literature. A more significant implication of this study is to better understand and design mitigation measures against geohazards.

Keywords. Dry granular flow, Discrete Element Method, Impact dynamics, Rigid barrier, Sphericity

1 INTRODUCTION

Granular mass flows are catastrophic events that substantially affect infrastructure and communities, particularly in mountainous regions characterized by rapid downhill movement of tremendous amount of granular material. They are often triggered by factors like steepening of slopes, cloudbursts, deforestation, seismic events, etc. [1, 2]. The profound consequences of such calamities, encompassing significant human casualties and substantial financial losses, have prompted the engineering community to comprehensively examine the design considerations and the intricacies of impact dynamics associated with landslide countermeasures. Various installations and safety structures, such as rigid barriers, gabion walls, flexible barriers, slit dams etc., have been deployed along the anticipated flow path to mitigate the destructive forces of granular mass flows across various parts of the world [1, 2, 3, 4, 5]. However, there still exists some lack of understanding of the fundamental physics of landslides involving granular mass flows.

The complex kinematics involving granular media and their corresponding impact dynamics against safety structures have been investigated to some extent in the existing literature by conducting experimental studies on instrumented inclined channels, field experiments and by employing analytical, physical and numerical modelling schemes [6, 7]. While experiments provide invaluable datasets for validating simulation results and providing real-world validation, numerical simulation complements these experimental studies by offering additional insights, scalability, repeatability, and cost-effectiveness in studying granular flow that is not easily accessible by physical experiments. In the realm of numerical simulations, different approaches have been utilized, such as modified versions of classical Finite Element Method (FEM), Smoothed Particle Hydrodynamics (SPH), Material Point Method (MPM), Discrete Element Method (DEM) etc. [7, 8]. Although some insights can be gained on the critical risk assessment factors within the continuum numerical framework (Arbitrary Lagrangian-Eulerian (ALE), Coupled Eulerian-Lagrangian (CEL), MPM, SPH etc.), the granular interaction within the particle assembly cannot be accounted for. Analyzing the particle interaction and their impact dynamics with barriers at a micro level is essential for comprehending the underlying mechanics and physics of granular flows. Traditional continuum numerical methods fall short of truly deciphering these characteristics of granular mass flow events. Then a natural and more rational choice is to employ a micromechanical analysis through a particle-based approach - DEM [6].

Utilizing its inherent formulation focused on particle interactions, Discrete Element Modeling provides a seamless way to explore the flow of granular materials. This investigation is crucial for understanding the interaction between flowing material and barriers for identifying paths along which force is transmitted in a granular ensemble [6, 9]. These aspects, although challenging to gain access through experimentation, are vital for enhancing energy dissipation efficiency and designing safety barrier systems. They can readily be probed using the rich amount of data obtained through DEM simulations. Notably, particulate media constitute the fundamental constituents of soil, exerting a pivotal influence on the overall macroscopic behaviour of the system and hence understanding its impact on the underlying granular physics of landslide and debris flow is of utmost importance.

As one of the most critical features, particle shape dictates various vital aspects of granular behaviour, including strength, deformation, shear, dilatancy and flow characteristics, as highlighted by several researchers [2, 3, 10, 12, 13]. Most DEM investigations involving granular flow analysis have utilized conventional spherical particles due to their ease of physical handling and computational efficiency. The insights offered thereafter are limited in their ability to capture the complex micromechanical interactions observed among the particulate system. Thus, the present study explores the particle shape effect (mainly focusing on regular shapes) on the dynamics of dry granular flows and their interactions with a rigid barrier. Particle shapes can be generated by clumping spherical particles or creating polyhedral elements [3, 7]. The clumped particles have simplicity in their modelling and contact detection and are widely used for particle breakage analysis [7], but the particle surface becomes knobbly, and the contacts are generally overestimated in this case. Hence, polyhedral elements have been used in this study along with ellipsoids and cylinders to replicate the effect of particle shape by generating rigid blocks of regular shapes. With algorithmic advancements and increased computing power, conducting relatively large-scale simulations with polyhedral particles has become possible [7, 13], and we take advantage of this aspect in our study to explore the effect of particle shape on granular mass flow events and the consequent impact dynamics with the barrier.

