Anura3D
MPM Research Community

Paper number: mpm2019.45
www.anura3d.com
www.mpm2019.eu

Modelling of debris flow impact on slit dams by discrete element method

S.X. Gong[1], T. Zhao[1,*]
[1]State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource and Hydropower, Sichuan University, Chengdu, 610065, China
* E-mail: zhaotao@scu.edu.cn

ABSTRACT

Debris flow is a common geological disaster with extremely rapid velocity and agitated state. It can usually cause catastrophic destructions to infrastructures. Thus, slit dams are widely constructed in mountainous areas to mitigate such destructive flows. In this paper, a numerical model by discrete element method (DEM) was employed to investigate the influence of relative post spacing (b/d_{max}) of slit dams on the debris-dam interactions. The run-out distance and the impact forces exerted by debris flows on the slit dams were analyzed. The numerical results show that the impact force decreases with b/d_{max}, whilst the run-out distance increases with b/d_{max}. Furthermore, the ratio of peak normalized kinetic energy of all granular materials to that of granular materials passing through the slit dams were analyzed to quantify the regulation efficiency of slit dams on debris flows. The obtained numerical results can provide insights into the optimization of relative post spacing.

KEY WORDS: Debris flow; slit dam; discrete element method; relative post spacing; particle shape.

INTRODUCTION

Debris flow is typically a solid-liquid two-phase flow which occurs commonly in mountainous areas. It occurs when masses of poorly sorted and agitated sediments surge down slopes in response to gravitational attraction (Iverson, 1997). Due to the high velocity, long runout distance and large entrainment of solid volume, debris flows often bring out significant hazards to human lives, infrastructures and lifeline facilities worldwide. As effective mitigation approaches of debris flow hazards, structural countermeasures, such as flexible barriers, check dams and an array of baffles have been widely used in the fields to minimize the destructive impact of debris flows.
For check dams, they are often blocked with sediments due to their narrow storage space and poor permeability (Lien, 2003). Besides, once the check dam is destroyed, it will lead to more devastating destruction and cause sediments-related disasters (e.g. floods, debris flows) with amplified scales (Zhou et al., 2013). To overcome this limitation, open-type dams have been developed in engineering practices. An open-type dam is designed to retain the debris from reaching downstream and control the peak discharge of the debris by passing relatively a small portion of debris materials with significantly reduced destructive power.

As a type of widely used open-type dam, the slit dam has been extensively adopted as active measures to alleviate the losses by dissipating the kinetic energy (Lien, 2003). The performance of a slit dam is commonly evaluated by the so-called relative post spacing. It is defined as the ratio of the post spacing (b) to the maximum particle diameter (d_{max}). The field investigation (Shima et al. 2016) shows that slit dams is more likely to be filled-up with narrower relative post spacing ($b/d_{max} \approx 1.5$). Han and Ou (2006) illustrated that three types of slit dam blocking by non-viscous debris flows exist in the fields, namely, total-blocking, opening and part-blocking.

Although advancements exist, a thorough understanding of the impact mechanisms and regulation function of slit dams is still needed. To this end, the current study investigates the influence of relative post spacing on debris impact force and flow energy reduction using the open source discrete element method (DEM) code ESyS-Particle.

DEM MODEL CONFIGURATIONS

The Particle-particle Contact Model

In the DEM, the application of Newton's second law of motion and a force-displacement law alternately is calculated at the contact. The contact forces between two particles are calculated using the linear-elastic contact, namely, the normal and tangential contact forces, expressed as:

$$F_n = K_n U_n \tag{1}$$

$$F_t^n = F_t^{n-1} + K_s \cdot dU_s \tag{2}$$

where Kn being the normal contact stiffness, Un being the normal overlap distance; F_t^n and F_t^{n-1} is the tangential forces calculated at current and previous iteration steps, K_s is the shear stiffness, and dU_s is the incremental tangential displacement.

