Numerical study of retention efficiency of a flexible barrier in mitigating granular flow comparing with large-scale physical modeling test data

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Abstract

Retention behavior of a flexible barrier in mitigating a granular flow is still an open problem not fully understood, especially due to the complexity of the granular material and the flexible barrier. Understanding the retention mechanism and quantifying the influencing factors of retention efficiency are desirable for optimizing the design and minimizing the maintenance cost of a debris-resisting flexible barrier. In this paper, a numerical model, based on the discrete element method, is presented, calibrated, and validated to analyze the interaction between a granular flow and a flexible net. A full-scale numerical simulation is first performed to compare with a large-scale physical modeling test in the literature and validate the applied parameters in the simulation. The interaction and deposition characteristics of the granular flow interacting with a flexible net are revealed. Afterwards, parametric study is performed to investigate the effects of the internal friction angle (φ) of debris material and the relative mesh size of flexible net on the retention efficiency and clogging mechanism of a flexible barrier. The simulation results illustrate that the particle passing ratio (P) increases with increment of the friction angle of particles and enlargement of the mesh size of a flexible net. Both parameters have critical effects on the retention efficiency of a flexible barrier in intercepting a granular flow. Therefore, the friction angle and the particle size distribution (PSD) characteristics of the debris material are suggested being used for optimization of the mesh size and more efficient design of debris-resisting flexible barriers.

Keywords: Discrete element method; Flexible barrier; Retention efficiency; Granular flow

1. Introduction

Gravity-driven flows of grain-fluid mixtures with free upper surfaces are common geomorphologic phenomena in mountainous regions, which can impose serious threats to human lives, properties and the infrastructure (Crosta et al. 2001; Cui et al. 2019; Sidle and Chigira 2011; Guo and Cui 2020; Hu et al. 2012). Flexible barriers have been increasingly utilized to prevent those geohazards (Guasti et al. 2011; Song et al. 2018). Compared to conventional rigid concrete check dams, flexible barriers are efficient in impact energy absorption, adaptable to various natural terrains, and friendly to eco-environment (Volkwein et al. 2015). A typical flexible barrier mainly consists of a flexible net, supporting structures, and foundations. The dynamic loads of a granular flow first impose on the flexible net, then transfer to the supporting structures, finally to the foundation (Volkwein 2014).

In the research of geohazard mitigation, large-scale physical modeling tests are preferred by researchers for discovering the interaction characteristics by reproducing impact loads comparable to real events (Bugnion et al. 2012; Iverson et al. 1992). However, based on our experience, a well-prepared physical modeling experiment for granular flow research requires a large-scale experiment facility, a comprehensive dynamic monitoring system, and a long period for preparing massive experiment materials (normally more than several tones), which are extremely time-consuming and environment-impacting. Numerical simulation, as a potential alternative, provides a useful supplement for systematically investigating the behavior of each component of the research system and quantitatively assessing different influencing parameters (Albaba et al. 2017; Cui et al. 2017; Gao and Meguid 2018). The numerical models for the study of granular flow interacting with a flexible barrier are mainly based on finite element method (FEM) (Volkwein 2014; Kwan et al. 2014; Koo et al. 2017; Leonardi et al. 2016) or discrete element method (DEM) (Cundall and Strack 1979; Li and Zhao 2018; Albaba et al. 2017; Leonardi et al. 2019; Zhou et al. 2020). Compared to FEM, which is appropriate for simulating continuous medium, DEM is more suitable for modeling the system where large relative displacements may occur owning to its inherent advantage in describing the behavior of granular materials. DEM has been utilized and developed in the past few decades for modeling granular flows (Zhou and Ng 2010; Teufelsbauer et al. 2011; Cui et al. 2018) and the interaction with flexible barriers (Hearn 1992; Bourrier et al. 2015; Li and Zhao 2018). Calvetti et al. (2017) conducted DEM simulations to investigate the influencing factors of the maximum impact force imposed by a granular flow on a rigid obstacle. Marchelli et al. (2019) analyzed the interaction of dry granular flows with silt dams and assessed the retention efficiency of a silt dam embedding an outlet with the help of DEM. However, few studies have focused on the retention efficiency of a flexible barrier intercepting a granular flow. The design of flexible nets should be optimized to properly trap hazardous boulders, tree trunks, large debris, but allow small particles and slurry pass through to increase the retention efficiency and reduce the burden of cleaning the filled barrier. Wendeler and Volkwein (2015) concluded from laboratory tests that a good retention ratio can be reached when the mesh size of the flexible net is equal to d_{90} (90% of the sample's mass is comprised of particles with a diameter less than this value) of the debris material. Huo et al. (2018) concluded that the mesh size of a flexible barrier is a significant parameter for enhancing the functionality of retaining granular flows. Tan et al. (2019) found that passing-through of a certain percentage of debris material can reduce the impact force on the flexible barrier. However, drawing useful conclusions from the results of numerical and experimental studies remains difficult but essential. Researches on the retention mechanism of flexible nets and the influencing factors, such as the mesh size of the flexible barrier and the internal friction angle of the debris materials, on the retention efficiency are still lacking.

The main objectives of this study are to investigate the retention mechanism of a granular flow with a flexible barrier including the clogging mechanism of particles behind the mesh openings and the influencing factors of debris retention efficiency. To realistically reflect the interaction and retention behavior of a granular flow, the data of a large-scale granular flow impact test in the literature (Tan et al. 2018) are used to calibrate and validate the numerical model established in this study. Basic parameters of particles in the simulation are elaborated based on the element tests of the granular material. Reliability of the numerical model is assessed by comparing the retention behavior of a full-scale simulation with the physical modeling test. Afterwards, the validated numerical model is used to investigate the influences of the friction angle of debris material and the mesh size of a flexible net on the retention efficiency and the clogging mechanism of granular flow interacting with a meshing net.

2. Numerical model setup

In this study, the DEM tool is adopted to simulate both the granular flow and the flexible barrier, which is modified from the software EDEM (www.edemsimulation.com). The numerical model tests were conducted using a workstation with the Intel i9-9900k processor. DEM explains the interaction between particles by solving the Newton's equation governing the translational and rotational motions of particles in the computational system. The sum of forces of a particle i consists of the gravity force and the contact forces with other particles:

$$F_i = m_i g + \sum_{j=0, i \neq j}^{N} F_{ij} \tag{1}$$

where F_i is the sum of forces for particle i, $m_i = \rho_i \frac{4}{3}\pi r_i^3$ is the mass of particle i with the density ρ_i and the radius r_i, N is the number of the contacts on particle i, F_{ij} is the contact force between particle i and particle j.

In the simulation, the contact force can be decomposed into the friction force ($F_{f,ij}$), the contact forces in the normal direction ($F_{n,ij}$) and the tangential direction ($F_{t,ij}$):

$$F_{ij} = F_{n,ij} + F_{t,ij} + F_{f,ij} \tag{2}$$

The contact model is shown in Figure 1. From this figure, the contact forces ($F_{n,ij}$, $F_{t,ij}$) are calculated following the Hertzian–Mindlin contact law by using the springs of stiffness, k_n and k_t, and the damping elements of constants, a_n and a_t. The friction force ($F_{f,ij}$) is calculated using a Coulomb-like criterion with a constant coefficient of sliding friction, μ_s.

2.1 DEM modeling principles for granular flow and flexible barrier

In this study, granular flow is simulated by spherical particle assembly as a compromise to computational efficiency. It is known that spherical particles cannot perfectly replicate the flow and deposition behavior of real irregular grains (Iverson 2015). To overcome this drawback, rolling resistance (μ_r) is added to the contact model (Girolami et al. 2012; Li et al. 2018; Marchelli et al. 2019). The rolling friction is expressed by generating a torque (M_i) to the contact point of a particle (Girolami et al. 2012):

$$M_i = \mu_r F_n \frac{\omega_r}{|\omega_r|} r_i \tag{3}$$

where μ_r is the coefficient of the rotation friction; F_n is the normal force; ω_r is the angular velocity vector objective at the contact surface; r_i is the distance between the center of the mass and the contact point.

The described contact model is used to update the position and orientation of each particle in the calculation domain at the given time step. The Young's Modulus and the Poisson's ratio of the particles are determined referring to the literature (Zhu et al. 2019). The friction coefficients (μ_s and μ_r) are calibrated by the element sliding tests, which will be described in the following section.

