

# A STUDY OF THE IMPACT FORCE OF DRY GRANULAR FLOW DOWN ON AN INCLINE PLANE

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**ABSTRACT:** The dynamic loading characteristics of dry granular flow on closed and/or open rigid barriers should be carefully considered in the design and implementation of debris flow mitigation measures. Proper design can ensure that the barriers are able to withstand the dynamic loads generated by the granular flow and reduce the risk of damage or failure of the barriers. This paper presents an experimental and numerical investigation performed to evaluate the effectiveness of open check dams in mitigating the impact of dry granular flows on an inclined plane. The study focused on two distinct patterns of sectional dams: V-shaped and Alpha-shaped configurations. The experimental and simulation results revealed key findings regarding the sediment control efficiency of these patterns. It was observed that the Alpha-shaped pattern demonstrated superior sediment trapping efficiency compared to the V-shaped configuration. The study also identifies several variables that influence the sediment trapping efficiency of open check dams. The patterns and sequence of check dams were found to significantly impact their performance. The investigation examined the critical role of pile spacing and grain size in designing effective open check dams. The results emphasized the importance of considering these factors to achieve optimal performance in sediment control. Both the experimental and numerical approaches contribute to a better understanding of the behavior and performance of open check dams in mitigating the impact of granular flows.

*Keywords: Dry granular flows, Open check dam, Trapping efficiency, Impact force reduction*

## 1. INTRODUCTION

Granular flows, encompassing phenomena like debris flows and rock avalanches, pose a substantial threat to infrastructure, particularly the protective barriers designed to mitigate their impact. The particle size within these granular materials significantly influences the flow's interaction with barriers. These flows are complex and unpredictable natural phenomena that can cause significant damage to infrastructure and communities.

Mitigating the risk of debris flows involves a combination of measures that reduce the likelihood and impact of this hazardous phenomenon. Closed and open check dams are commonly constructed across a river or stream to slow down the flow of water and reduce erosion. In the case of closed check dams, such as walls or embankments, the flow can generate a pressure pulse on impact that can result in significant dynamic loads. For open check dams, the dynamic loading characteristics of the flow can depend on the spacing (openings or slits, [1]) and orientation of the check dams. When the spacing is too small or the orientation of the check dams is not optimal, the coarse sediments can cause the check dam to clog and fail, resulting in a significant increase in the dynamic load [2-7]. V- and/or alpha (A)-shape sectional dams with piles represent one form of open-type check dams designed to trap and retain a substantial portion of flowing granular material [8, 9].

To better understand and mitigate the risks associated with debris flows, experimental and numerical investigations have been performed to study the behavior of debris flows and their interactions with countermeasures. Existing studies on flow-structure interaction have specific objectives and limitations regarding scope and resources. Experimental investigations involve performing physical tests using scale models or full-scale simulations to study debris flow behavior. In these experiments, researchers can vary the parameters such as the slope angle, the size and shape of the particles, and the velocity of the flow to study their effects on the behavior of the flow [10-14]. By employing countermeasures, researchers are able to quantify the impact forces exerted by the debris flow on the countermeasures and analyze the obtained data to acquire a deeper understanding of the flow dynamics.

Multiple rows of structural countermeasures on sloped terrain can provide several advantages, notably enhanced flow control and improved energy dissipation. Studies on flow-structure interaction, which focus on a single row of countermeasures, have been performed more frequently and extensively compared to those involving multiple rows. These studies have shown that the design and placement of barriers can significantly influence their ability to withstand the dynamic loads generated by the granular flow [11, 15].

Numerical investigations involve creating computer simulations of granular flows using computational fluid dynamics (CFD) or other modeling approaches [16-19]. These simulations can model the flow of particles, the interaction of the flow with the countermeasures, and other relevant factors such as erosion and sediment transport. By varying the parameters in the simulation, researchers can study the behavior of debris flows and their interactions with countermeasures in a virtual environment. Advanced simulations (e.g., Discrete Element Method, DEM) have increasingly been employed to explore granular microstructure in terms of granular texture (the organization of particles and their contacts in space), force transmission, and friction mobilization. In this sense, DEM provides an understanding of physical phenomena characterized experimentally ([9], [16-19]). Studying flow-structure interaction becomes increasingly complex as the number of structural countermeasures and their arrangements increases. Each row of countermeasures can introduce additional interactions and dependencies.

