Impact dynamics of debris flow against slit dam: experimental and numerical investigation

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Abstract. Debris flows are gravity-driven phenomena common in mountainous regions that are hazardous to downstream facilities. To mitigate the impacts of these disastrous processes, structural countermeasures such as slit dams are constructed in gullies and along mountain slopes. Existing studies on the impact dynamics of debris flows against slit dams typically focus only on the flow characteristics but fail to take the geometry of the structure into account. Here we develop an analytical model, derived from the momentum approach, that allows for the estimation of the runup height and impact load of debris flows on slit dams. The model is validated against discrete element simulations and small-scale flume experiments. It is found that the runup height is controlled by both the Froude number and slit size. The proposed analytical model can predict the runup height well within a certain range of Froude numbers. Results from experiments further reveal that the fontal dynamic pressure is sensitive to the flow properties whereas the peak dynamic pressure is strongly affected by the slit size.

1 Introduction

Debris flows are gravity-driven mixtures of differently sized particles (from sand to boulders) saturated in muddy slurry [1]. These flows are massive and highly mobile and therefore pose significant risks to human lives and facilities downstream [2,3]. Mitigation structures, such as slit dams [4], are commonly installed strategically along the expected flow path to mitigate such destructive hazards. Such structures, which consist of rigid planes (posts) and openings (slits), disperse flow energy thereby arresting the flows [5].

The interaction between debris flows and structural countermeasures is a complex process involving impact, deceleration, deposition, and discharge. For engineering design and hazard mitigation, it is essential to comprehend runup behaviors and impact mechanisms [6]. Several analytical models have been proposed to predict the runup height of debris flows against obstacles [7] and a wide range of continuum-loading models have been used to calculate impact loads. However, the dynamic interaction between debris flows and slit dams, which significantly affects the runup height and impact load, is still poorly understood.

Here, we propose an analytical model based on the momentum approach to predict the impact dynamics of debris flows on slit dams. The interaction between debris flows and slit dams are studied numerically using the Discrete Element Method (DEM). Simulations of debris flows with varying Froude numbers N_{Fr} impacting slit dams with different slit sizes are carried out. In addition, a series of flume experiments of debris flow impacting model check dams and slit dams are carried out to study the influence of slit size on the impact loads.

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2 Theoretical model and simulations

2.1 Analytical model for the run-up height

Using the momentum approach, a depth-averaged continuum model has been developed to estimate the runup height. This analytical model is based on shock theory [8]. It is predicted that a flow impinging on an obstacle is a one-dimensional dynamic problem that can be interpreted from the emergence of a shock. When a steady flow encounters a vertical obstacle, a shock (or shock wave) develops instantly and travels upstream. Shocks are characterized by abrupt jumps in the velocity, density, and height. It is assumed that the incoming flow on a horizontal channel is continuous, steady, uniform, compressible, and unaffected by the backwater effect.

Fig. 1(a) illustrates a shock that forms when a debris flow impacts a check dam as viewed from the (top) side and (bottom) from the top. A shock forms and travels upstream with depth-invariant velocity u, height h, and bulk density ρ. A granular dead zone develops simultaneously between the shock and the dam. The conservation of mass and momentum across the shock travelling at a speed s can be expressed as:

$$\rho_0 h_0 (u_0 + s) = \rho_1 h_1 (u_1 + s) \tag{1}$$

$$\rho_0 h_0 u_0 (u_0 + s) + \int_0^{h_0} \sigma_{0_{xx}} \, \mathrm{dz} = \rho_1 h_1 u_1 (u_1 + s) + \int_0^{h_1} \sigma_{1_{xx}} \, \mathrm{d}z \tag{2}$$

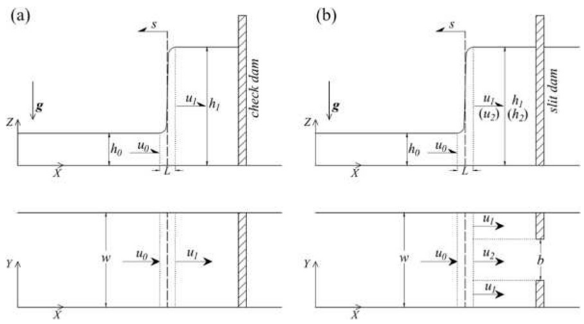

Fig.1. A (top) side-view and (bottom) plan-view schematic diagram of runup against (a) a check dam and (b) a slit-dam.