The flexible barrier is simulated by a modified method for DEM originated from the built-in bonding model in EDEM. Discrete particles with remote parallel bonds were originally used for modeling rockfall-resisting wire mesh fence (Nicot et al. 2001; Bertrand et al. 2008; Thoeni et al. 2013). Nowadays, this method has also been adopted to simulate the flexible net of a more complicated debris-resisting flexible barrier (Li and Zhao 2018). To study the retention behavior, a flexible mesh net is simulated by the following steps:

(a) A real rhombus wire mesh net has been digitalized to provide a reference for the arrangement of the net (see Figure 2a). Pre-arranged particles are used to replace the cylindrical mesh wire for simulating its contact with granular particles with a center-to-center distance of 15 mm. The diameter and density of the particles are referring to the parameters of the flexible mesh net in the flexible debris-mitigation system.

(b) A remote contact referring to a virtual bar-like “glue bond” is used to connect two neighboring net particles, as shown in Figure 2b. This bond has no weight but can sustain normal and tangential forces (F_n, F_t) and moments (M_n, M_t) (Potyondy and Cundall 2004). By utilizing this type of bond, the simulated flexible barrier can sustain large deformation similar to a real flexible mesh net.

3. Calibration of parameters

Key parameters need to be calibrated before processing numerical modeling simulations. The contact model on the frictional properties of the granular mass is investigated, which establishes a link to the flowing parameters of natural debris material. The internal friction coefficients (μ_s and μ_r) of the debris material and the basal friction coefficient between the granular material and the slope base ($\mu_{s,c}$) are calibrated by reproducing simple tests recommended in the literature (Hutter and Koch 1991; Zhou et al. 2014). It is difficult to simulate a real-scale granular flow using particles of original diameters due to the high calculation cost of DEM in simulating a massive number of particles. Reasonable amplifications for both particle diameter and mesh size are applied in this study to increase calculation efficiency. In order to realistically reflect the flow and retention behavior of the granular flow in the large-scale physical modeling test, necessary calibration tests of the modified simulation system are conducted. Basic parameters of the amplified particles, such as the internal friction angle and the friction coefficient with the slope base, are first calibrated using the results of the element tests of real debris material. Moreover, appropriate amplification factors for the particles and the mesh size of the flexible net are determined by calibration tests to guarantee that the simplified simulation system can replicate the retention characteristics of the real-scale particle-net system.

3.1 Calibration of friction coefficient by conical sand-piling test

Hutter and Koch (1991) identified the angle of repose of the cone pile as the internal angle of friction (φ) of granular material. Simple conical sand-piling test was performed to determine the angle of friction by pouring granular material on a rough surface (Hutter and Koch 1991; Miura et al. 1997; Zhou et al. 2014). The test follows three simple steps: (a) fill granular material into a PVC tube (length: 1.5 m, diameter:0.2 m); (b) lift the tube gradually and let the granular particles freely pile on the rough ground surface to form a cone. The angle of repose can be measured from the side view photograph of the cone (see Figure 3) by averaging the angles of the shoulders (φ_1, φ_2) and the angle calculated from the cone shape $\varphi_3 = \arctan\left(H/B\right)$. Repeated tests were conducted to obtain reliable results. Using this method, the measured angle of repose for the granular material is 30°. The same process is replicated using the DEM model to calibrate the sliding friction coefficient (μ_s) and rolling friction coefficient (μ_r) of the amplified particles in the simulation system, and the simulation results are obtained when the residual kinetic energy vanishes. By simulating the sand-piling tests with different friction coefficients, the corresponding friction coefficients for specific friction angles are obtained in Table 1. Those parameters will be used in the following sections for parametric study.

3.2 Calibration of interface friction coefficient by column sliding test

The interface friction coefficients are calibrated by the column sliding test (Zhou et al. 2014). A short PVC tube (height: 0.1 m, diameter: 0.2 m) was filled by granular particles on a steel plate with a similar roughness as the slope base, as shown in Figure 4a. The PVC tube was lifted 5 mm up to avoid the contact between the tube and the basal plate. The test was started by tilting the steel plate gradually. Meanwhile, a gentle push was imposed on the column in the sliding direction until the tube starts to slide continuously. The final tilting angle for continuous sliding of the column was measured as the interface friction angle between the granular material and the slope base. Three tests were repeated to obtain reliable data. For the material and slope base in this study, the measured interface friction angle is 21°. This test procedure is replicated in the numerical model to calibrate the interface friction coefficients of the simulated particles, as shown in Figure 4b, c, d. The calibrated parameters of the steel plate are also adopted to define the frictional contact between the granular material and the flexible net considering the similar properties of metallic material. The calibrated friction coefficients are listed in Table 2.

3.3 Calibration of the amplification factors for particles and mesh size

Two simplifications are adopted to increase the calculation efficiency of the DEM simulation. First, the particles are categorized into four groups by the diameter (see Figure 5). Second, the mesh size of the flexible net is amplified 1.5 times from 50 mm to 75 mm for less barrier particles and bonds. To validate those simplifications, the Uniformity coefficient (Cu), Coefficient of gradation (Cc), and sorting coefficient of simulation are calculated and compared with the large-scale experiments to indicate the similarity, as listed in Table 3. Moreover, the amplification factor of the particles is determined by comparing the simulation results of the real-size particle-net system with the amplified system using a scale-down simulation domain. The scale-down domain contains a small-scale channel with the width of 0.5 m and a segment of net with the dimension of 0.5 m×0.5 m. Simulations are performed to calibrate the amplification factor of the particle system by comparing the retention behavior of the amplified particle-net system with the real-size system. To quantify the retention efficiency of the flexible net, the Particle Passing Ratio (P) is introduced to quantify the percentage of the passing particles, which can be written as:

$$P = \frac{m_p}{m_t} \times 100\% \tag{4}$$

where m_p is the mass of the leaked granular particles, and m_t is the total mass of the granular flow.

Results of the calibration tests are plotted in Figure 6, which shows that the appropriate amplification factors of the particle system and the flexible net are 1.8 and 1.5, respectively.

4. Simulation process and results of full-scale calibration test

A full-scale DEM simulation is performed to validate the calibrated parameters by replicating a large-scale physical modeling test presented in the literature (Tan et al. 2018). The gravel mass and the geometries in the simulation are kept the same with the physical modeling test. Generation of the granular particles follows the particle size distribution characteristics of the granular material in the physical modeling test. As mentioned in the above section, the particles are categorized into four groups by the diameter, and the mesh size of the flexible net as well as the particle system are amplified 1.5 times and 1.8 times, respectively, to increase calculation efficiency.

4.1 Model setup for granular mixture and flexible barrier

The granular assembly is generated in a storage tank located at the upper end of the slope with the front door closed. Particles with a total mass of 6000 kg are generated in a cubic pattern above the storage tank obeying the predefined categorizing rule. The "sand pluviation technique" is utilized in the material preparation process for unifying the bulk density (Iqbal 2012). In the large-scale experiments, the door flipped up in a short period to avoid the interference to the initiated debris flow with the assistance of an original door-opening system (Tan et al. 2020). To simplify the fast door-opening process, the door is set to be removed by virtualizing the front surface in the numerical simulation after the particles are generated and settled. The model setups of a granular mixture and a flexible mesh net located at the lower end of an inclined slope are illustrated in Figure 7. The dimensions of the simulation geometries are marked in this figure, which are kept the same with the physical modeling facility in Tan et al. (2018). Since this study mainly focuses on the retention efficiency of a flexible barrier, the parameters of the connecting bond between particles are referring to the calibrated data in Li and Zhao (2018), and the critical stress which representing the strength of the flexible net is set relatively high to guarantee that the net is unbreakable under the impacts of a granular flow. Table 4 summarizes the adopted parameters for the particulate granular mixture and the flexible mesh net together with the controlling parameters of the DEM simulation.