Model Configuration

In this study, we configure the numerical model analogous to the experiments by Zhou et al. (2018) of a natural debris-flow sloping channel in Kangding, Sichuan, China. As shown in Figure 1(a) and (b), the numerical model consists of a storage tank, a debris transportation zone with two different slope angles and an outflow plain. Initially, solid particles were generated in the storage tank with the dimensions of 0.8 m in length, 0.6 m in width and 0.4 m in height. This granular assembly consists of 60,090 polydispersed spherical particles with diameter ranges from 10 mm to 30 mm. Particles were initially retained by a trigger gate, which could be released from the tank in order to generate mobilized debris flows. In the numerical model, the channel base is made of a layer of fixed spherical particles of the same radius of 10.0 mm, while in the outflow plain, the fixed particles have radii of 25 mm. For simplicity, the plain strain boundary condition is employed by using two frictionless rigid walls in the lateral sides. This approach can effectively reduce the influence of boundary walls on the granular dynamics (Utili et al., 2015). The slit dams are rectangular prism with a height of 0.3 m and varied width. They are installed at 2.8 m upstream of the channel slope toe (see Fig. 1(a)).

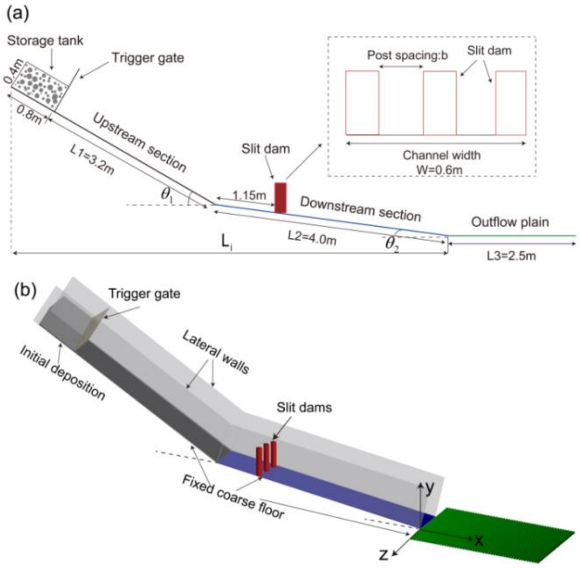

Figure 1 (a) Sketch of the experimental flume, (b) Numerical model configuration

In this model, the input parameters of the DEM simulations are listed in Table 1.

Table 1 Input parameters used in the simulations

DEM parameters	Value	DEM parameters	Value
Debris particle diameter, d (mm)	5-15	Particle friction coefficient, μ_1	0.5774
Debris particle density, ρ (kg/m^3)	2650	Particle-channel friction coefficient, μ_2	0.1763
Young's modulus of particle, E (MPa)	1×10^2	Gravitational acceleration, g (m/s^2)	9.81
Particle Poisson's ratio, υ	0.25	DEM time step size, Δt (s)	1×10^{-5}
Viscous damping coefficient, β	0.05	Normal stiffness, K_n (N/m)	1×10^7

According to the experimental results (Han and Ou, 2006), slit dam has been proved effective in reducing debris impact for slit density $\sum b/W$ ranging from 0.2 to 0.5. Therefore, five different relative post spacing ratios (b/d_{max}) have been used in a series of simulations (see Table 2). As a comparison, the case of $b/d_{max} = 0$ is also included (e.g. $b = 0$), such that the influence of post spacing on the debris flow behavior can be clearly identified.

Table 2 Parameters of the slit dams.

