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Discrete-element investigation of granular debris-flow runup against slit structures

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Abstract

Runup of granular debris flows against slit dams on slopes is a complex process that involves deceleration, deposition and discharge. It is imperative to understand the runup mechanism and to predict the maximum runup height for the engineering designs and hazards mitigation. However, the interaction between granular flows and slit dams, which affects the runup height significantly, is still not well understood. In this study, a numerical investigation of granular debris flow impacting slit dams by the discrete element method (DEM) was then conducted. The influence of the opening size of slit dams characterizing by the relative post spacing $R=b/d$ (b: post spacing; d: particle diameter) on runup height was studied. Numerical study illustrates that there is a critical value of relative post spacing (R_C): within the critical value, the maximum runup height is insensitive to the relative post spacing; once b/d exceeds the critical value, the maximum runup height decreases rapidly as the relative post spacing increases.

Keywords: Granular debris flow; soil/structure interaction; discrete element method

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1. Introduction

Granular debris flows comprise a wide range of particle sizes (Jakob et al., 2005), surging down slopes in response to gravitational attraction (Iverson et al., 1997). Due to the high mobility and huge entrained solid volume (Shen et al., 2018), granular debris flows can potentially result in disastrous consequences to downstream human lives and facilities (Hungr et al., 1984). To mitigate such destructive hazards, slit structures such as slit dams (Watanabe et al., 1980) and an array of baffles (VanDine et al., 2012) are often strategically installed along the predicted flow path because such structures are effective in impeding flow mobility and dissipating flow energy (Choi et al., 2014a). Granular debris flows impact rigid structures and transfer momentum vertically into runup, potentially overtopping the obstacles (Ng et al., 2016). Design of structural countermeasures requires estimates of runup height to prevent overtopping downstream (Chu et al., 1995). However, runup of debris flows against obstacles is a complex process that involves a combination of flow deceleration and redirection that challenges the ability of physically based debris flow models to calculate the maximum runup heights accurately (Iverson,2016).

In this study, a discrete-element investigation of granular debris flows impacting a slit structure under varying Froude conditions (N_{Fr}) and relative post spacing (b/d) was carried out. The runup mechanisms of granular flows in different Froude condition were observed. The influence of flow regime and relative post spacing on runup height was elaborated.

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2. Discrete element method

2.1. Numerical model setup

The 3-D particulate flow code EDEM (TranscenData, 2007) is adopted to simulate the dynamics of granular flow in this study. In the DEM, contact forces and displacements of a stressed assembly of particles are found by tracing the movement of individual particles. Discrete elements displace independently of each other and interact at contacts between particles and boundaries. The particle motion of each discrete element is calculated from forces acting on it by Newton's law of motion and finite displacements of discrete elements are computed progressively during the simulation (Ng et al., 2013).

Figure 1 show a plan view and a side view of the numerical model setup, respectively. Planar rigid geometry is constructed to model the channel bed and the slit dam. The sidewalls adopt the periodic boundaries condition (PBC) which is applied along the flow direction and spans the width of the channel (*w*=200 mm). The PBC is required to eliminate the unrealistic particle arrangement at the wall boundary caused by the constraint of particle sizes in discrete element simulations (Rapaport, 2004). Slit dam with rigid barriers and an adjustable opening *b* is positioned downstream of the flows. The rigid barriers are set to *H*=2000 mm in perpendicular height, which is high enough to avoid potential overflows so that the maximum runup height can be captured.