4.2 Results of the full-scale numerical simulation

The flow and interaction behavior of the simulated granular flow are compared with the granular flow impact test (Test 1) presented in Tan et al. (2018). Figure 8a compares the particle passing ratio in the simulation with the value in the large-scale experiment for calibrating the debris retention behavior of particles in the simulation. It shows that the trapped particles by the flexible net can settle down and form a stable deposition dam within 2 seconds, and the particle passing ratios in the simulation and the large-scale test are both around 1.7%. The identical particle passing ratio during impact process in the full-scale simulation test shows that the numerical model can well reflect the interaction behavior between granular flow and flexible net. The interaction characteristics at typical times are plotted in Figure 8b. To be constant with the time in the physical modeling test, the starting time of impact is set to 0 s in the figures plotting the simulation results. When the granular flow initially impacts on the flexible barrier, the majority of particles are trapped by the flexible mesh net, and a small proportion of particles pass the flexible barrier through the mesh openings. Afterwards, the trapped particles settle down and form a triangle deposition zone, while the unstable particles still can slowly leak from the mesh openings. With deposition of the granular flow, the interface between the granular material and the flexible barrier enlarges gradually, which accelerates leakage of particles at this stage. During the growth of the deposition wedge, the granular front moves on the top surface of the deposition wedge and losses its velocity gradually due to the inter-layer friction. The belated granular flow deposits behind the dead zone instead of directly impacting on the flexible barrier. From Figure 8, it can be concluded that the interaction behavior and the passing-through characteristics of a granular flow impacting on a flexible net in the numerical simulation fit well with the observation and measurement in the physical modeling test. Figure 9 further compares the lateral displacement and the deposition height in the simulation with the large-scale experiment to quantitatively calibrate the stiffness of the flexible barrier and the deposition behavior of particles in simulation. In Figure 9a, the flexible net first has a large deformation under consecutive impacts of a granular flow in the first second, which is mainly due to rearrangement and contacts of rings in the primary net. As a comparison, the lateral deformation of the flexible net in simulation increases linearly with the impact time because the flexible mesh net does not behave as a discrete ring net. Even though, the total deformations in simulation and in large-scale experiment are similar. In Figure 9b, the deposition height of particles in simulation shows an identical trend with the large-scale experiment. The illustrated comparison results validate that the established numerical model and the calibrated parameters can be utilized to further investigate the retention mechanism of a granular flow interacting with a flexible mesh net.

5. Parametric study of influencing factors for debris retention

There are some key factors that could affect the debris retention behavior of debris material during the interaction of a granular flow with a flexible net, *e.g.* friction angle, mesh size of a flexible net, shape of openings, and slope angle. Among those influencing factors, friction angle (φ) and relative mesh size, which represent the shear strength of debris material and the debris retention ability of flexible mesh net, respectively, are of great importance and can provide a valuable reference for the design of debris-resisting flexible barriers. Therefore, parametric study is performed for two important influencing factors: the friction angle and the relative mesh size of a flexible net. Correspondingly, two groups of simulation tests are performed and analyzed, as shown in Table 5. The geometries in the simulations are kept the same with the full-scale simulation test. Since conducting a full-scale DEM simulation is extremely time-consuming, the particle amount in the parametric study is halved, and the height of the flexible barrier is also reduced to 2/3 of the original one to make sure that the particles can fill the flexible barrier and present a similar flow behavior with the full-scale simulation test. The results of the parametric study are presented and analyzed in the following sections.

5.1 Influence of internal friction of debris material

The friction coefficients of geophysical flows could be various. The materials of dry granular flows normally have high friction coefficients. While the friction coefficients of saturated debris flows are relatively low due to the friction inhibiting effects of pore fluid pressure (Chen and Lee 2000). Marchelli et al. (2019) suggested that debris material has a relatively low angle of repose down to 10 degree due to the friction inhibiting effects of pore fluid pressure, and an angle of repose higher than 30 degree can be selected as a typical value for dry and coarse grains. Kwan (2012) also found that the equivalent friction angle of debris flow material could exceed 30 degree. Therefore, investigating the influence of internal friction angle of debris material on the retention behavior has great necessity for design of flexible barriers for mitigating geophysical flows.

The influence of the friction coefficient on the impact behavior and the retention capacity of a flexible barrier is examined for a barrier with a uniform mesh size of 75 mm. From the friction coefficients obtained in Section 3, the sliding frictional coefficient of granular particles is varied from 0.233 to 0.8 to represent the corresponding angle of repose from 19° to 35°. Particle passing ratio *v.s.* impact time for debris flows with various angles of repose is plotted in Figure 10a. Notably, a lower friction coefficient generally leads to a higher particle passing ratio. When the granular mixture has an equivalent friction angle higher than 30°, the particles can form a stable deposition dam efficiently within 2 seconds after the first contact. For the simulation of particle mixture with relatively low friction angle (19° to 24°), it took a longer time to form stable arches and clog the mesh openings, which therefore leads to a higher particle passing ratio of around 5%. Figure 10b presents the final deposition wedges of the granular particles with different friction coefficients. With the decrease of the sliding friction coefficient (μ_s), the deposition wedge tends to be higher and shorter, and more particles travel *via* the top surface of the debris deposition wedge and pass the flexible mesh net through the upper openings. Reverse segregation of the deposited particles is observed in the retention process, which has been explained by Johnson et al. (2012) using large-scale physical modeling tests and simulated by Zhou and Ng. (2010) using DEM simulations as well. Distributions of small particles and large particles along the deposition height have also been plotted in Figure 10b to quantify the reverse segregation of the deposited granular particles behind the flexible net. Due to the reverse segregation during the deposition process, small particles tend to be deposited in the flexible net initially, and large particles with higher energy are likely to pass through the upper zone of the flexible mesh net. Therefore, we suggest reinforcing the flexible mesh net in the upper section to prevent unexpected damage of the flexible barrier.

5.2 Influence of barrier mesh size (75 mm, 105 mm, 135 mm, 150 mm)

Mesh size of the flexible net is another important parameter that could directly affect the retention efficiency of a flexible mesh net and should be carefully optimized in the design of flexible barriers for mitigating granular flows. From the observation of the physical modeling test in the literature and the former full-scale simulation test, particles with a much smaller diameter than the mesh size still can jam the mesh openings in a short period. To investigate the influence of mesh size on the retention efficiency of a flexible barrier, flexible mesh nets with four different mesh sizes: 75 mm (used in the full-scale simulation), 105 mm, 135 mm and 150 mm (flexible net and rigid netting barrier) are modelled. Five simulation tests are correspondingly performed by generating the same package of particles with the internal friction angle (φ) of 30° to impact on the flexible net with different mesh size, as shown in Table 5. A dimensionless parameter named relative mesh size (D_{rm}) is introduced to quantify the relationship between the mesh size (d_m) and the typical particle diameter (d_{90} as an example), which is defined as:

$$D_{rm} = \frac{d_m}{d_{90}} \tag{5}$$

where d_{90} indicates that 90% of particles in the assembly have smaller diameters.

The particle passing ratios with time in the simulation tests of flexible nets with different mesh sizes are plotted in Figure 11. For the simulations of the flexible nets with the mesh sizes of 75 and 105 mm (D_{rm} equal to 1.74 and 2.44), the deposited particles clog the mesh net and settle down within 2.5 seconds from the first contact. While, the flexible net with a larger mesh size (135 mm, D_{rm}=3.14) needs a much longer time (in 4 s) for the deposited particles to form a stable deposition zone. For the flexible barrier with the largest mesh size of 150 mm (D_{rm}=3.49), the particles are unable to form stable arches or clog the mesh openings, and the particles pass through the mesh net consecutively. The gradual leakage of the deposited granular particles can be an efficient way to reduce the maintenance cost after trapping a granular flow. Marchelli et al. (2019) discussed the clogging mechanism of a retaining wall with an outlet and concluded that the clogging speed of particles in the outlet has a close relationship with the ratio of the outlet width to the particle diameter, which is consistent with our findings of debris-resisting flexible barriers. To study the influence of barrier flexibility on the clogging mechanism of particles interacting with barrier, a simulation test using a rigid netting barrier (RNB) with the mesh size of 150 mm is also performed. From Figure 11, it is found that the rigid barrier with larger mesh openings has a higher particle passing ratio but still can form a stable deposition dam within 3 seconds, which indicates that the mesh size could affect the particle passing ratio, and the flexibility has great influence on the clogging mechanism of particles. To further investigate this phenomenon, force chains and arches in the five tests are plotted in Figure 12. From this figure, it can be observed that the particles can form arches behind the mesh openings when the mesh size is smaller than 150 mm and the RNB with a larger mesh size (150 mm). On the other hand, the flexible net with a large mesh size (150 mm) cannot form stable arches during the impact process except the basal gap between the net and the rigid basal plate, which explains the phenomenon that the particles can pass through the meshes continuously.