This study involved performing laboratory tests and numerical simulations to investigate the interaction between granular flow and structures. Some results derived from laboratory tests aimed at investigating the flow-structure interaction and trapping efficiency will be presented. The interaction of granular flow against a barrier will be numerically evaluated by the discrete element method.

## 2. RESEARCH SIGNIFICANCE

Debris flows are complex and unpredictable natural phenomena that can cause significant damage to infrastructure and communities. To better understand and mitigate the risk associated with debris flows, experimental and numerical investigations can be carried out to study the behavior of debris flows and their interactions with countermeasures. The results of experimental and numerical investigations can help inform the design and implementation of measures to mitigate the risks associated with debris flows. For example, researchers may use the results to design more effective countermeasures, such as check dams, or to improve infrastructure design to withstand the impact of debris flows.

## 3. MODEL SETUP

### 3.1 Experimental flume setup

Experimental investigations involve performing physical tests using scale models or full-scale simulations to study the behavior of granular flows. A laboratory flume comprising a length of 7.2 m, a channel width of 0.40 m, and a depth of 0.55 m with

an adjustable slope (Fig. 1) was used to investigate the flow behavior of dry granular materials through an open check dam. A storage tank which has a length of 0.60 m is set to open manually by a gate. Two sides of the flume were made of transparent acrylic sheets. In this study, the flume bed was made of a steel plate, providing an interface friction coefficient between dry granular materials and the flume bed ( $\delta$ ).

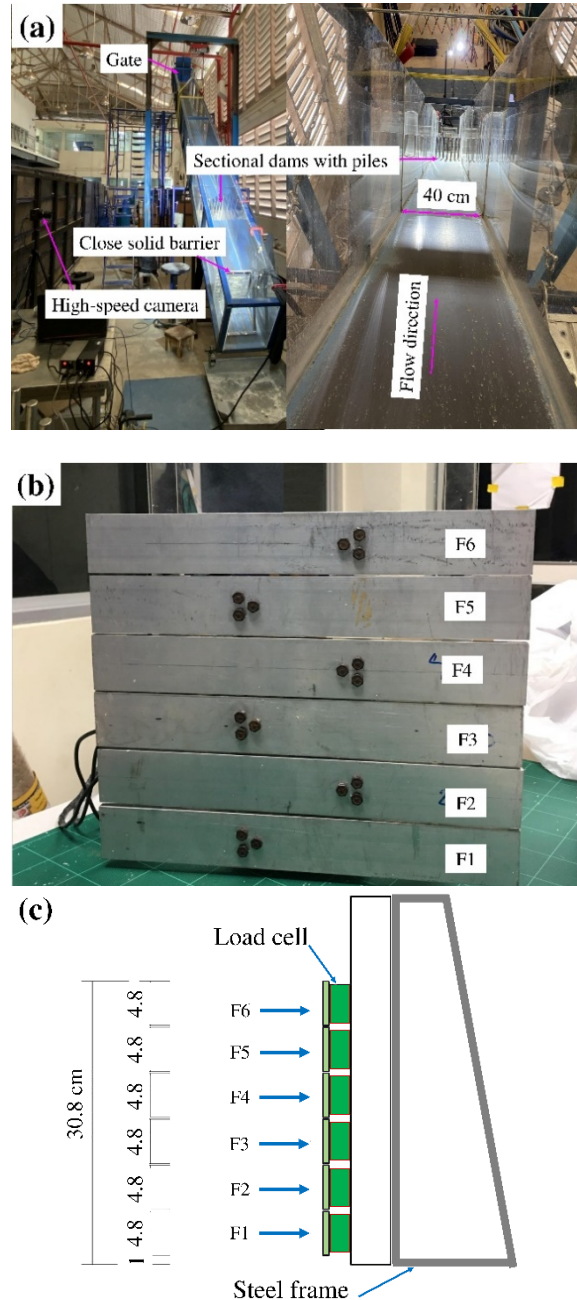


Fig.1 Physical model setup; (a) Image of flume modeling and its equipment; (b) Closed rigid barrier for measuring impact force; (c). Load measurement devices equipped on a closed rigid barrier.