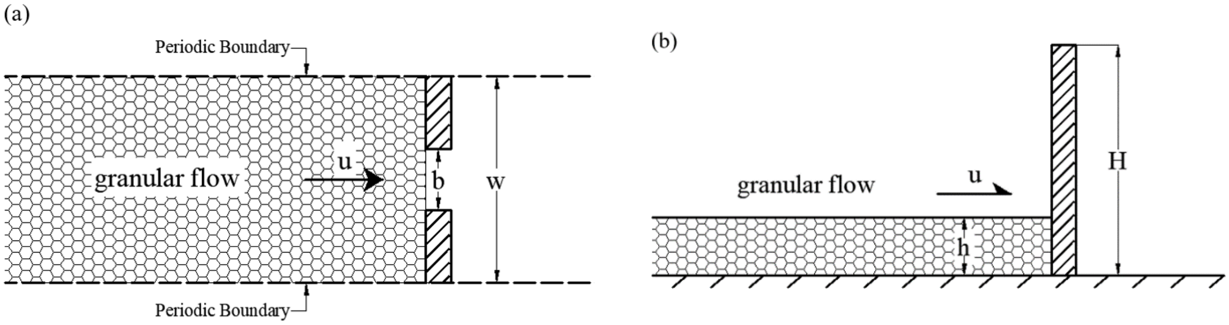

Fig. 1. Numerical model: (a) plan view; (b) side view

2.2. Input parameters

The granular flow is composed of an assembly of 30000 rigid spherical particles with a uniform diameter of 0.01 m. According to the commonly used values in numerical simulations of granular medium, the material density of each particle is 2630 kg/m3 and the material shear modulus is set to be 24,000 MPa. The contact friction angle of discrete elements is set as 35°(Pudasaini et al. 2005; Pudasaini and Hutter 2007; Mancarella and Hungr 2010; Ng et al. 2013; Choi et al. 2014b; Law et al. 2015). The interface friction angle is set as 16.6°which is consistent with the values adopted by Choi et al. (2016) in laboratory tests. Based on field and laboratory tests (Azzoni and Freitas 1995; Robotham et al. 1995; Chau et al. 2002), the coefficient of restitution is set as 0.5. Details of the input parameters are given in Table 1.

Table 1. DEM input parameters

Input parameter	Value
Number of discrete elements	30000
Particle diameter (m)	0.01
Density (kg/m^3)	2630
Total mass (kg)	41.4
Shear Modulus (MPa)	24000
Discrete element/wall friction	0.3
Discrete element friction	0.6
Rolling friction coefficient	0.01
Coefficient of restitution	0.5

The numerical study is divided into two stages: preparation stage and impact stage. In the preparation stage, a steady granular flow with a uniform depth is prepared right behind the slit dam. The initial flow depth h is fixed at 50 mm, which is 5 times the particle diameter. In the impact stage, initial velocities ranging from 0.38m/s to 5.7m/s are uniformly applied to the assembly of particles in order to obtain incoming flows with different flow regimes(Froude condition). The Froude number of the approach granular flow is set between the range of 0.5 and 7.5 which is consistent with the Froude number range of the reported channelized debris flow ranging from 0.5 to 7.6 based on field observations (Hübl et al. 2009; Scheidl et al. 2013;Cui et al. 2015). Gravitational acceleration (9.81m/s^2) acts downward along the vertical direction. The channel inclination is fixed as 20° to supply the acceleration along the flow direction during the runup process. Slit dams with relative post spacings (b/d) ranging from 2 to 12 were constructed and the transverse blockage ranged (R) from 10% to 60%. A control test without opening was also conducted for reference.

3. Interpretation of DEM results

3.1. Granular flows runup mechanism

Froude number (N_{Fr}) which indicates the ratio of inertial force to gravitational force can capture the bulk characteristics of a flowing medium. Subcritical and supercritical flow conditions are characterised with Froude numbers less and greater than unity, respectively (Choi et al., 2015a). Figure 2 shows a side view of the impact and runup process of subcritical flow(N_{Fr}=0.5) and supercritical flow(N_{Fr}=6.5), respectively. At t = 0 s, both subcritical and supercritical flows approach the barrier with an identical flow height (Fig.2 a1 and b1). For subcritical flow, a typical pile up mechanism can be observed; at t = 0.1s, granular flow impacts the barrier, most particles in front of the flow deposits behind the rigid barrier, forming a ramp-like dead zone at the base of the barrier while a small amount of particles pass through the opening (Fig.2 a2). As subsequent flow material impacts the existing deposits, the pile up continues to develop and the dead zone expands upward (Fig.2 a3). Thereafter, the dead zone continues to thicken until the arrest of granular motion for all particles (Fig.2 a4 and a5). Numerical simulation results indicate that the subcritical granular flow exhibits a distinct pile up characteristics which is consistent with Armanini et al.(2011) and Choi et al. (2015b).