The present research within a discrete element framework offers new insights applicable to practical engineering scenarios. A comparison between the outcomes derived from conventional spherical particles and those from regularly shaped particles (Dodecahedron, Octahedron, Tetrahedron, Ellipsoid and Cylinder considered in this study) is drawn within the computational setting of DEM. This evaluation explores their sphericities, a widely utilized shape parameter [14] for distinguishing the effects of various particle configurations on the flow kinematics as well as the impact dynamics.

2 METHODOLOGY

The numerical computation is carried out with PFC3D software package utilizing the soft sphere technique of DEM, where particles can overlap at contacts [6]. The subsequent sections elucidate the specifics of the Discrete Element modelling approach and the model configuration. This includes an emphasis on the contact mechanics between interacting bodies and the procedure for updating particle position and orientation.

2.1 Numerical Modelling Scheme

Discrete element modelling technique entails the direct computation of equilibrium contact forces and particle displacements within a granular assembly, achieved by monitoring the trajectories of individual particles [6]. The calculation involves an iterative process where the force-displacement law determines the contact forces, and Newton's second law of motion is utilised to update the particle position and orientation. Throughout this cycle, the interactions between particles are continuously monitored at contacts, and the movement of each particle is tracked, assuming constant velocity within each numerical timestep [9]. This is implemented in the present study as follows:

2.1.1 Contact Model

A non-linear Hertz-Mindlin contact model is applied in the present study, which originates from the elastic theory of non-conforming spherical bodies and includes the development of contact area [5, 9]. The forces at contact are calculated as follows:

$$F_c = F_n + F_t \tag{1}$$

Total normal force,

$$F_n = F_n^h + F_n^d \tag{2}$$

$$F_n = k_n \delta n_{ij} - \gamma_n \dot{\delta} n_{ij} \tag{3}$$

Total tangential force

$$F_t = F_t^h + F_t^d \tag{4}$$

$$F_t = k_t \delta t_{ij} - \gamma_t \dot{\delta} t_{ij} \tag{5}$$

where,

$$k_n = \frac{4}{3} E^* \sqrt{R^* \delta n_{ij}} \tag{6}$$

$$\gamma_n = -2\sqrt{\frac{5}{6}} \beta(C_R) \sqrt{2E^* \sqrt{R^* \delta n_{ij}} m^*} \geq 0 \tag{7}$$

$$k_t = 8G^* \sqrt{R^* \delta n_{ij}} \tag{8}$$

$$\gamma_t = -2\sqrt{\frac{5}{6}} \beta(C_R) \sqrt{8G^* \sqrt{R^* \delta n_{ij}} m^*} \geq 0 \tag{9}$$

where F, k, δ and $\dot{\delta}$ are the force, stiffness, overlap distance and relative velocity, respectively for particles i and j. Superscript h, d are used for hertzian and damping components while the subscripts n,t are used for normal and tangential directions, respectively.

$$\frac{1}{R^*} = \left(\frac{1}{R_i} + \frac{1}{R_j} \right) \tag{10}$$

$$\frac{1}{m^*} = \left(\frac{1}{m_i} + \frac{1}{m_j} \right) \tag{11}$$

$$\frac{1}{E^*} = \frac{(1 - \nu_i^2)}{E_i} + \frac{(1 - \nu_j^2)}{E_j} \tag{12}$$

$$\frac{1}{G^*} = \frac{2(2-\nu_i^2)(1+\nu_i^2)}{E_i} + \frac{2(2-\nu_j^2)(1+\nu_j^2)}{E_j} \tag{13}$$

$$\beta = \frac{\ln C_R}{\sqrt{\ln^2 C_R + \pi^2}} \tag{14}$$

where R^*, m^*, E^* and G^* are the effective radius, mass, elastic modulus, and shear modulus, respectively, and β is a constant that depends on the coefficient of restitution (C_R).