A closed rigid barrier and sectional dams with

piles, which were made of aluminum, were mounted at a distance of 475 and 610 cm downstream from the gate of the storage tank, respectively. Six load transducers were fitted with aluminum plates to quantify the impact forces exerted by the close rigid barriers employed in the reference tests. Each plate, with a dimension of 4.80 x 39.00 cm, was stuck with a steel frame. The impact force perpendicular to each plate was measured. The total impact force ( $F$ ) can be expressed as the summation of each force:

$$F = \sum F_i \quad (1)$$

where  $F_i$  represents the impact force from different parts of the load measurement transducers ( $F_1$  to  $F_6$ ).

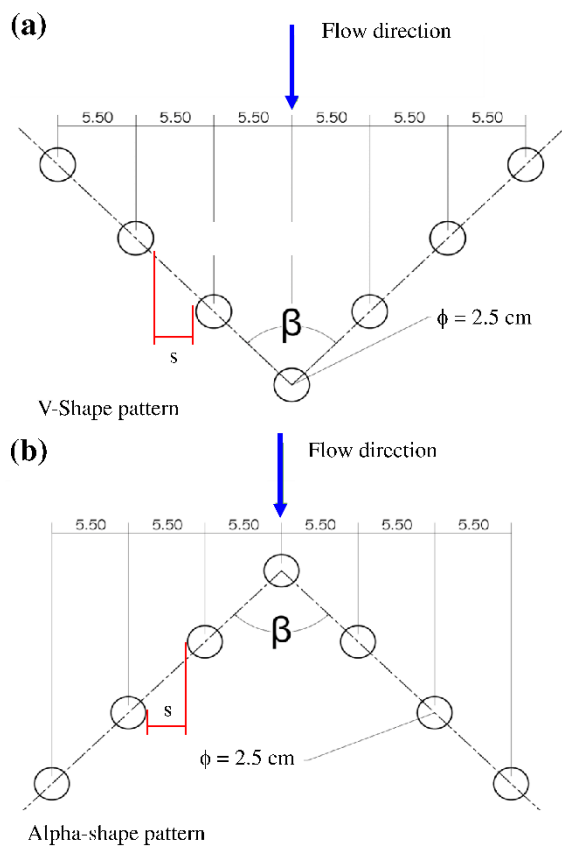


Fig.2 Sectional dam with piles in V- and Alpha-shape patterns.

Sectional dams with piles, which are one type of open check dams, comprise 7 cylindrical tubes with a diameter of 2.5 cm and a height of 27 cm. Each pile was set with a spacing ( $s$ ) of 3 cm perpendicular to the flow direction. Two configurations were tested: V- and Alpha-shaped patterns (with internal angles of  $\beta = 80, 90,$  and  $100^\circ$ ). The definition of these shape patterns in the sectional dam with piles concerning the flow direction is shown in Fig.2. Table 1 provides an overview of the several test programs performed

in this study. Smaller and finer materials travel through the openings, while more enormous boulders get temporarily trapped or accumulated. The attenuation rate of impact force ( $R$ ) and sediment trapping, or retention rate ( $E$ ) can be expressed as:

$$R = \frac{F_c - F_s}{F_c} \quad (2)$$

$$E = \frac{V_e - V_s}{V_e} \quad (3)$$

where  $F_c$  is the total impact force on a single row of close rigid barriers;  $F_s$  is the total impact force flowing through the sectional dams with piles on close rigid barrier;  $V_e$  and  $V_s$  are the original volume material and the granular volume flowing through the sectional dams with piles, respectively.

Table 1 Test program

Test code	Barrier pattern	Internal angle, $\beta$ , ( $^\circ$ )	Flume slope, $\theta$ , ( $^\circ$ )
V80-C0	V-shaped	80	25, 30, 35
V90-C0	V-shaped	90	25, 30, 35
V100-C0	V-shaped	100	25, 30, 35
A80-C0	Alpha-shaped	80	25, 30, 35
A90-C0	Alpha-shaped	90	25, 30, 35
A100-C0	Alpha-shaped	100	25, 30, 35
C0	Closed type	-	25, 30, 35

Note:  $\theta$  stands for the flume slope in each test.