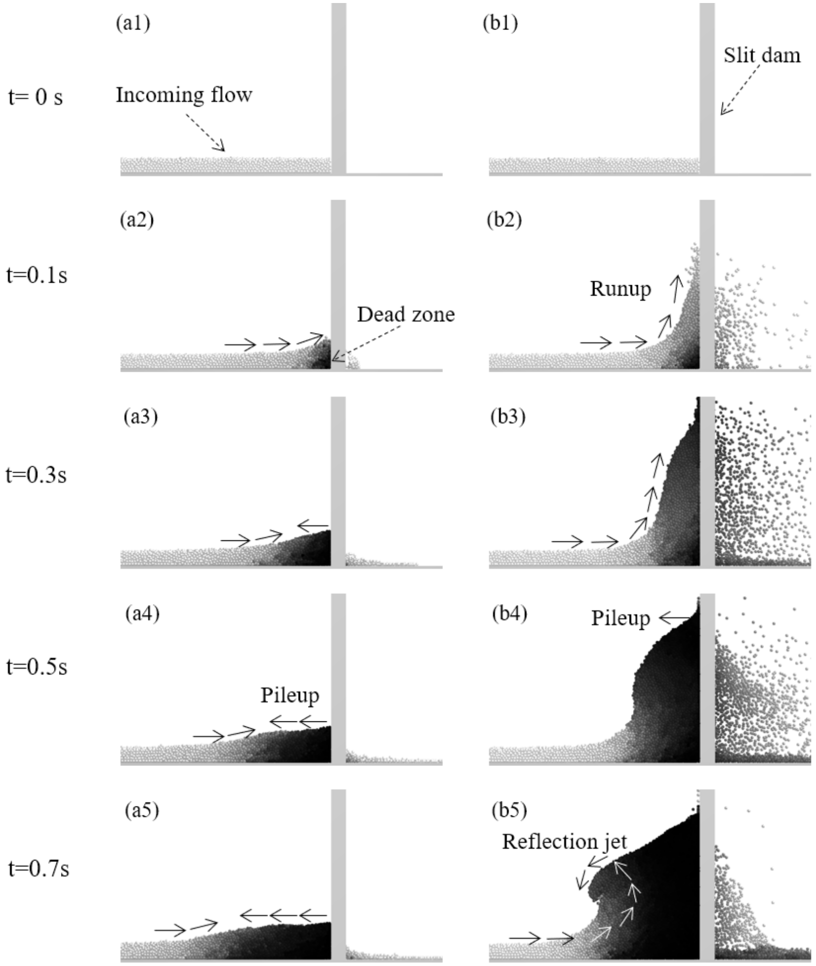

Fig. 2. Simulated flow kinematics for subcritical flow (a1-a5) and supercritical flow (b1-b5), *b/d*=2.0. The color of particles denotes the velocity of particles and the darker the color, the lower the velocity.

Supercritical granular debris flow resulted in a combination of a vertical jet runup and a pileup mechanism. At t = 0.1 s, a distinct upward jet along the barrier forms as the supercritical flow impacts the slit-dam (Fig. 2 (b2)). Such a runup mechanism is more reminiscent of the vertical jet mechanism described by Armanini et al. (2011) and Choi et al. (2015b) for liquid flows and is consistent with Ng et al. (2017) for granular flows of large glass particles. Subsequently, runup continues to develop and the runup height keeps increasing. Simultaneously, a large number of particles discharge the spacing and discharge dispersedly in a downstream jet. (Fig. 2 (b3)). When the maximum runup height is reached, the runup process ceases. Concurrently, the pileup process begins: the dead zone keeps thickening while its height remains unchanged (Fig. 2 (b4)). The numerical simulation results demonstrate that the runup mechanism between subcritical and supercritical granular flows are quite different, subcritical granular flows only exhibit a pileup mechanism while supercritical flows show a combination of vertical jet runup and pileup mechanism.