In the case of slit dams (Fig. 1(b)), a more complex process that involves flow deceleration, redirection, and downstream discharge is observed. As the incoming flow encounters the slit dam, a shock forms and rapidly travels upstream. In contrast to the check dam case, the slit dam's regulation causes the downstream flow from the shock to change into two types: (*i*) one slows down and deposits with speed u_1, creating a granular dead zone between the shock and the dam similar to the check dam case; (*ii*) another propagates downstream with speed u_2 and then passes through the slit. The conservation of mass and momentum across the shock travelling at speed *s* can be expressed as:

$$\rho_0 h_0 (u_0 + s) = (1 - B)[\rho_1 h_1 (u_1 + s)] + B[\rho_2 h_2 (u_2 + s)] \quad (3)$$

$$\rho_0 h_0 u_0 (u_0 + s) + \int_0^{h_0} \sigma_{0_{xx}} \,\mathrm{dz} = (1 - B) \left[\rho_1 h_1 u_1 (u_1 + s) + \int_0^{h_1} \sigma_{1_{xx}} \,\mathrm{dz}\right] + B\left[\rho_2 h_2 u_2 (u_2 + s) + \int_0^{h_2} \sigma_{1_{xx}} \,\mathrm{dz}\right] \quad (4)$$

where subscript 0 denotes properties of the flow upstream of the shock, subscript 1 denotes properties of the (*i*) retarding flow downstream of the shock while 2 denotes properties of the (*ii*) outgoing flow. $B = b/w$, where *b* is the width of the spacing between posts and *w* is the width of the channel, is the transverse blockage of the slit dam, σ_{xx} is the longitudinal normal stress.

It is reasonable to assume that the density and the height of the flows downstream of the shock are equal, i.e., $\rho_1 = \rho_2$ and $h_1 = h_2$. Downstream of the shock, the flow deposits at a speed u_1, forming a granular dead zone between the shock and the dam. The velocity u_1 can then be supposed to be equal to 0. The outgoing flow between the shock and the slit dam is characterized by strong flow curvatures, flow redirection, and the formation of dead zones in the corners. Without a thorough theory for the outgoing flow, we consider an empirical linear relationship between the outgoing velocity u_2 and the velocity of the incoming flow u_0. By combining these simplifications, the momentum jump condition equation (4) reduces to:

$$Fr_0{}^2[1 - 2B\alpha + B\alpha^2 - AB\alpha^2 + AB^2\alpha^2] - \frac{1}{2}k\left[A\frac{h_1}{h_0} - \frac{h_1}{h_0} - 1 + A^{-1}\right] = 0 \quad (5)$$

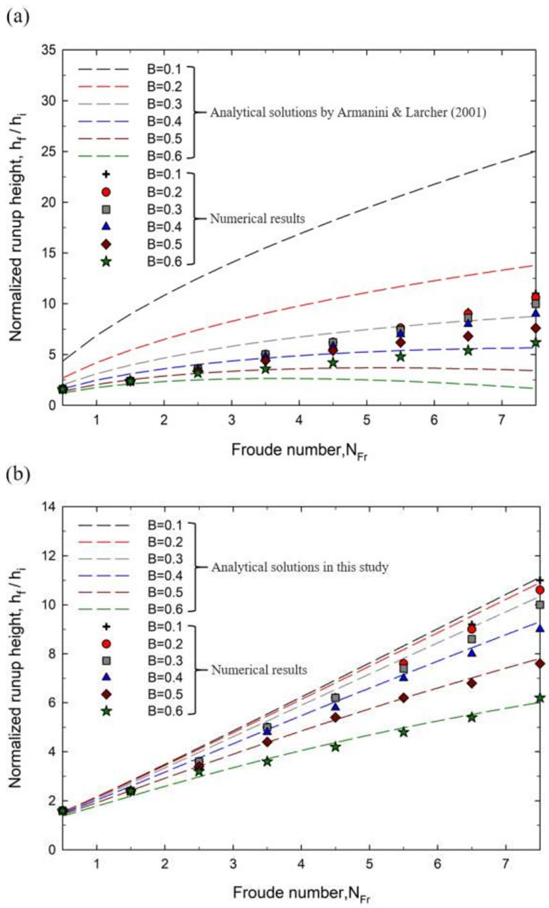

Fig. 2. Comparison of theoretical normalized runup height predicted by (a) the energy approach and (b) the momentum approach with the DEM results.