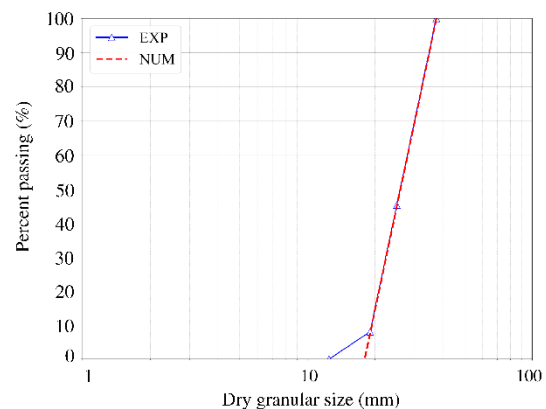


Fig.3 Grain size analysis of dry particles for experimental (EXP) and simulation (NUM) investigations.

### 3.2 Material properties

The size of particles in granular flows can significantly influence their behavior upon interaction with a barrier. Dry river gravels were used in this study. The grain size distribution of these gravels is illustrated in Fig.3. Considering the spacing

of each pile and  $D_{90}$  (the diameter corresponding to 90 % finer in the particle-size distribution) the opening ratio of  $D_{90}/s = 0.86$  was then defined. This opening ratio was also considered for the simulation. The material properties are also shown in Table 2. To prepare the samples, these gravels were thoroughly washed to minimize dust generation and then dried using the oven. For each test, a 30 kg mass of gravel was initially set to a bulk density of  $2650 \text{ kg/m}^3$ . The initial geometry of this sample was triangular.

Table 2 Material properties

Parameters	Values		Unit
	Exp.	Num.	
Bulk density	2650	2650	$\text{kg/m}^3$
Max. diameter	37.50	37.50	mm
Min. diameter	13	18	mm
Particle friction coefficient	0.35	0.35	-
Particle-bed friction coefficient	0.89	0.89	-



Fig.4 Dry particles (a) physical experiment; (b) numerical computation

### 3.3 Numerical model

Granular flows often consist of particles with varying sizes, which can be referred to as polydispersity. Understanding the role of polydispersity remains a challenging task that is often analyzed with nearly monodisperse systems. The numerical computation was performed using a three-dimensional discrete element method, the non-smooth contact dynamics (NSCD) approach, namely the LMGC90 software, developed initially at the LMGC laboratory [20-22]. To closely replicate the dry gravels utilized in the real experiment (Fig.4), a total of 3080 dry granules with different shapes and a density of  $2650 \text{ kg/m}^3$  were employed in the simulation. According to the LMGC90 software, granulometry creation refers to the process of creating a list of particles with minimum and maximum values

that are distributed uniformly in terms of quantity. The grain size distribution of experimental and numerical investigations can only align within the range of  $D_{10} - D_{100}$ .

The friction coefficients of 0.35 (dry particle-bed) and 0.89 (dry particle) were set. However, due to the smooth surface of the simulated granules, a limitation of the DEM, the simulation assumed that the dry granules would not crack nor deform (i.e., they are perfectly solid particles), and the restitution coefficient was set to zero. The LMGC90 simulation framework encounters limitations in accurately capturing the interaction between a polyhedron and a cylinder within an open check dam with piles.

The chosen geometry was suited to replicate the characteristics of closed and open check dams. The configuration comprised an idealized channel featuring a rectangular cross-section, with a length of 7.2 m and a width of 0.4 m, providing a conducive framework for the incorporation of the desired slope, denoted as  $\theta$ . To establish a coherent reference framework tied to the local topography, an orthogonal coordinate system was employed. In this system, the z-axis was oriented perpendicular to the channel floor, while the x-axis aligned with the downslope direction, as visually represented in Fig.5. To address the inherent constraints in simulating polyhedron-cylinder interactions, a polygon with 16 uniform sides was generated, ensuring regularity in shape. Subsequently, each side of the polygon was extended in an extrusion process to form a cylindrical rod (Fig.6). This transformation was executed to imitate the geometry of the sectional dam with piles observed in laboratory conditions.

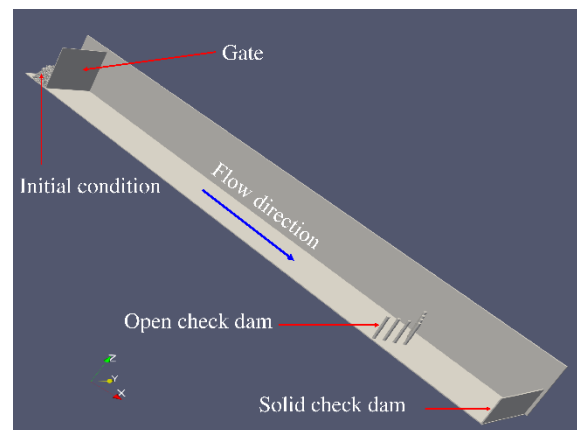


Fig.5 Numerical flume model setup

## 4. RESULTS AND DISCUSSION

### 4.1 Flow characterization and impact force on barriers

The experimental and numerical setups of a study of the dynamic loading of granular flows against open

and closed type rigid barriers typically involve several components, including the granular material and barrier geometry.