Channel width W (m)	Maximum diameter d_{max}	Post spacing b (m)	Relative post spacing b/d_{max}	Slit density $\sum b/W$

0.6	0.03	0 0.03 0.09 0.15 0.21	0 1.0 3.0 5.0 7.0	0 0.1 0.3 0.5 0.7

Particle Shape

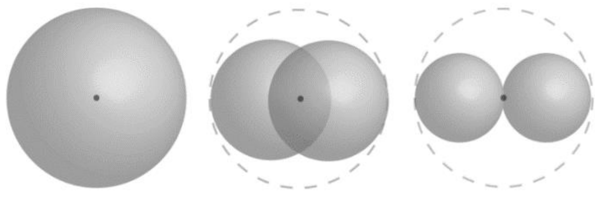

Figure 2 Schematic of different aspect ratio (α) particle(a) α = 1, spherical particle; (b) α = 3/2, ellipsoid shape particle; (c) α = 2, strip shape particle.

A schematic view of individual particle and particle clumps with same mass is shown in Figure 2, where the black dot represents the mass center of particles with various aspect ratios α (α = r/r_0, where r is the radius of individual particle and r_0 is the radius of clumps). The method used in this study to reproduce the shape of a real particle with overlapping spheres requires the representation of the particle surface as a cloud of points in space, while the particle mass and the total number of particles is maintained constant.

RESULTS

Dynamics of Debris-Slit dam Interaction

This section investigates the interaction between debris flow and slit dam with different relative post spacing (b/d_{max}). In particular, a relative post spacing of 3 has been chosen to study the debris dynamics during the impact. For better illustration, in the analyses, the granular materials were divided into five parts along the sliding direction (P1, P2, P3, P4 and P5) with each part of the same number of particles.

Figure 3 shows a side view of the interaction between debris flow and slit dams. The head of debris flow collides the slit dams at t = 1.7s (Fig. 3a). At t = 2.0s (Fig. 3b), a small amount of particles in P1 discharge through the slits, while the rest remains behind the dam forming a wedged shape deposition. This peculiar debris deposition pattern enables the run-up of approaching debris materials, leading to the subsequent debris overtopping (see Fig. 3c). In addition, the overflow starts to cascade over the slit dam. As more incoming debris materials deposit behind the dam, the volume of static debris zone increases gradually. This static zone can effective reduce the debris dynamics as the granular kinetic energy is dissipated via particle collision and friction (Shen et al., 2018). Because of the rapid dissipation of kinetic energy, the pile-up of debris materials is observed and the wedge angle remains constant (see Fig. 3d and Fig. 3e). At t = 5.0 s (Fig. 3e), a stable debris deposition forms and only a small amount of debris materials can pass through the slits. It is also interesting to note that the height of retained debris materials is higher than that of the dams.

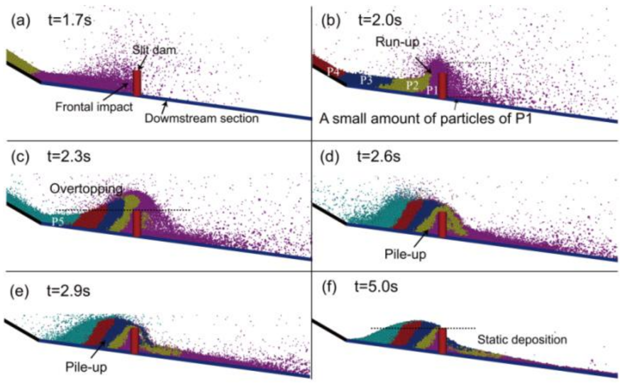

Figure 3 Dynamic interaction between debris flow and slit dam with b/d_{max} = 3, α = 1.

Run-out Distance

According to Lo (2000), the runout distance (L) is an important parameter to evaluate the destructive power of debris flow. It is measured as the boundary between 90% and 10% of the deposit mass (i.e. 10% of the fragment mass is spreading ahead of the boundary). In the analyses, the normalized runout distance is defined as $[L]=L/L_i$, in which L_i is the length of channel in the x-coordinate. Figure 4 illustrates that the normalized runout distance increases with b/d_{max} following an exponential relationship, while it decreases with α for a specific value of relative post spacing. At relatively small b/d_{max} (<1), the run-out distance is very small, indicating that only a small portion of particles can pass through or overtop the dam. Considering the difference of less than 0.05 between $b/d_{max} = 0$ and $b/d_{max} = 1$, the contribution of debris passing is very small. Such a tendency may be attributed to the fact that the slit dam is almost completely blocked in the case of $b/d_{max} = 1$. As the b/d_{max} increases, such blockage effect evolves to partly−blocked with increased debris run-out distance.