where Fr_0 is the Froude number of the incoming flow, indicating the ratio of inertial forces to gravitational forces. Equation (5) yields a runup formula based on the momentum approach and takes into account both the upstream Froude conditions (N_{Fr}) and the slit size (*B*). Finally, the solutions of the runup formula can be obtained. Consequently, if the Froude number of incoming flow and the geometry of slit dam are known in advance, the runup height of debris flows against it can be predicted.

2.2 Comparison of runup prediction models

The comparison between the simulated normalized runup heights and the analytical model of [4] is shown in Fig. 2(a). The results show that this approach is unable to accurately predict the runup heights of the simulated granular flows. The predictions are either overestimated when the relative post spacing is low or too conservative when it is high. This is because this strategy assumes that the runup process is under the hydraulic jump condition, making it inappropriate for frictional dense granular flows, where the pileup mechanism dominates the flow-structure interaction process.

The momentum approach is said to be able to accurately predict runup heights and capture the runup behavior of granular flows [9]. Figure 2(b) compares the simulated normalized runup heights with predictions obtained from equation (5). Results indicate that our proposed model can accurately predict the runup heights of debris flows against slit dams. The numerical simulation results and the runup heights predicted by the model exhibit similar tendencies: higher Froude numbers (N_{Fr}) and lower transverse blockage (B) lead to higher runup heights. The maximum deviation of the calculated results from the predicted runup heights is less than 15.6%. Therefore, engineers anticipating a dense granular debris flow can safely estimate the height needed for the slit dam to prevent hazardous overtopping using the proposed equation. In addition, the results show the influence of the upstream Froude conditions (N_{Fr}) on runup heights for granular flows against slit dams. The maximum runup height increases monotonically with the Froude number of incoming flows, which is consistent with [10].

3 Small-scale flume experiments

3.1 Experimental parameters

Designing safe and effective countermeasures against debris flows involves accurate predictions of the impact load. Currently, there has been abundant research focused on the mechanisms of debris flows impacting structures. Impact loads can be estimated using existing hydrodynamic models. However, less attention has been paid to the effect of slit size on the impact load. In this section, the frontal impact pressure and the total impact force influenced by slit size and solid volume fraction will be discussed.

The relative post spacing b/D_{max}, where b is the size of slit and D_{max} is the maximum particle diameter, is a dimensionless parameter that characterizes the slit size. During the frontal impact, the peak impact pressure P_{peak} can be detected by force sensors positioned at the bottom of the dam [6]. The frontal dynamic pressure coefficient α_1, a dimensionless parameter that quantifies the dynamic load, is expressed as function of P_{peak}, i.e $\alpha_1 = P_{peak}/(\rho v^2)$, where ρ is bulk density, v is the frontal velocity. An important parameter considered in the design of mitigation structures is the peak total impact force acting on them $F_{peak}{}'$. The peak impact force is calculated by integrating the impact pressure along the dam height. The peak dynamic pressure coefficient α_2, which encodes information on the dynamic and static load, can be calculated through $F_{peak}{}'$, i.e $\alpha_2 = F_{peak}{}'/(\rho v^2 h)$, where h is the maximum approaching flow depth.

3.2 Frontal impact pressure

Fig. 3(a) shows the relationship between α_1 and b/D_{max}. In theory, α_1 equals unity if there is no static load exerted on the dam. However, the momentum of the flow impact is not always along the direction of the channel. When $\alpha_1 < 1$ part of the impact load is transferred vertically along the dam surface due to significant run-up [4]. In addition, α_1 is mainly related to the momentum of frontal debris flow instead of b/D_{max}, which means that α_1 does not change with b/D_{max}. Consequently, it can be said that the peak frontal impact pressure is not affected by slit size.