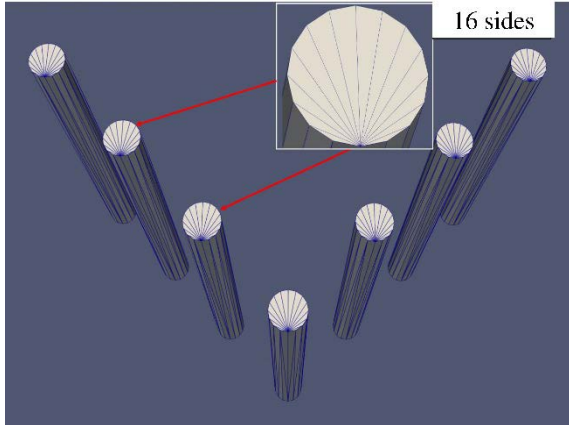


Fig.6 Model setup of a sectional dam with piles

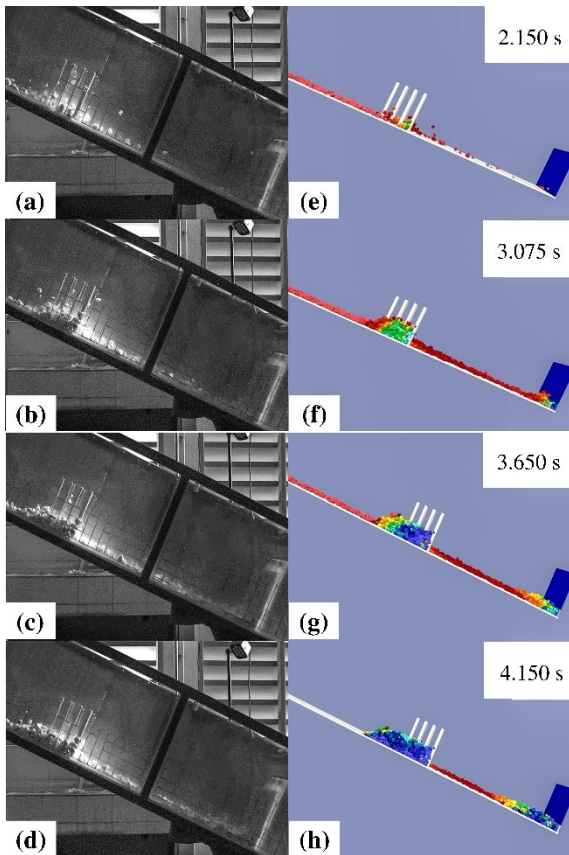


Fig.7 Snapshots of comparison of physical and numerical models from the test A80-C25; (a), (b), (c), (d) physical experiment; (e), (f), (g), (h) numerical computation

Figures 7 shows a comparative analysis of flow characteristics between experimental and simulated scenarios. The time history commences when the dry particles initiate their flow. Some particles scattered when they hit the sectional dam with piles in the experimental setup. The simulated model, on the

other hand, had less scatter because it had a zero-reflection coefficient. The simulation revealed a pile-up mechanism occurring as the particles traversed the sectional dam with piles, resulting in a significant attenuation in both velocity and impact force.