6. Conclusions

In this study, numerical simulation offered a significant contribution to understanding the retention mechanism and, more importantly, quantifying the key influencing factors on granular flow retention of a flexible barrier as well as investigating the clogging mechanism of particles interacting with flexible mesh net and RNB. A model based on DEM has been proposed to simulate the impact process of a granular flow on a flexible mesh net. This model was validated by the data from a large-scale physical modeling experiment in the literature, and the important input parameters were calibrated by simple element tests (piling and sliding tests) of the debris material. Although the modeling process still relies on a series of simplifications, the model can address the typical impact and deposition characteristics of a real granular flow interacting with a flexible barrier by quantitatively comparing with the physical modeling test. The validated DEM model was consequently used to investigate the retention efficiency of a flexible barrier in trapping granular flows. Two typical parameters: the internal friction angle of the debris material and the relative mesh size of the flexible net were selected for characterization of retention efficiency. The results indicate that the majority of particles can be trapped by the flexible barrier when the mesh size is 3 times larger than 90% of particles or the stiffness of the flexible net is relatively high due to the clogging mechanism, which has been revealed by the force chains and arches of particles behind the mesh openings in a flexible mesh net or a RNB. Reverse segregation has also been observed during the formation of the deposition wedge. Small particles were deposited behind the barrier to form a deposition wedge first, and large particles with higher energy impacted on the upper part of the mesh net by overtopping the deposition wedge. For the flexible net with a mesh size 3.5 times larger than the d_{90}, particles in the granular flow cannot form stable arches behind the large mesh openings but continuously leaking through the flexible mesh openings. The gradual leakage of debris can reduce the maintenance cost of cleaning the filled flexible barrier after mitigating a debris flow event. Therefore, we suggest using a flexible barrier with a large mesh size in the lower section but reinforcing the barrier in the upper section to resist the impacts from large particles, which can provide a more efficient design method to extend the service life and provide a safer protection. Researches should be progressively conducted to provide more reliable explanations and update the existing guidelines in order to define a more rational design procedure of debris-resisting flexible barriers.

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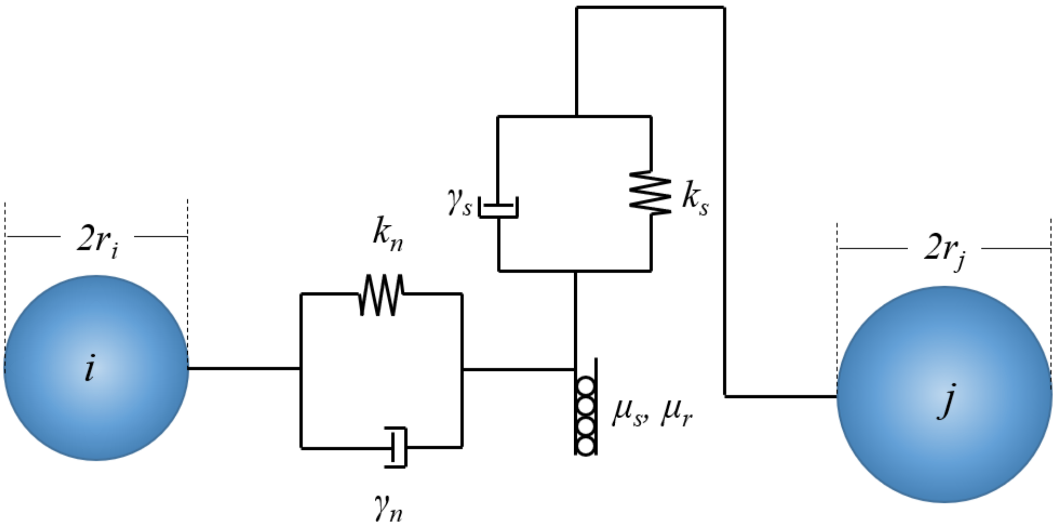
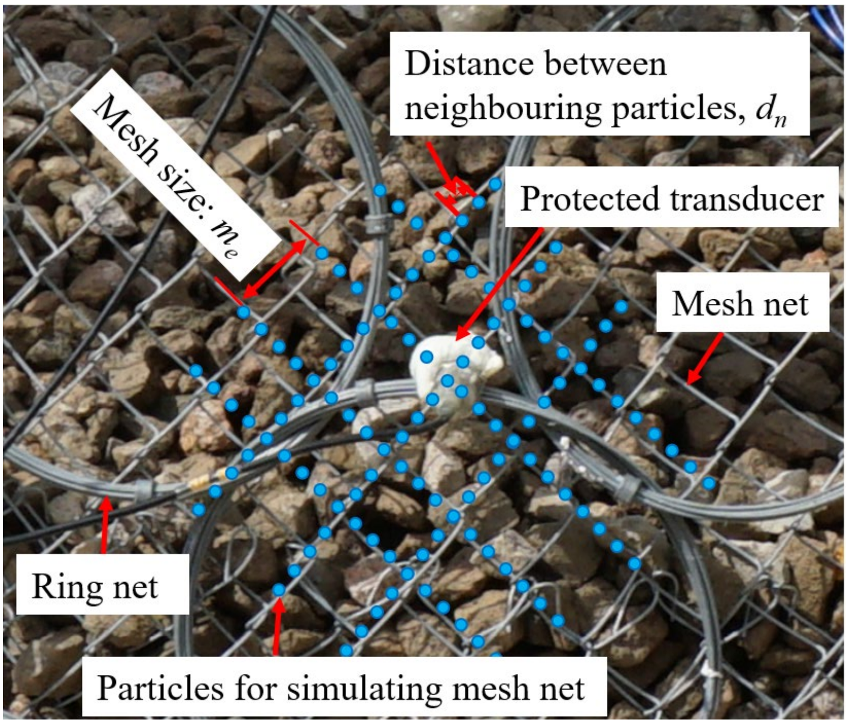


Figure 1. Conceptual representation of the contact model



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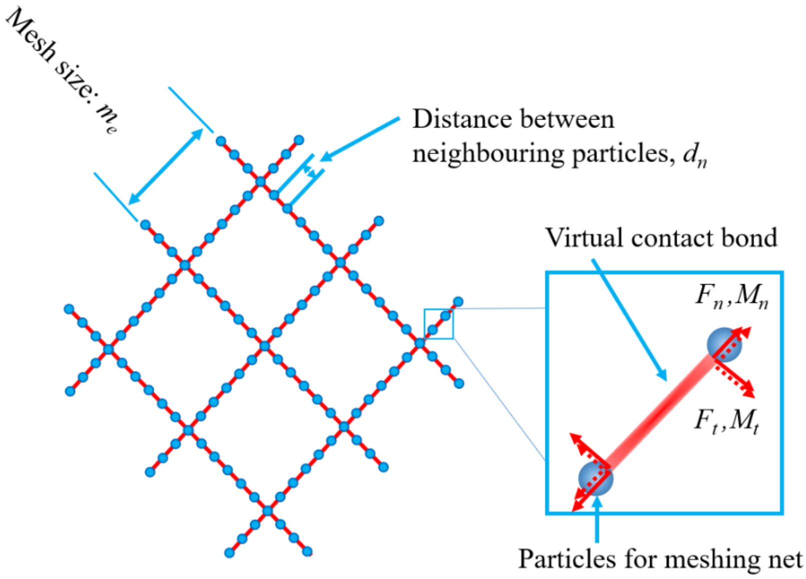

(b)