2.1.2 Time Integration Scheme

A central difference Velocity-Verlet time integration scheme is employed in the present study for calculating particle position ($\boldsymbol{x}$) and rotations ($\boldsymbol{\theta}$). It includes the calculation of total forces between particles by using known locus of particles at a given time t [9]. Then the resultant forces ($\boldsymbol{F_b}$) and moments ($\boldsymbol{M_b}$) acting on particle at time t results in the net acceleration of each particle, which is integrated as follows to calculate the velocity and displacement to update the particle location at subsequent timestep $(t+\Delta t)$:

$$m_b(\ddot{x_b})_i = \sum (F_b)_i \tag{15}$$

$$I_b(\ddot{\theta_b})_i = \sum (M_b)_i \tag{16}$$

Velocity,

$$((\dot{x_b})_i)_{\left(\frac{t+\Delta t}{2}\right)} = ((\dot{x_b})_i)_{\left(\frac{t-\Delta t}{2}\right)} + \left[\frac{\sum (F_b)_i)}{m_b}\right]_t \Delta t \tag{17}$$

$$((\dot{\theta_b})_i)_{\left(\frac{t+\Delta t}{2}\right)} = ((\theta_b)_i)_{\left(\frac{t-\Delta t}{2}\right)} + \left[\frac{\sum (M_b)_i}{I_b}\right]_t \Delta t \tag{18}$$

Displacement,

$$((x_b)_i)_{(t+\Delta t)} = ((x_b)_i)_t + ((\dot{x_b})_i)_{\left(\frac{t+\Delta t}{2}\right)} \tag{19}$$

$$((\theta_b)_i)_{\left(\frac{t+\Delta t}{2}\right)} = ((\theta_b)_i)_t + ((\dot{\theta_b})_i)_{\left(\frac{t+\Delta t}{2}\right)} \tag{20}$$

Now, the particle position and the respective orientation is updated. The calculated displacement of the particle is used to update the forces and moments acting on these bodies. This calculation is repeated for new time increments till the end of the simulation process.

2.2 Model configuration

This investigation involves configuring DEM modelling of granular flow in a dry state impacting a rigid barrier according to Goodwin and Choi's (2021) experimental and numerical analyses [5]. The numerical framework encompasses several vital components describing the experimental setup. These components involves a storage container at the uppermost part of the flume, an inclined flume with a 30° inclination angle, and a rigid barrier at the flume's lower end. The geometric dimensions of these elements are represented in Figure 1.

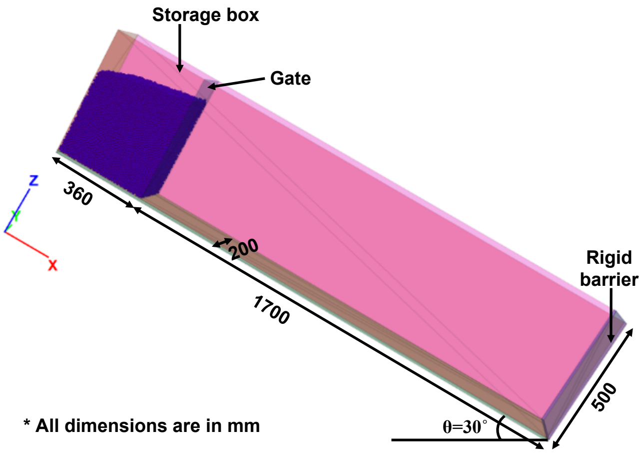


Figure 1: Flume geometry (after [5])

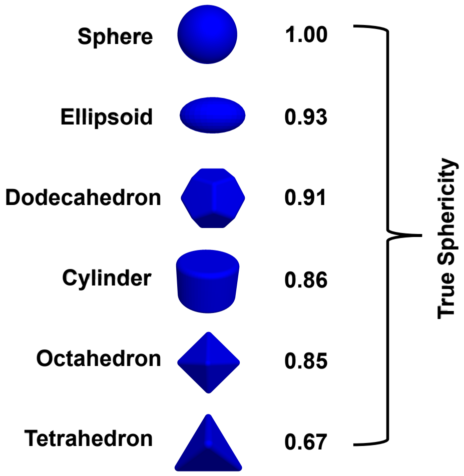


Figure 2: Regular particle shapes considered in this study

The storage container is filled with a total of 30,000 poly-dispersed particles in similar lines of the previously reported literature as by Goodwin and Choi. These particles, sized at 10 ± 1 mm, are generated randomly and follow an approximate Gaussian distribution. This choice of distribution serves to mitigate the introduction of an artificial crystalline arrangement. The initial deposition of particles within the container is controlled by the gravitational force, and subsequently, the direction of gravity is adjusted to simulate the inclined channel flow. The particles are allowed to reach an equilibrium state under this new gravitational orientation. After this phase, the simulation replicates a dam-break scenario by removing the frontal trigger gate (Figure 1), an interface between the storage container and the flume. Consequently, the particles are allowed to flow through the inclined flume, followed by an eventual collision with the rigid barrier (Figure 1).