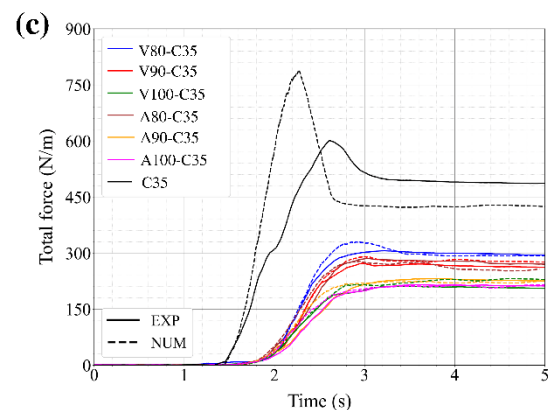
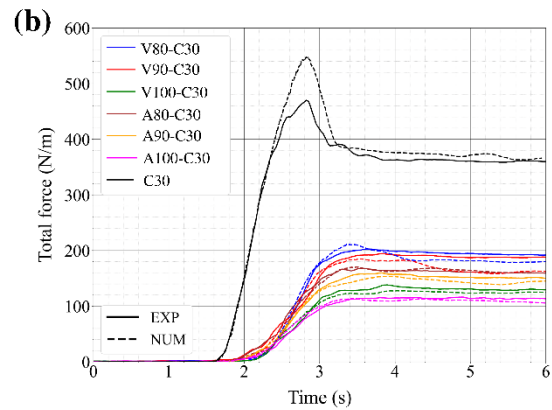
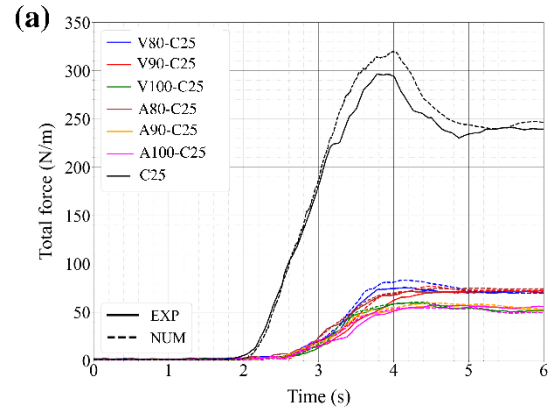


Fig.8 Total normal impact force; (a)  $\theta = 25^\circ$ ; (b)  $\theta = 30^\circ$ ; (c)  $\theta = 35^\circ$

Considering the summation of  $F_1 - F_6$  as shown in Fig.8, the flume slope affects the difference between the maximum impact force and the residual force. In the case of double rows, where a sectional dam with piles in different patterns was set in front of the solid close barrier, the impact forces measured from the solid barrier decreased significantly. A higher

attenuation rate in total force impact could be observed when the flume slope increased.

In the context of a closed rigid barrier, dry granular flow against the obstacle led to the generation of the maximum impact force, denoted as  $F_1$  at the bottom. The force  $F_2$  was found to be approximately two-thirds of  $F_1$  at an inclination angle ( $\theta$ ) of  $25^\circ$ , whereas the upper parts ( $F_3$  to  $F_6$ ) could hardly be observed. This was due to the pile-up mechanism which controlled the flows against a barrier. As the inclination angle increased to  $30^\circ$  and  $35^\circ$ , the impact forces  $F_2$  and  $F_3$  were approximated to be two-thirds and one-half of  $F_1$ , respectively.

The pattern of the sectional dam with piles did not affect the total force when the flume slope was low. An observable difference in total force became apparent with an increase in the flume slope. For  $\theta = 35^\circ$ , it was observed that V- and Alpha-shape patterns with an internal angle of  $\beta = 100^\circ$  (V100-C35 and A100-C35) showed more attenuation of flow impact than those patterns. This may be the result of the diagonal spacing of each pile. The numerical results could satisfactorily reproduce the total force for each pattern.

### 3.2 Trapping efficiency

The effectiveness of an open check dam in trapping debris flows is influenced by various factors. These factors determine how effectively the dam can capture and retain coarse particles while allowing finer particles to pass through. Fig.9 displays the trapping efficiency of open check dams in both experimental and simulated scenarios. The design of a sectional dam with piles, including the spacing of the openings ( $D_{90}/s$ ), influenced its ability to trap the particles. It can be observed that the experimental trapping efficiency was slightly lower than the simulation. This discrepancy can be attributed to the inherent physical properties of dry particles and the friction induced by their contact. The simulation, due to the surface of the modeled particles, allows for a higher degree of contact and consequently more friction as the particles flow through the sectional dam with piles. This disparity leads to a higher trapping efficiency value in the simulation compared to the experimental investigation.

The flow velocity of dry granular material was a critical factor. Increased velocities, as observed for the tests with  $\theta = 35^\circ$ , could reduce trapping efficiency as the force of the flow could dislodge or carry away trapped sediments. Fig.10 also shows an example of trapped particles for test A100-C35 in which a satisfactory agreement between the experimental and numerical results could be observed. Regarding design considerations, the Alpha-shaped patterns consistently exhibited higher trapping efficiency in comparison to the V-shaped patterns. Furthermore, the results demonstrated a direct

relationship between trapping efficiency and the expansion of the internal angle within the sectional dam with piles.