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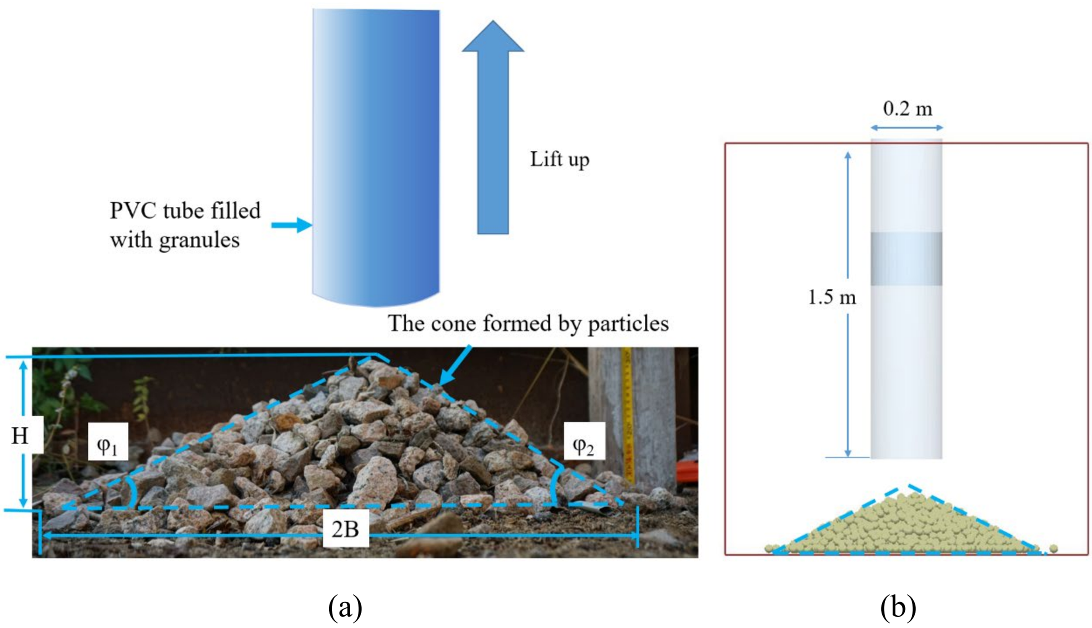

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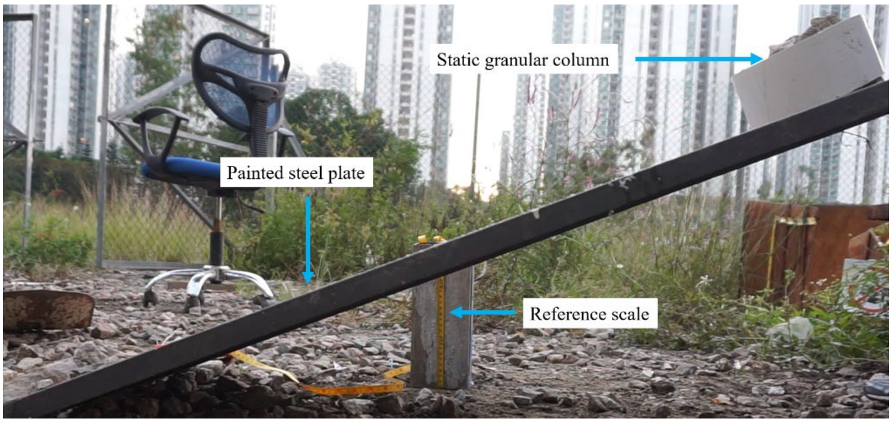

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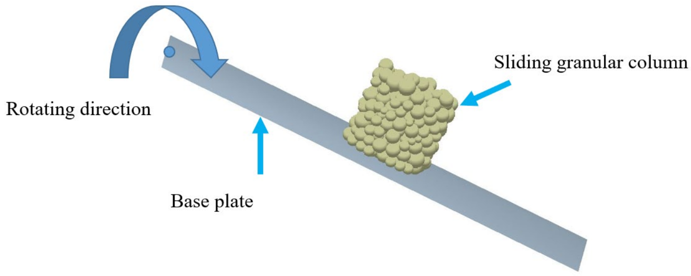

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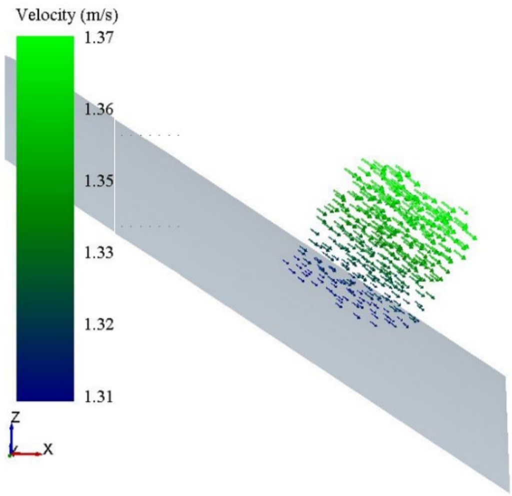

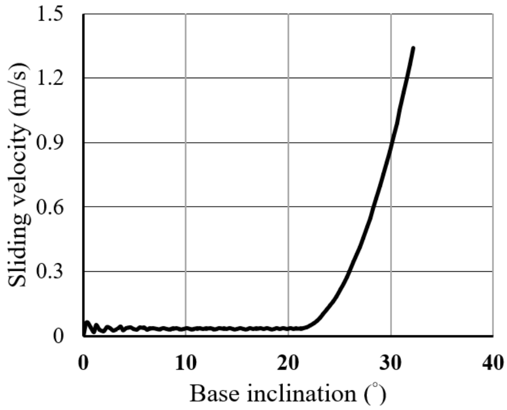

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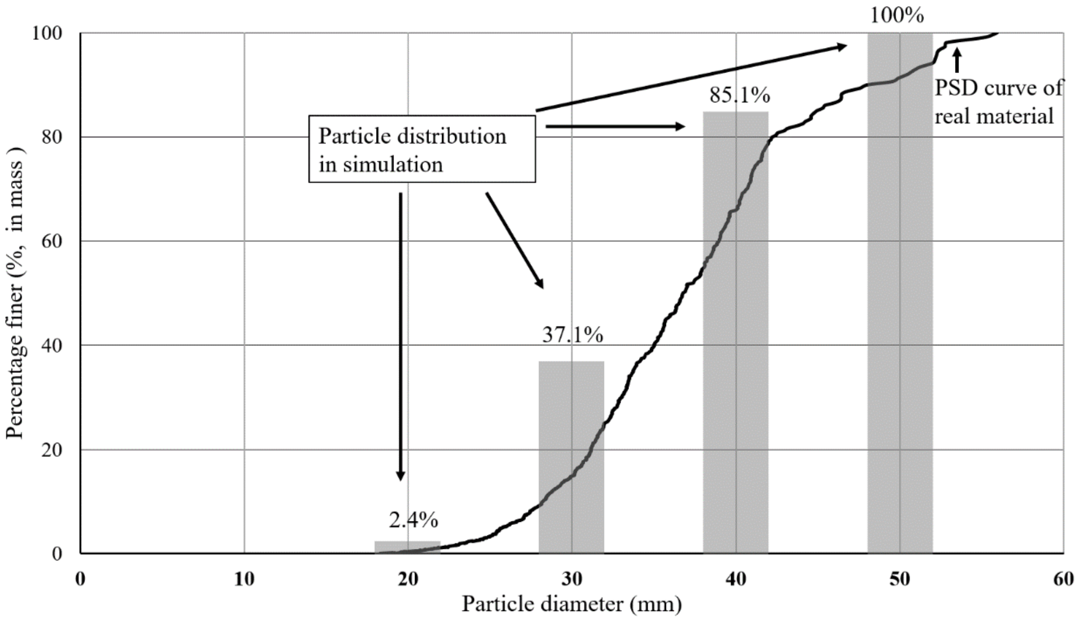

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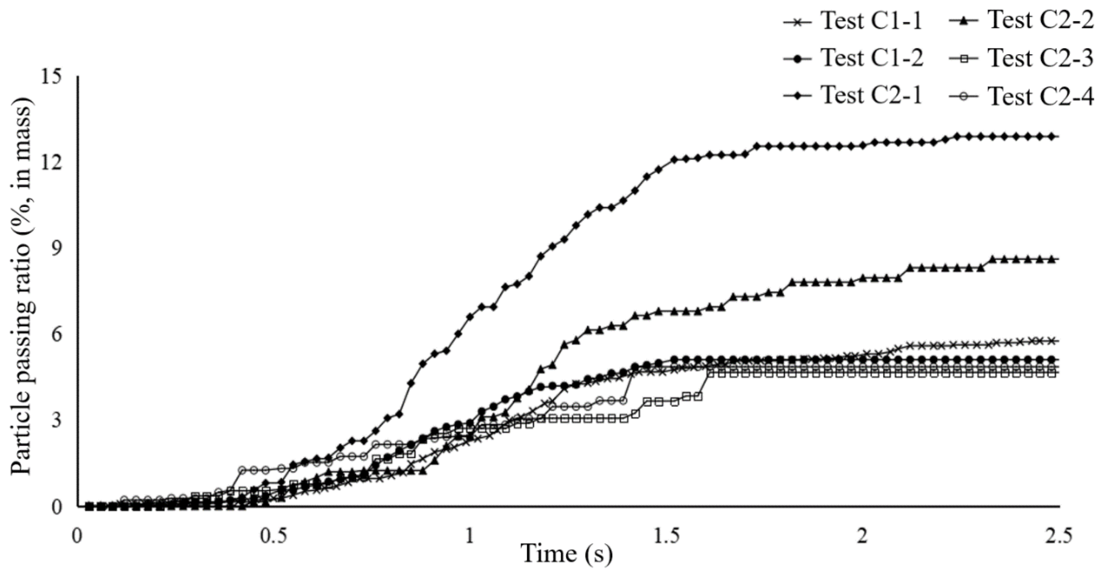