Debris flows with low solid fraction ($C_s = 0.4$) are controlled by strong inertial stresses, resulting in large α_1. Dilute debris flows easily deflect upward along the dam surface and the momentum of the flow is transferred to the base of dam efficiently during the collision. Meanwhile, debris flows with $C_s = 0.6$ have larger frictional stresses resulting from the increased interaction between particles. This leads to greater energy dissipation within the flow and consequently the attenuation of the frontal impact pressures.

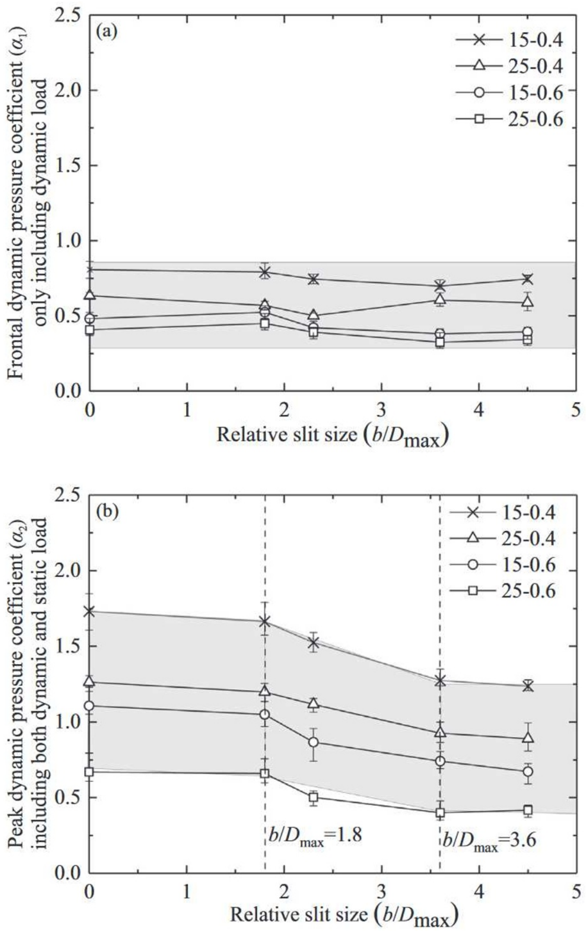

Fig. 3. (a) Frontal dynamic pressure coefficient (α_1) and (b) peak dynamic pressure coefficient (α_2) at different relative slit size (b/D_{max}). The legend displays flume inclination angle – solid fraction.

3.3 Total impact load exerted on slit dam

Fig. 3(b) shows the relationship between α_2 and b/D_{max}. Since information on the static load is included in α_2, i.e the weight of retained debris flow materials, α_2 is significantly greater than α_1. For $b/D_{max} \leq 1.8$, the slit size has minimal influence on α_2. This means that the slit sizes below this limit are too small for debris flow materials to pass through that they function similar to check dams. Increasing the relative post spacing to $1.8 \leq b/D_{max} \leq 3.6$, decreases α_2 by ~23% for tests with Cs = 0.4, and by 30% ~ 40% for tests with $Cs = 0.6$. However, when $b/D_{max} \geq 3.6$, α_2 remains constant which means that $b/D_{max} = 3.6$ is a critical limit in which slit dams can still efficiently trap debris flows. Hence, the influence of slit size should be considered when estimating the impact of debris flow.

4 Conclusions

An analytical model based on the momentum approach was derived to predict the runup heights of debris flows against slit-dams. Debris flows impacting slit-dams are investigated through discrete element method (DEM) simulations. It is found that the runup height is controlled by both the Froude number and slit size. The proposed model captures relevant runup mechanisms of debris flows against slit-dams and is able to provide good predictions of the runup heights within a certain range of Froude numbers.

To study the influence of slit size on the impact loads, a series of flume experiments of debris flows impacting model check dams and slit dams are carried out. Measurement of the flow velocity, depth, impact load, total basal normal stress, and basal pore-fluid pressure enable a comprehensive evaluation of the impact characteristics. Tests reveal that the peak frontal impact pressure is largely unaffected by the slit size of structural countermeasures but is sensitive to the debris-flow properties. However, the slit size obviously influences the peak force experienced by the structures. A critical relative post spacing of 3.6 is determined wherein slit dams can effectively mitigate debris-flow hazards.

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