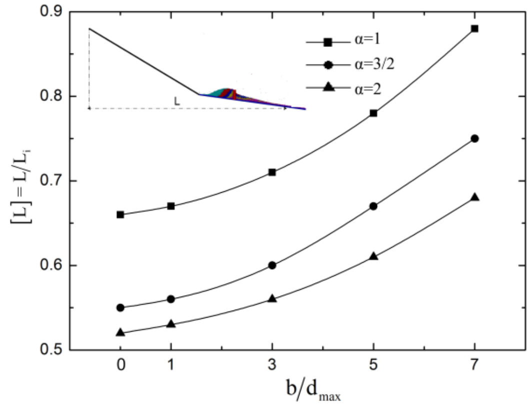

Figure 4 Influence of b/d_{max} and α on the normalized runout distance

Impact Force Applied to the Slit Dam

The current DEM model also evaluates the impact forces of debris flows on the slit dam for test conditions of various relative post spacing values. This force response has been considered to be an important factor for slit dam design in a cost-effective manner. In the analyses, the total impact normal force (F_n) is calculated by summing up all the normal contact forces of particles in contact with the slit dam. The calculated impact force is normalized by the granular mass (G).

Figure 5 shows the normalized maximum and residual impact force acting on the slit dam for the full range of investigated b/d_{max} and α. This result indicates that the normalized maximum and residual impact force is inversely proportional to the b/d_{max}。 The normalized maximum and residual forces are found to be strongly influenced by α. For α = 3/2, the normalized maximum force is much larger than the other two cases, and a higher normalized residual force is observed. Afterwards, the curve flattens out with the increasing b/d_{max}, which indicates that the influence of α becomes negligible when the b/d_{max} is small.

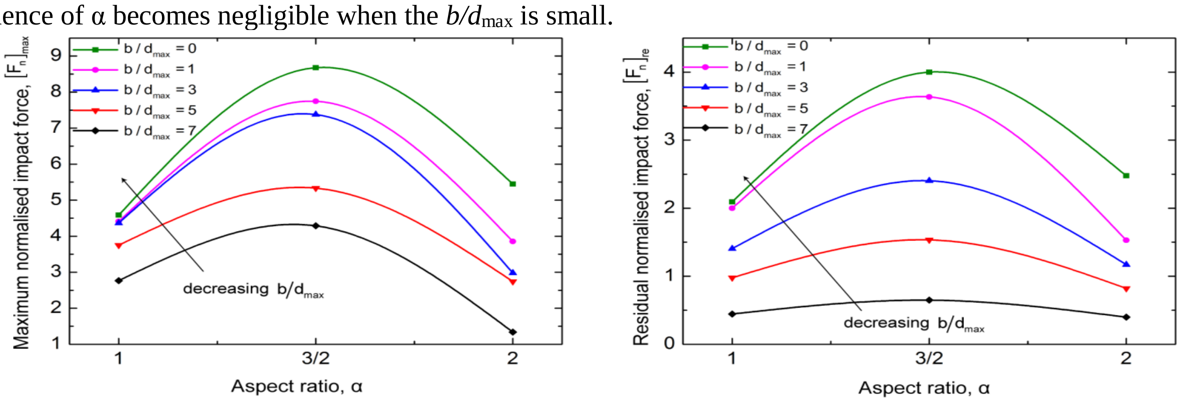

Figure 5 Normalized maximum and residual impact forces acting on the slit dams. G is the gravity of all debris particles

Scale Effect

As stated in Iverson (1997), a set of dimensionless parameters can be used to classify debris flows and identify the limiting styles of behavior. Among these parameters, the Froude number, F_r, is very important in designing physical models for achieving dynamic similarity between model and prototype, which can describe the regimes of debris flow. The Froude number can be defined as the ratio of inertial forces to the gravitational forces as $F_r = v/\sqrt{gh\cos\theta_2}$, where v is the frontal velocity reaching the slit dams; g is the gravitational acceleration; h is the approaching flow depth reaching the slit dams and θ_2 is the inclination angle of the downstream section.