The immobile plane, representing a rigid barrier, follows a well-established convention described in existing literature [5]. The essential input parameters for the DEM simulation have been extracted from DEM studies carried out by Goodwin and Choi. These crucial parameters, which significantly influence the simulation, are listed down in Table 1.

The initial step of the study involves employing spherical particles to establish a reference point for the current investigation. This allows for an analysis of the impact force against the safety barrier. Subsequently, various typical particle shapes are considered

Table 1: DEM input parameters (after [5])

Number of Particles	-	30,000
Grain diameter	m	0.01±0.001
Particle density (ρ_s)	kg/m^3	2650
Young's modulus (E)	MPa	10
Shear modulus (G)	MPa	3.85
Poisson's ratio (ν)	-	0.3
Interparticle friction (ϕ_p)	-	0.36
Particle-wall friction (ϕ_w)	-	0.306
Coefficient of restitution (C_R)	-	0.5
Time step (Δt)	sec	1×10^{-5}

to encompass unique morphological characteristics of particles. These diverse shapes are created within the DEM framework as rigid blocks. Figure 2 illustrates the different shapes (Sphere, Ellipsoid, Dodecahedron, Cylinder, Octahedron and Tetrahedron) and their associated sphericity, calculated using the well-recognized Wadell's true sphericity formula for three-dimensional particle shapes [11, 14]. The true sphericity is expressed as follows:

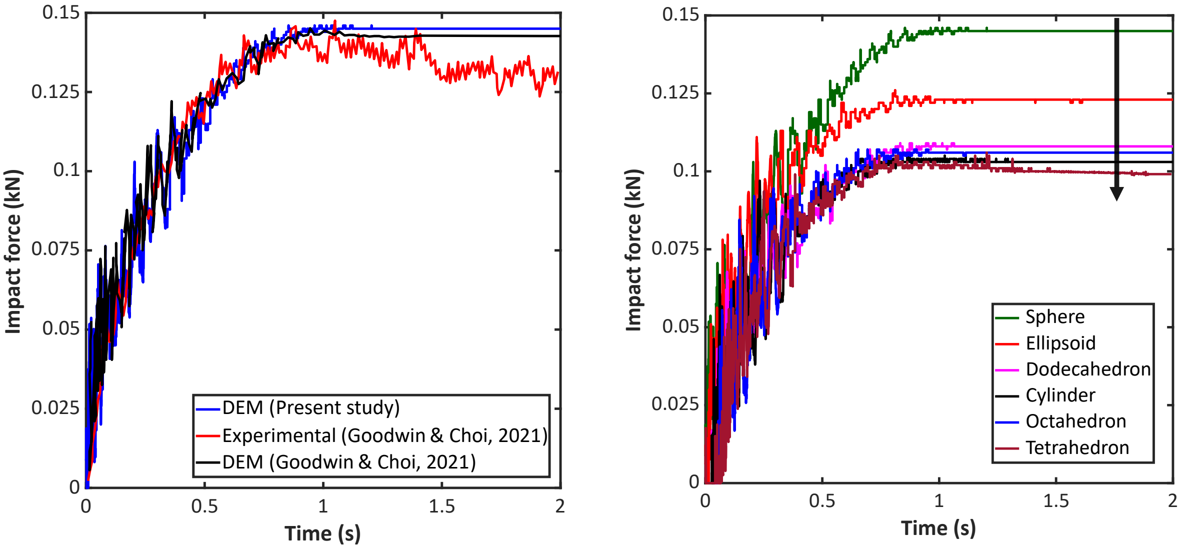
$$\text{True Sphericity} = \frac{\text{Area of sphere having same volume as particle}}{\text{Area of particle}}$$

In order to maintain a consistent mass of the granular assembly, the rigid blocks are produced with their volume matched to that of the spherical particle examined in the research by Goodwin and Choi [5].