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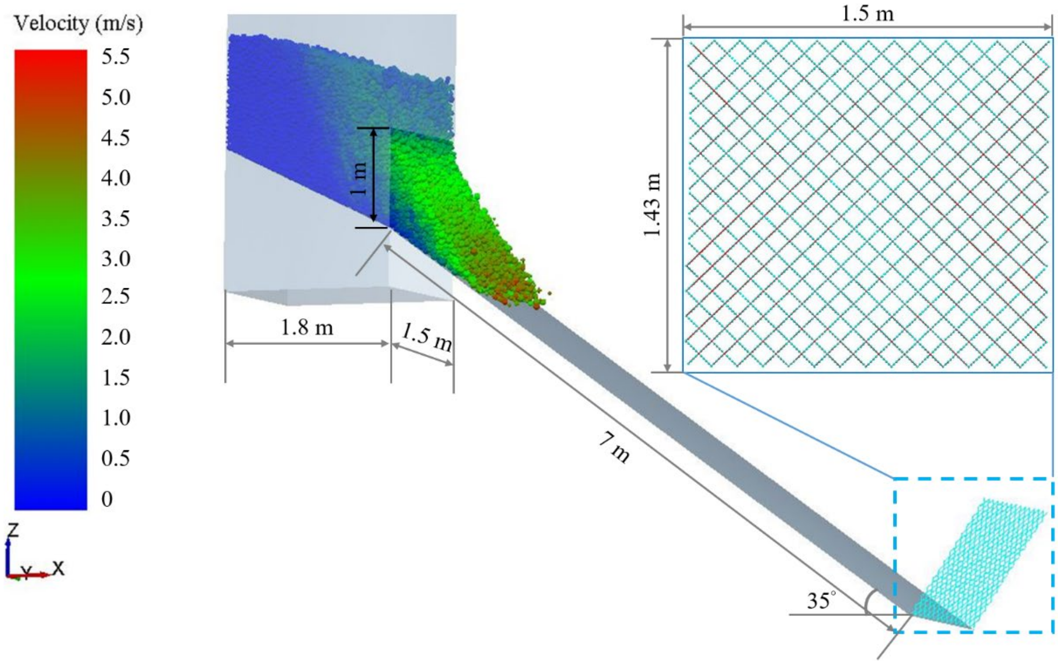

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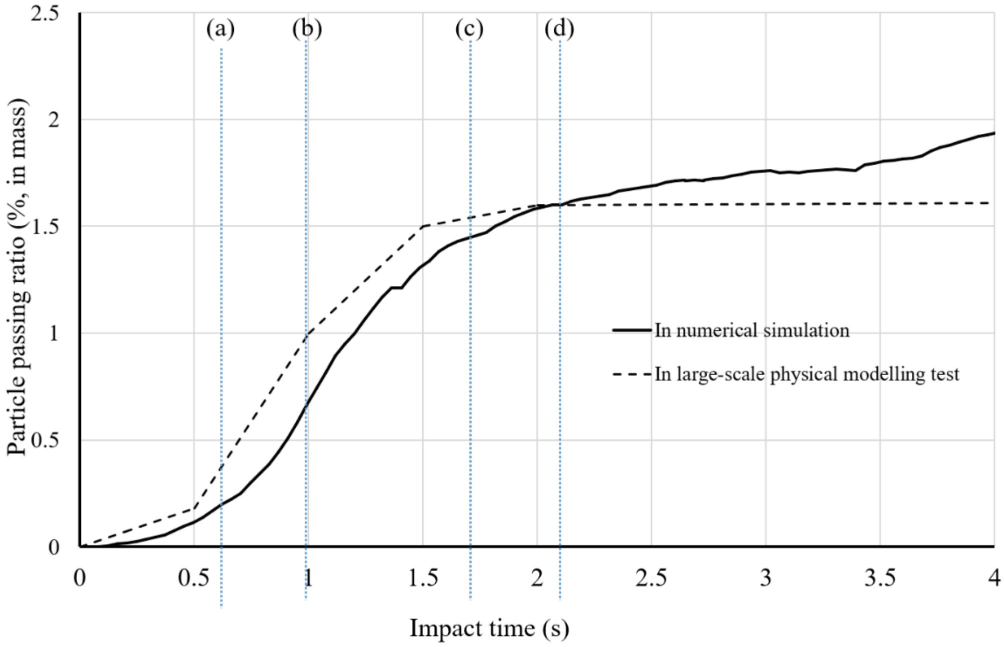

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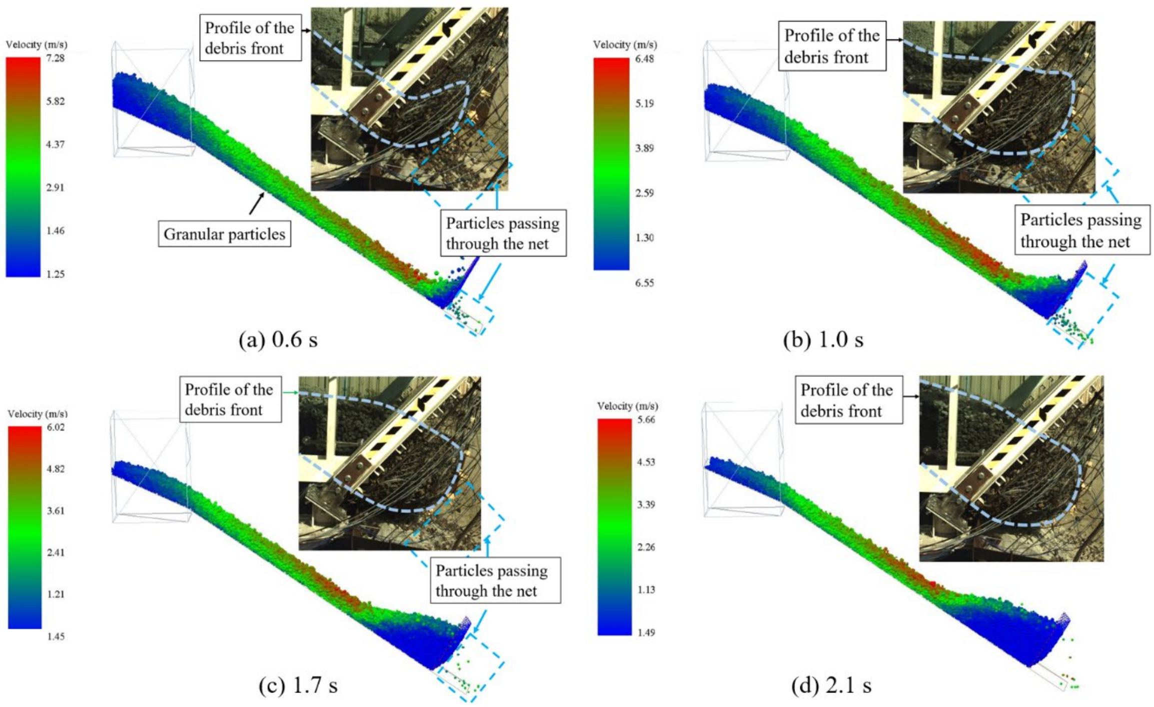

(b)