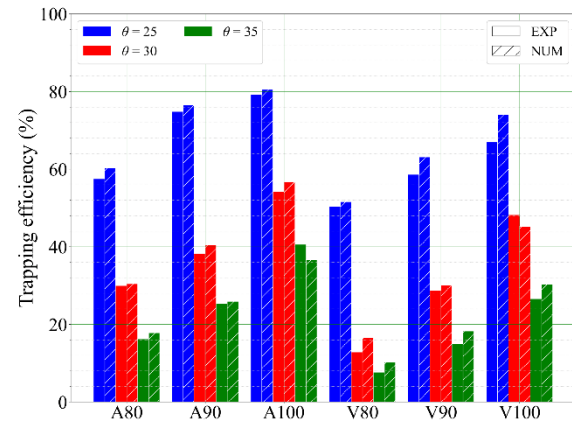


Fig.9 Trapping efficiency of sectional dams with piles.

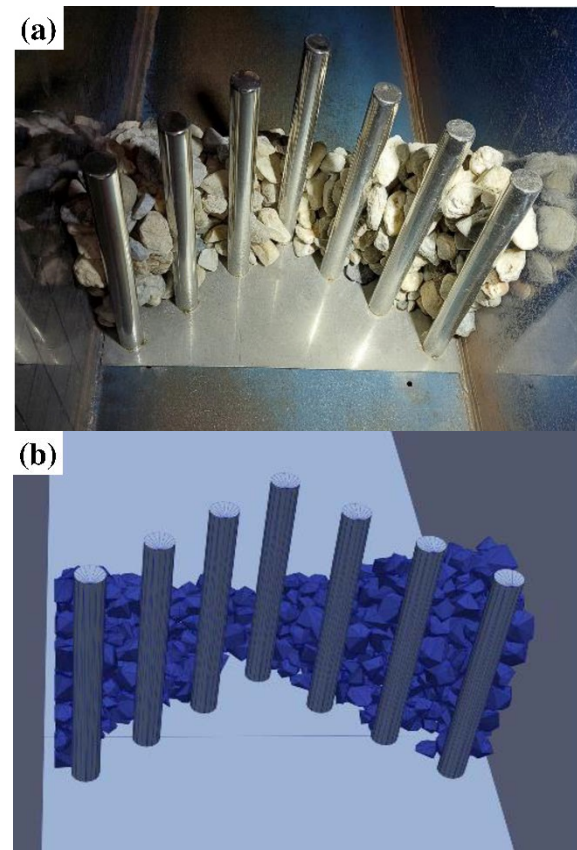


Fig.10. Trapped particles (a) experimental and (b) numerical observations for the test A100-C35

## 5. CONCLUSIONS

Closed and open check dams are commonly constructed across a river or stream to slow down the granular flows and minimize their destructive consequences. Laboratory experiments and

numerical modeling play a crucial role in advancing our understanding of granular flow dynamics, providing controlled environments that allow researchers to investigate the behavior of granular materials under controlled conditions.

This study aimed to assess the quantitative effectiveness of open check dams (sectional dams with piles) in controlling dry granular flows. The investigation was performed using both experimental and numerical approaches. Despite its limitations, including scaling challenges and the difficulty of precisely duplicating field conditions, laboratory-scale experiments provide vital insight into the behavior of granular flows and serve as a complement to field observations and numerical simulations. The integration of experimental and numerical studies provides a more comprehensive understanding of granular flow phenomena and facilitates the advancement of knowledge in this field.

This study demonstrated the effectiveness of open check dams in controlling dry granular flows. The Alpha-shaped patterns exhibited superior performance in force attenuation while increasing internal angles improved trapping efficiency. Numerical simulations exhibited consistency with the experimental results, confirming the efficacy of Alpha-shaped patterns in reducing impact forces.

V-shaped patterns exhibited lower trapping efficiencies compared to Alpha-shaped patterns. Additionally, an augmentation in trapping efficiencies was observed with an increase in the internal angle of the open check dams. It is important to note that the experimental trapping efficiency was lower than the simulated results, possibly due to the differential effect of surface roughness and friction between the granular material and open check dams.

## 6. ACKNOWLEDGMENTS

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