Cui et al. (2015) stated that in most cases, debris flow has the Froude number between 2.5 to 5.9. For physical model studies, F_r normally ranges from 0.5 to 7.6. In particular, F_r can occasionally exceed 10 in water-laden debris flows (Choi et al., 2015). In this study, the Froude number of dry debris flow is calculated as 5.3 when the flow front approaches the slit dams. This value can reasonably match those observed in fields and physical model tests. Thus, the current numerical analyses can be regarded reliable in investigating the interaction between debris flow and slit dam..

CONCLUSIONS

This paper has investigated the impact of dry debris flows on slit dams with different relative post spacing via the open source DEM code ESyS-Particle. Based on the analyses, four key interaction stages were identified, namely the frontal impact, run-up, pile-up and static deposition. Each stage is characterized by different debris deposition pattern and energy evolution. In addition, the normalized normal impact force is inversely related to the relative post spacing b/d_{max}. The evolution of impact force is featured by three typical distinct regimes, namely the rapid acceleration region, rapid deceleration region and static deposition region, which corresponds to the dynamic interaction stages. According to numerical results, slit dams have been shown to be effective with b/d_{max} ranging from 3 to 5 which provide the normalized run-out distance of 0.73 to 0.80 with the residual normalized impact force from 1.0 to 1.5. The slit dam is almost completely blocked in the case of $b/d_{max} = 1$.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (grant 41602289) and the Fundamental Research Funds for the Central Universities in China (grant 2017SCU04A09).

REFERENCES

Choi, C.E., Ng, C.W.W., Au-Yeung, S.C.H., Goodwin, G.R. (2015). Froude characteristics of both dense granular and water flows in flume modelling. *Landslides,* 12, 1197-1206.

Cui, P., Zeng, C., Lei, Y., 2015b. Experimental analysis on the impact force of viscous debris flow. *Earth Surface Processes and Landforms.* 40, 1644-1655.

Han W, O.G. (2006). Efficiency of slit dam prevention against non-viscous debris flow. *Wuhan University Journal of Natural Science.* 11(4), 865-869.

Iverson. (1997). The pyhsics of debris flows. *Reviews of Geophysics*. 34(3), 244-296.

Lien, H.P. (2003). Design of slit dams for controlling stony debris flows. *International Journal of Sediment Research.* 18(1), 74-78.

Shen, W., Zhao, T., Zhao, J., Dai, F., GGD, Z., 2018. Quantifying the impact of dry debris flow against a rigid barrier by DEM analyses. *Engineering Geology*. 241(2018), 86-96.

Shima, J., Moriyama, H., Kokuryo, H., Ishikawa, N., Mizuyama, T., Prevention and Mitigation of Debris Flow Hazards by Using Steel Open-Type Sabo Dams. *International Journal of Erosion Control Engineering*. 9(3), 135-144.

Utili, S., Zhao, T., Houlsby, G.T., 2015. 3D DEM investigation of granular column collapse: Evaluation of debris motion and its destructive power. *Engineering Geology*. 186, 3-16.

Zhou, J., Cui, P., Yang, X., 2013. Dynamic process analysis for the initiation and movement of the Donghekou landslide-debris flow triggered by the Wenchuan earthquake. Journal of Asian Sciences. 76, 70-84.

Zhou, G. G. D., Hu, H. S., Song, D., Zhao, T., & Chen, X. Q. (2018). Experimental study on the regulation function of slit dam against debris flows. Landslides. doi: 10.1007/s10346-018-1065-2.