3 RESULTS AND DISCUSSION

3.1 Validation

This section involves a comparison between the results acquired from analyzing spherical particles and the experimental and DEM findings presented by Goodwin and Choi [5]. The process includes allowing particles to flow through an inclined flume and collide with the rigid barrier positioned at the flume's lower end (Figure 1). Upon impact, the particles exhibit a runup mechanism until reaching a specific height, followed by a subsequent backflow. As time progresses, more particles collide, leading to a progressive rise in the impact force on the barrier (Figure 3(a)). This rise in impact force continues until a particular period, at which point the force acting on the rigid obstacle becomes constant. Figure 3(a) shows that the impact force on the rigid barrier follows a hyperbolic nature in the same manner as the earlier reported findings by Goodwin and Choi [5]. This behaviour is attributed to a decline in the kinetic energy of the particles resulting from inter-particle interactions during granular flow.



(a) (b)

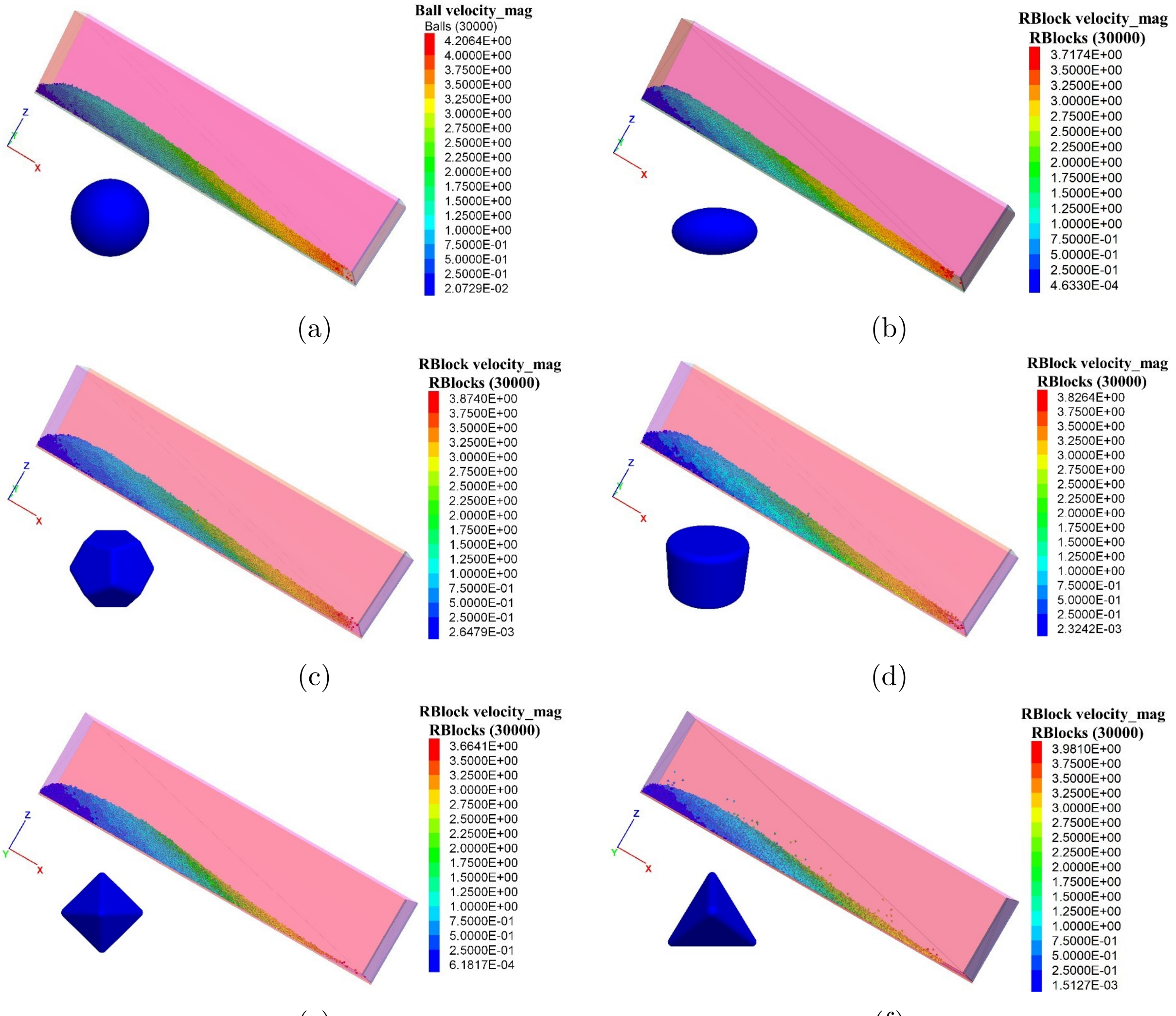
Figure 3: Impact force vs normalized time plot (a) Benchmarking [5], and (b) effect of particle shape