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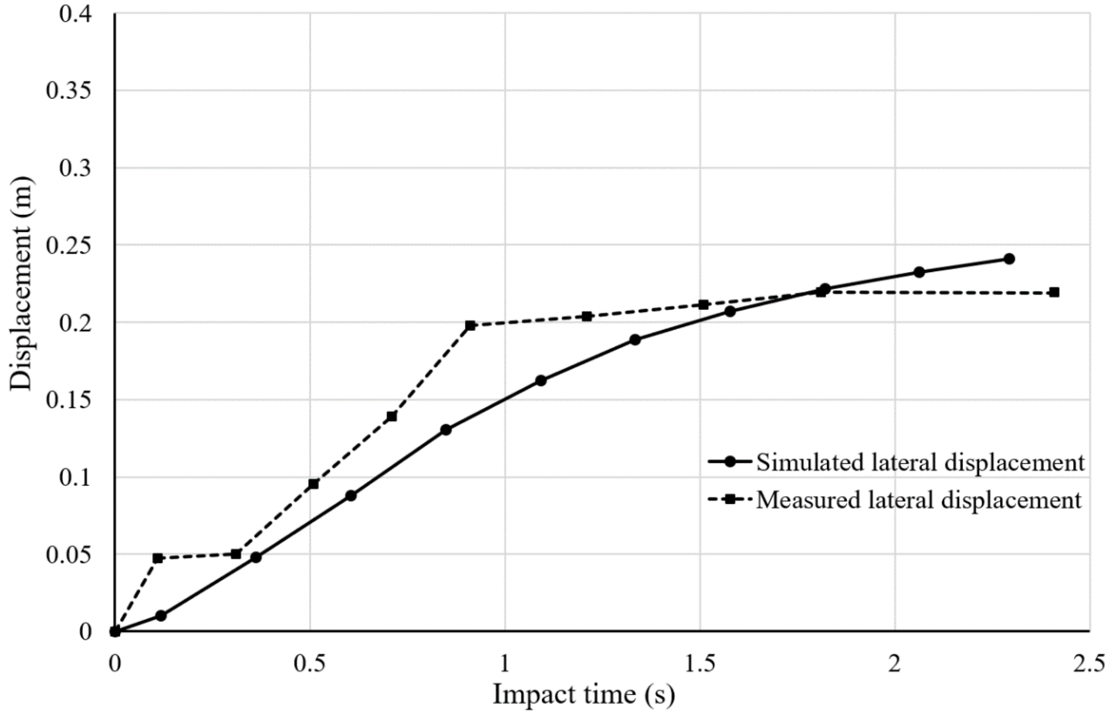

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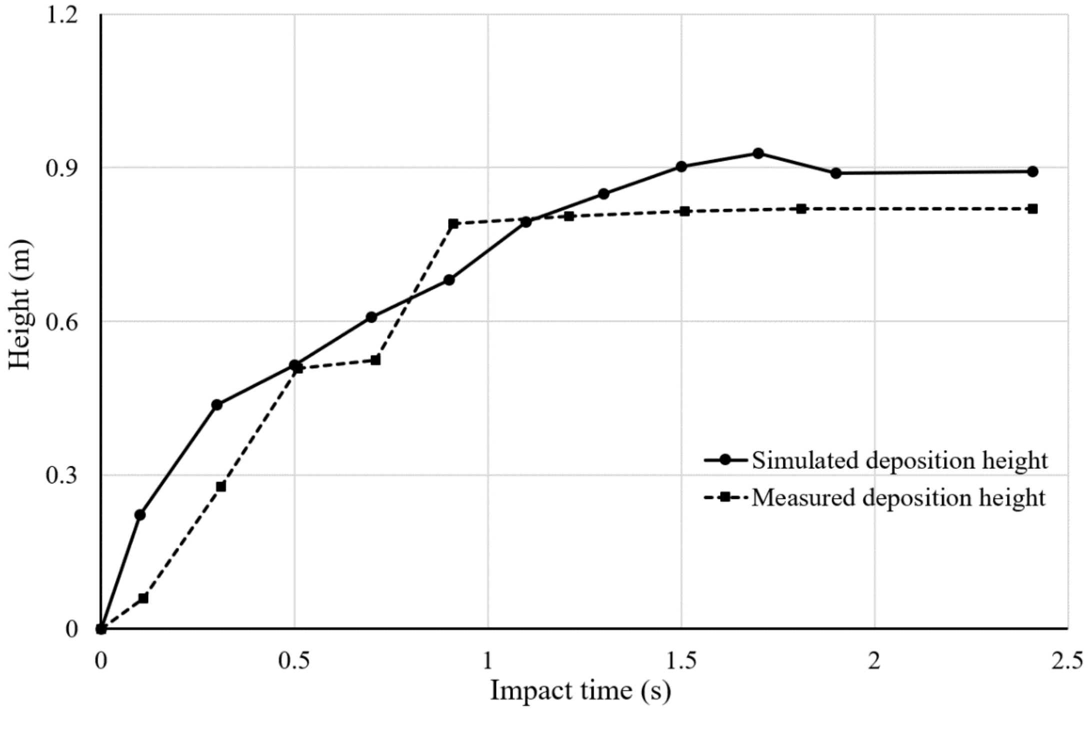

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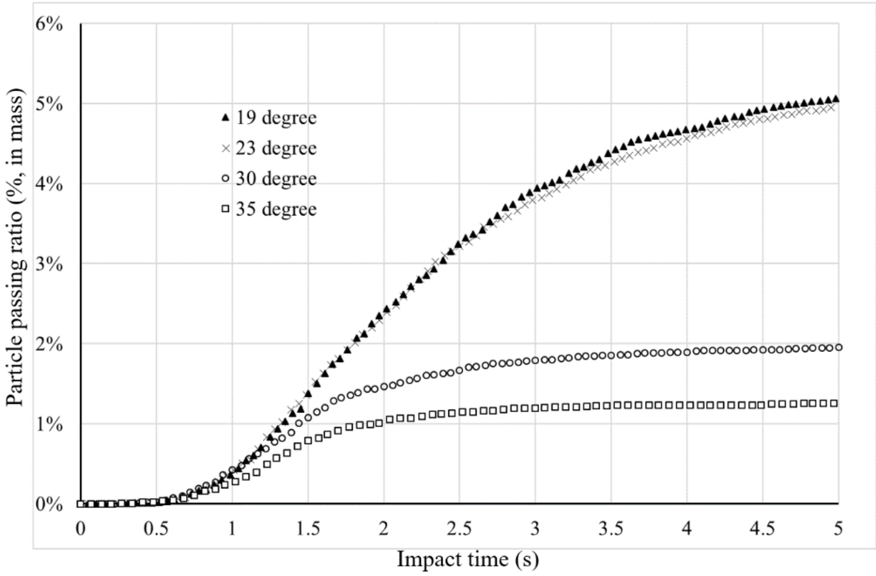

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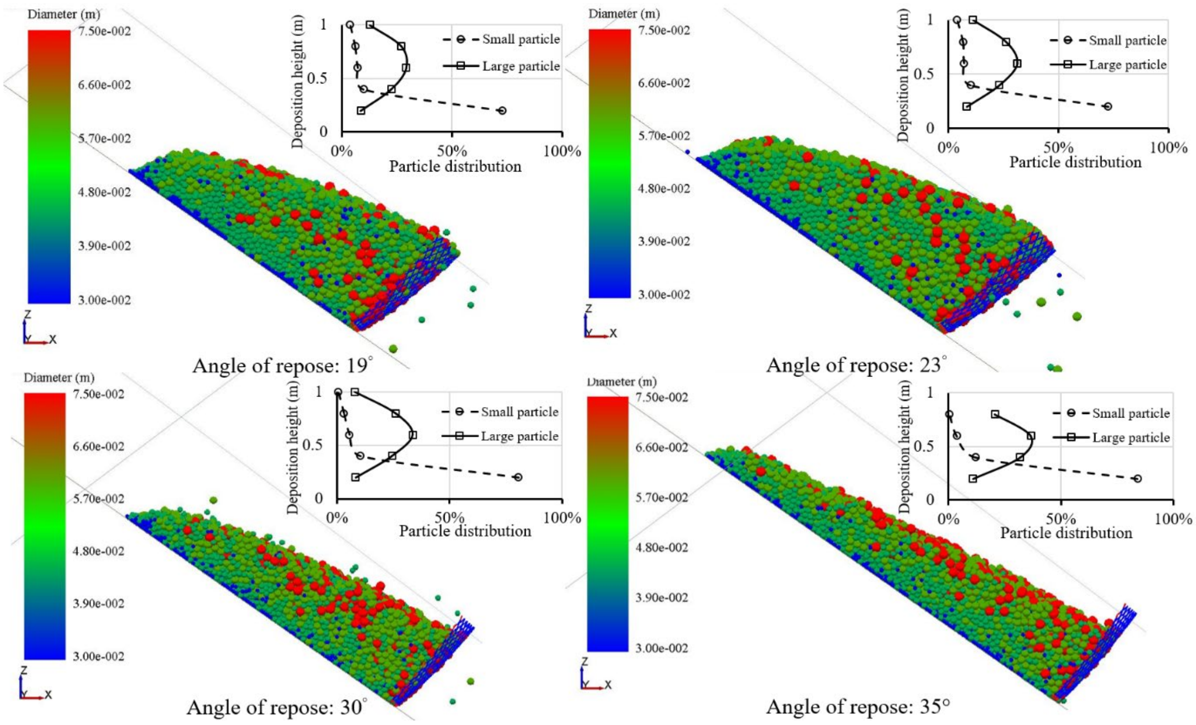