In this numerical study, the incoming flow is homogeneous, steady and uniform so that the runup height grows without intense fluctuation and the secondary wave phenomenon reported by Iverson(2016) is not observed. Figure 3(a) shows the time series of runup heights in simulations of different flow regimes (Froude numbers). For the flows of low Froude numbers(e.g. N_{Fr}<3.5), the runup height reaches its peak values rapidly and then almost maintains a constant level. For the flows of high Froude numbers s(e.g. N_{Fr}>5.5), the runup height increases over time until the maximum runup height is reached. This increase is non-linear that the growth rate varies in different periods. At first, the runup heights increase rapidly and the growth rate reach its peak value as the flow front impacts the dam. Thereafter, the growth rate decreases over time meanwhile the runup process tends to rest gradually. After reaching the peak value, the runup heights decrease slowly and then maintains a constant level, indicating that the pile up process is underway.

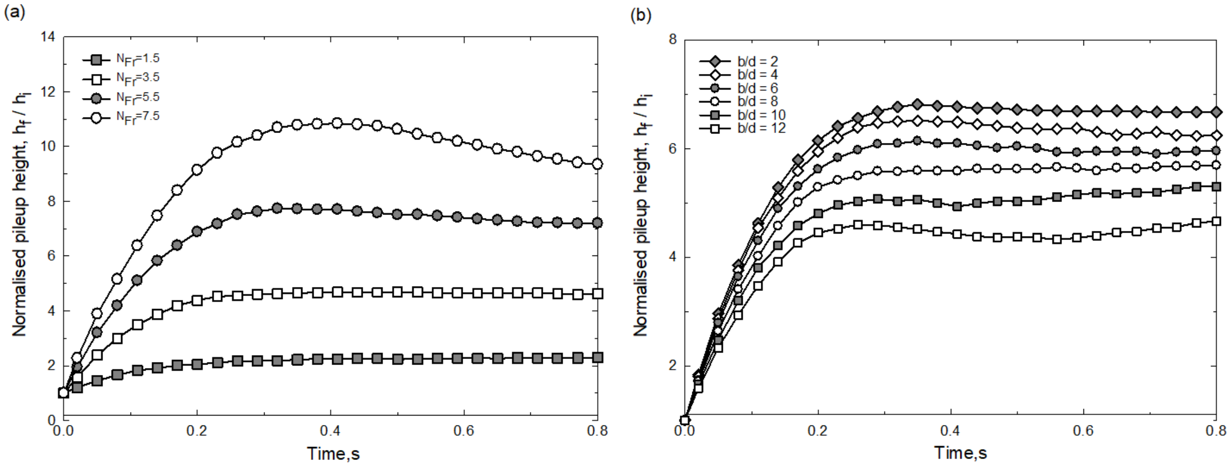

Fig. 3. Evolution of the runup height. (a)b/d=2.0, (b)N_{Fr}=4.5, zero time corresponds to the time instance at which the flow front reaches the dam.

Figure 3(b) shows the time series of runup heights in different relative post spacings. Numerical simulation results reveal that the evolutions of runup height in different relative post spacings share the similar tendency: the runup height increases over time to peak value then almost keeps a constant level. The relative post spacing controls the peak value that the higher the relative post spacing, the lower the maximum runup height. And the runup height in higher relative post spacings tend to reach its peak value earlier, indicating that the slit size affect the runup processes of granular flows against slit dams.

3.2. Influence of the relative post spacing on runup height

Figure 4 shows the relationship between the normalized maximum runup heights and relative post spacings. The numerical simulation results are compared with experimental data (Choi et al.,2016), which has the similar configurations in channel geometry, granular material property and slit structure type while Froude numbers are no more than 2.3.