Further, the present study is validated based on the impact force acting on the rigid obstacle. To facilitate this comparison, time is normalized such that $t = 0$ seconds corresponds to the instance of the initial collision with the rigid barrier. Figure 3(a) shows a reliable measure of qualitative and quantitative estimates that align well with the outcomes of Goodwin and Choi's experimental and numerical analyses. Besides this, the maximum frontal velocity obtained as 4.2 m/sec in the current study shows a good correlation with that reported with high fidelity in the literature, i.e. 4.0 m/sec [5] for spherical particles. With these observations, a successful validation of the current research has been achieved.

3.2 Effect of particle shape

Following the successful validation of DEM simulations for dry granular flow against a rigid barrier using conventional spherical particles, a detailed investigation of the granular flow behaviour and its interaction with a safety structure has been undertaken by incorporating particle morphological attributes. The granular flow analysis focuses on the well-defined geometries depicted in Figure 2, particularly emphasising their true sphericity [14].

Focusing on particle morphological effects, the key comparison revolves around the flow kinematics and impact dynamics of granular mass flows. Figure 3(b) provides a more detailed comparison of the peak impact loads exerted by geophysical flows when interacting with rigid barriers. It is evident from this plot that both the peak and residual impact forces decline with reduction in particle sphericity (Figure 3(b)). This trend is related to reduced flow kinematics of particles with less sphericity due to more flow resistance of-