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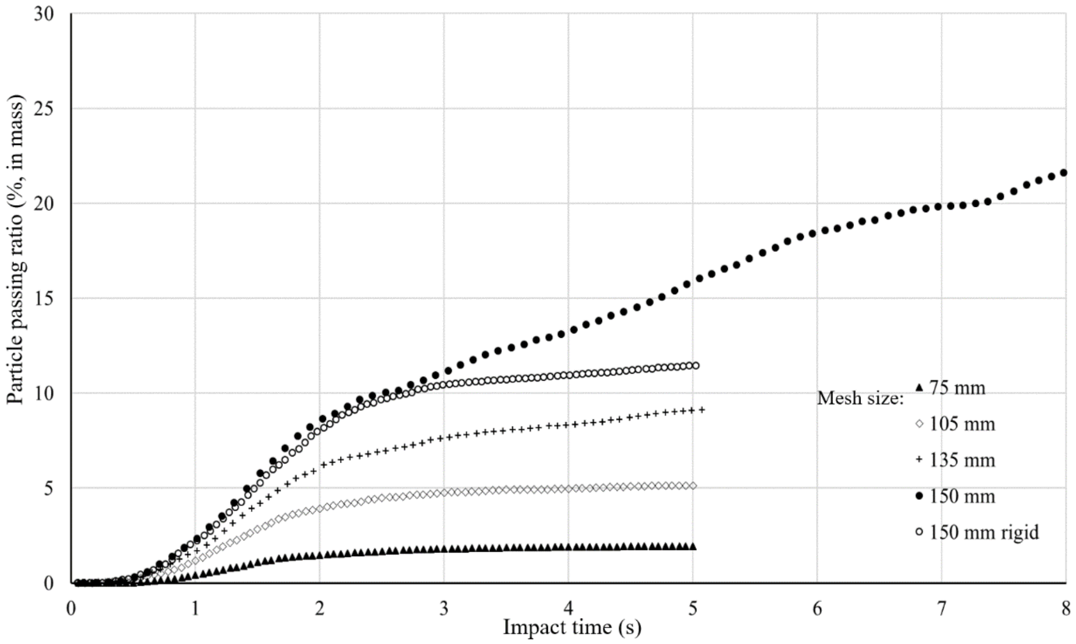

Figure 11. Particle passing ratio with impact time in the simulations

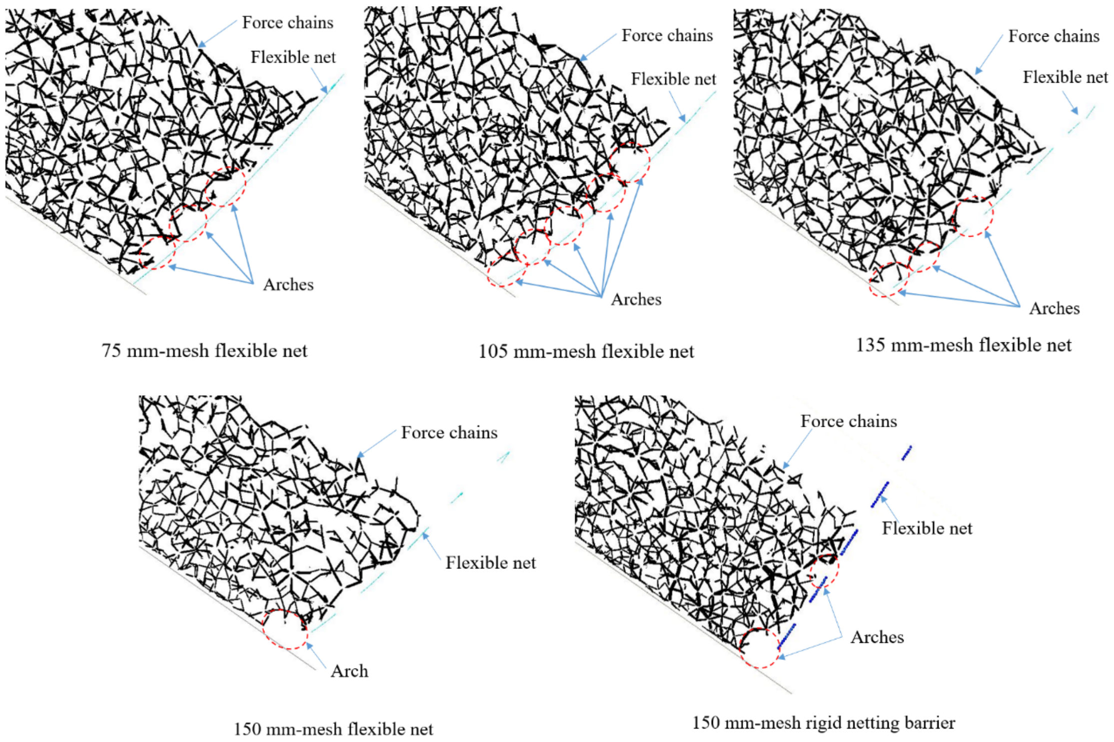

Figure 12. Force chains and arches in granular flow behind flexible nets with different mesh sizes and the rigid netting barrier

Table 1. Relationship between the angle of repose of granular material and the friction coefficients in piling tests from DEM simulation

μ_r	μ_s	Equivalent angle of repose (°)
0.068	0.233	19
	0.364	24
	0.6	30
0.1	0.8	35

Table 2. Parameters of calibration tests for particle amplification factor

Test type	Mesh size of net (mm)	Total mass of particle (kg)	Particle amplification factor	Test No.
Original particle-net system	50	100	1	C1-1
		120	1	C1-2
Amplified particle-net system	75	120	1.5	C2-1
		120	1.7	C2-2
		120	1.8	C2-3
		100	1.8	C2-4

Table 3. Comparison of parameters between simulation and large-scale experiments

	Large-scale experiment	**Numerical simulation**
D10	28.2	22
D30	33	28
D50	36.8	32.8
D60	39	34.8
D90	48	43
Cu	1.38	1.58
Cc	0.99	1.02

Table 4. Model parameters in DEM simulations of a full-scale granular flow impact test

	Parameter	Value
Granular particle	Density (kg/m^3)	2650
	Granular-granular Young's modulus (GPa)	70
	Granular-geometry/ Granular-barrier Young's modulus (GPa)	200
	Poisson's ratio	0.25
	Restitution coefficient	0.8
	Total mass (kg)	6025
	Number of debris particles	35568
	Interparticle sliding friction coefficient μ_s	0.6
	Rolling friction coefficient μ_r	0.068
	Particle-base sliding friction coefficient $\mu_{s,c}$	0.488
Flexible barrier	Particle diameter (m)	0.01
	Number of bonded particles for simulating barrier	3310
	Number of bonds	3698
	Particle density (kg/m^3)	7650
	Restitution coefficient	0.4
	Distance between neighbouring barrier particles (m)	0.015
	Mesh opening size (m)	0.075
	Width of mesh net (m)	1.5
	Original height of mesh net (m)	1.45
Simulation and geometric setup	Time step (s)	1.71×10^{-7}
	Slope channel width (m)	1.5
	Slope inclination angle (°)	35
	Slope length (m)	7

Table 5. Groups of tests for parametric study in DEM simulations

	Test No.	Angle of repose φ (°)	Mesh size (mm)
Group 1	1-1	35	75
	1-2	30	
	1-3	24	
	1-4	19	
Group 2	2-1	30	75
	2-2		105
	2-3		135