In low Froude number conditions, the runup heights of numerical study are very close to the values measured by Choi et al. (2016). The results show that the normalized maximum runup height is not strongly influenced by the relative post spacing. This is because stable arches can easily form at the slit, provided that the Froude number of the incoming flow is low($N_{Fr} \leq 3.5$). In this case, there is no significant difference between slit dams of different slit sizes since the stable arches can block the outlet and halt the flows. When the Froude number is high, supercritical flows with high velocities can break arches easily. Pardo and Sáez (2014) observed that the arch strength evidently depends on its length: shorter arch is generally stronger since higher contact stresses can be sustained in constrictions. The length of arch is directly related to the relative post spacing and the probability of formation of stable arches decreases as b/d increases (Janda et al., 2008). In this case, the relative post spacings affect the runup height significantly. In general, the maximum runup height declines as the b/d increases. Numerical results show that there is a critical value of relative post spacing (R_C): within the critical value, the maximum runup height is insensitive to the relative post spacing; once b/d exceeds the critical value, the maximum runup height decreases rapidly as the relative post spacing increases. Such a critical value has been studied in many previous works and it is noted that it does not exist an exact value for Rc (Zuriguel et al.,2005; Janda et al.,2008).

As shown in Figure 4, the numerical results can be interpreted by dividing two zones. Zone I ($b/d \leq R_C$, in grey): the runup heights of granular flows against slit dams maintain a constant level within a critical range of the relative post spacing. The Rc decreases with the increase of N_{Fr} so that Zone I shrinks as the Froude number of incoming flows increases; Zone II ($b/d \geqslant R_C$, in white): the relative post spacing has a significant effect on runup heights that the maximum runup height decreases rapidly as the b/d increases. Zone II expands as N_{Fr} increases and eventually spans the full range of the relative post spacing(N_{Fr}=7.5). In this case, the arching structures no longer work and the runup height decreases monotonically as the relative post spacing increases. According to these results, engineers anticipating a dense granular debris flow can safely use the principle in this study to estimate the height required for the slit-dam to avoid dangerous overtopping.

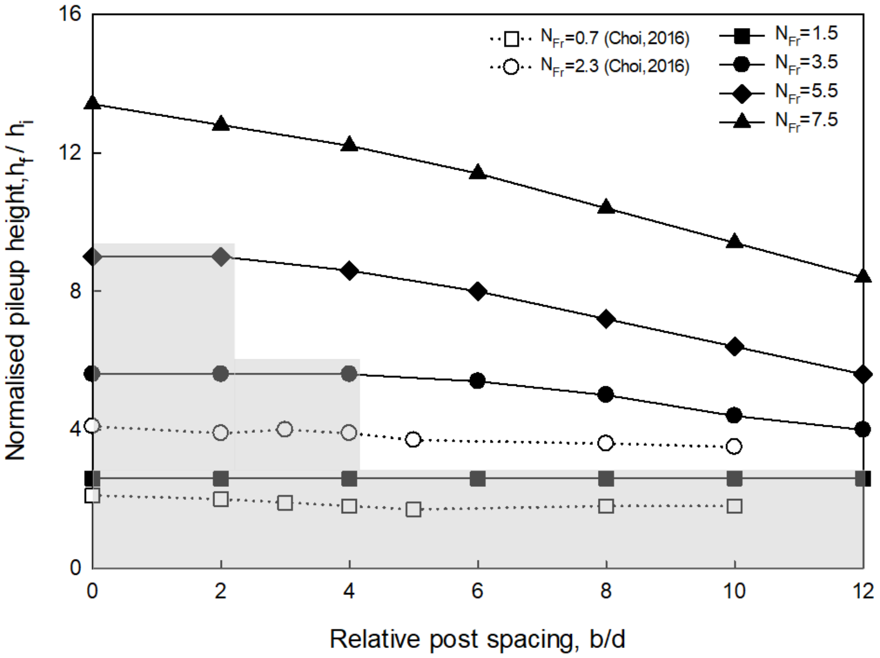

Fig. 4. Relationship between runup height and relative post spacing (Zone I: gray region; Zone II: white region).

4. Conclusions

A numerical study of granular debris flows impacting slit dams by discrete method was conducted. The numerical results were compared with the analytical models and the experimental data. From the initial results, it can be observed that the subcritical granular flows resulted in a typical pile up mechanism, whereas supercritical flows led to a combination of vertical jet runup and pile up mechanism. The relative post spacing of slit dams could affect the runup height. There is a critical value of relative post spacing (R_C): within the critical value, the maximum runup height is insensitive to the relative post spacing; once *b/d* exceeds the critical value, the maximum runup height decreases rapidly as the relative post spacing increases.

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