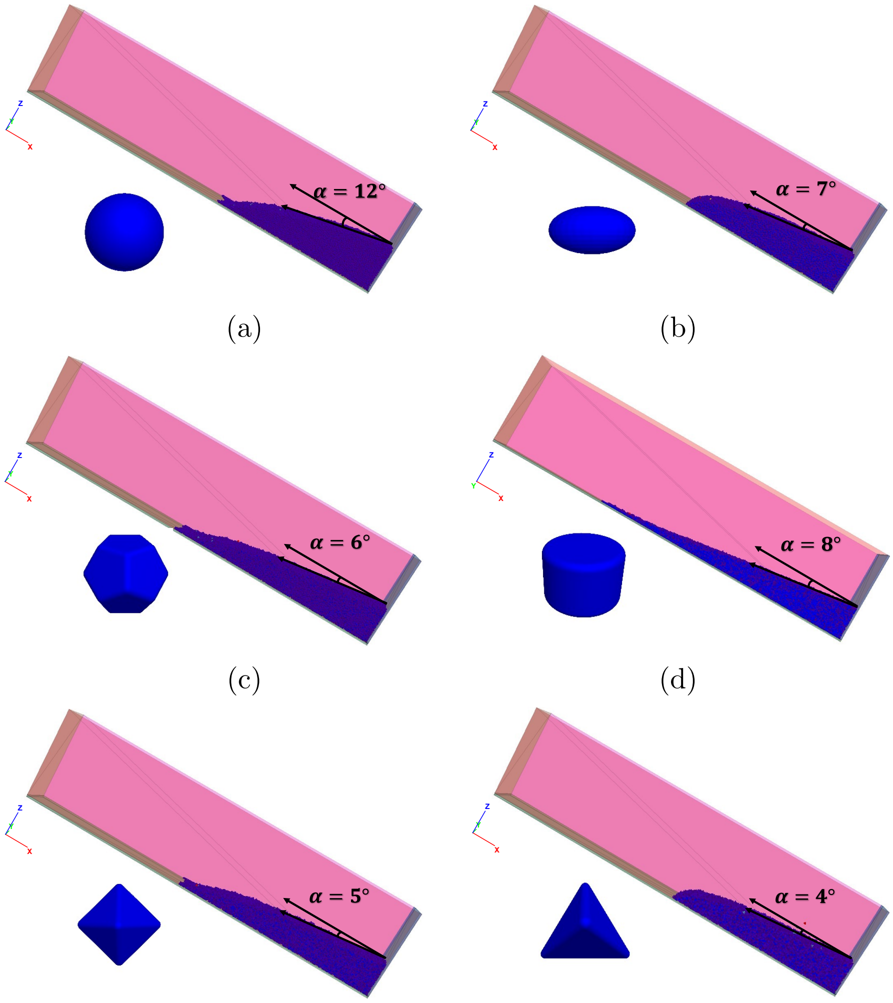


(a) (b) (c) (d) (e) (f)

Figure 4: Particle velocity (in m/sec) profiles just before impact with rigid barrier

fered by angular particles. The present study signify the importance of evaluating particle shape effect on granular mass flows and their interactions with barriers due to the prevalent occurrence of non-spherical particles in nature. Traditional landslide safety structure designs often incorporate excessive impact dynamics of spherical particles (Figure 3(b)), leading to a conservative and economically inefficient design.

During the interaction between granular flow and a rigid barrier, the influence of particle shape on the key stages of interaction has been noticed. These stages include the initial frontal impact (Figure 4), the subsequent run-up, and the final static deposition (Figure 5). It has been noticed that, with decreasing sphericity the frontal impact observed to be more delayed and less pronounced (Figure 4). This phenomenon results from decreased kinetic energy within the flow, resulting in lesser runup height for less spherical particles. Subsequently, the runup process is succeeded by a backflow, initiating the onset



(a) (b)

(c) (d)

(e) (f)

Figure 5: Dead zone formation for different shapes of particles

of the pileup mechanism. The deceleration of granular material upon impact with the rigid obstacle creates a dead zone upstream of the barrier. Throughout this progression, the dissipation of granular energy is primarily facilitated through interparticle viscous damping and frictional interactions.

Moreover, the steepness of the dead zone surface that forms behind the barrier is most prominent when using perfectly spherical particles. This steepness gradually lessens as the sphericity of the particles decreases (Figure 5). A comprehensive depiction of the dead zone characteristics of particles of varying shapes is presented in Figure 5. This plot shows an ultimate reduction in residual impact force acting on the barrier with decreasing sphericity of particles. The ultimate dead zone configuration for various particle shapes, as shown in Figure 5, reaffirms the trend of diminishing residual impact force as seen in Figure 3(b) with decreasing sphericity. This outcome arises due to the inverse relationship between particle angularity and the concentration of granular material near the barrier.

Consequently, the channel bed absorbs more of the overall force from this granular flow, particularly in flows containing particles with reduced sphericity.

These findings establish that particle shape dictates both the flow kinematics and impact dynamics of granular mass flows. Therefore, considering the particle shape effect in the analysis of such flows and their interactions with barrier system is crucial for refining design strategies and enhancing the accuracy of safety assessments while optimizing economic efficiency.

4 CONCLUSION

Numerical flume tests were conducted to examine the effects of dry granular flows colliding with a rigid barrier. The simulations considered the impact of particle shape by utilizing rigid blocks with different polyhedral shapes (Dodecahedron, Octahedron and Tetrahedron), Ellipsoids and Cylinders. The results obtained from these simulations discover the intricacies of interactions between the flowing granular material and the barrier. The analyses indicate that the non-spherical particles employed in the DEM simulations can accurately replicate the dynamics of granular flows. The findings of this study can be summarized in the following manner:

- The analysis concludes that particles with lower sphericity experience an increased flow resistance. This can be attributed to the additional resistance to rolling present in non-spherical particles, a factor not considered in conventional spherical particles.
- Numerical investigations have revealed that employing the conventional DEM model with exclusively spherical particles substantially overestimates granular flow dynamics. As a result, this approach could make the design of safety structures economically unfeasible.

The numerical outcomes obtained through this study offer novel perspectives on the interaction between granular flows and rigid barriers considering particles with different shapes. In the present research, the sphericity of grains has been considered for the characterization of particle shape. To represent the general form of grain morphology, other than the sphericity of grains, the aspect ratio, convexity, and surface roughness should be considered in future studies of granular flows.

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