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Modelling the impact of particle flow on rigid structures: experimental and numerical investigations

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ABSTRACT
Gravity-driven debris flow of granular particles down an inclined slope is a problem of growing concern in mountainous regions and poses a significant risk to people, roads, and other infrastructure. Different aspects of the problem have been previously investigated using physical modelling and numerical analysis. However, three dimensional pressure distribution on a barrier wall resulting from debris flow over a rough slope is scarce in the literature. In this study, a series of experiments are conducted to track the movement of granular particles down a slope and measure the impact pressure imposed by the flowing particles on a nearby vertical wall. The particles are released from a container located at the top of the slope and the velocity profiles are recorded using marked pebbles and a high-speed camera. The effect of the debris volume, slope angle, and distance to the wall on the velocity profiles and impact forces are investigated. Validated using the experimental results, discrete element simulations are performed using PFC^{3D} to evaluate the effect of particle sizes on the flow characteristics and final impact pressure on the structure. Analysis showed that impact energy is highly affected by the slope inclination, particle velocity, and runout distance.

1. INTRODUCTION

The numerical modelling of granular mass movement under the influence of gravity (e.g. debris flows, avalanches, etc.) has received significant research attention over the past decade. Various methods have been used to investigate the flow-like mass runout behaviour including finite element analysis (Crosta et al., 2002; 2003) and discontinuous deformation analysis (DDA) (Wu, 2010; 2011). The DDA method represents debris flow using sliding blocks and therefore, this method may not be suitable to model the rapid movement of loose particles.

Discrete element method (DEM) was first proposed by Cundall and Strack (1979) and because the method naturally takes discontinuity into account, it has been successfully used to simulate debris flow problems (Li et al., 2012; Liu and Koyi, 2013; Zhao et al., 2015). However, very few studies focused on the three-dimensional analysis of gravel movement over a rough inclined surface considering the dynamic impact of the moving particles on nearby structures. McDowell et al. (2011) and Li et al. (2012) studied the dynamic behaviour of flowing particles using different sizes of four-ball clumps validated using velocity profiles measured in the laboratory. Lo et al. (2010) decomposed fluctuating particle flow velocity filed on rough inclines into best-fit and fluctuating components using three-dimensional DEM. These studies provided some insight into the effect of surface roughness on the dynamic behaviour of flowing particles, however, the impact of particle flow on nearby protective structures is yet to be fully understood.

In this study, an experimental investigation is conducted to understand the mechanics of debris flow over rough inclines in a controlled laboratory environment. High-speed camera and tactile pressure sensors are used to track particle movement and measure the impact force on a barrier wall, respectively. Discrete element analysis is also performed using walls and spheres to model the laboratory experiment for three different slope angles. Preliminary results are presented and conclusions are made regarding the recorded velocity profile for each slope inclination and the associated displacements as well as stress distribution resulting from the impact of particles on the vertical wall.

2. EXPERIMENTAL PROGRAM

The experiments were performed using river pebbles with an average particle diameter of 5 cm, as shown in Figure 1.

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Figure 1: The river pebbles used in the experiments.

The surface of the slope and the horizontal runout section are designed and built using smooth aluminum plates, lined with perforated sheets to create a bumpy (rough) surface. A stiff rubber sheet of 2 mm in thickness is used to simulate the rough surface. The sheet is punched with round holes 5 cm in diameter arranged in a hexagonal pattern at 8 cm center spacing (See Figure 2).

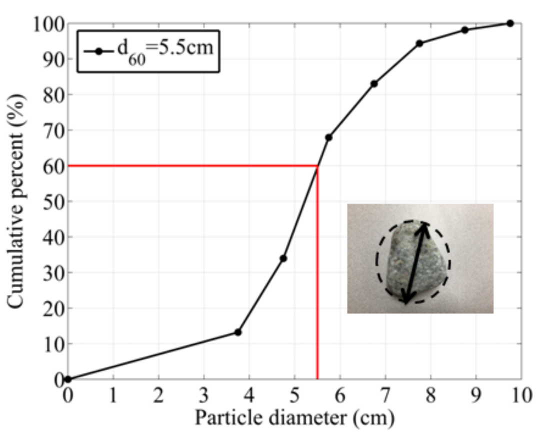


Figure 2: Particle size distribution.

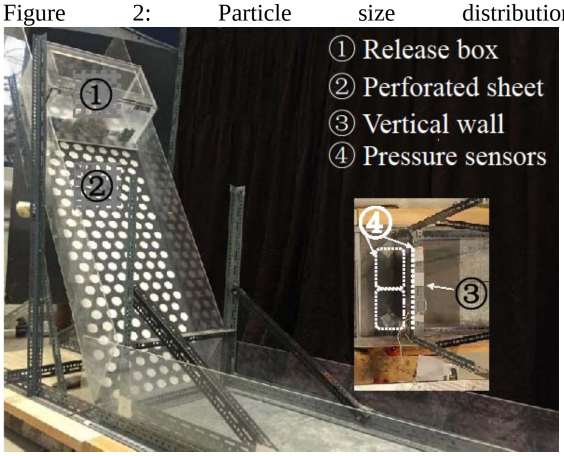


Figure 3: Experimental setup.

2.1 Test Setup

The slope, 1.82 m long and 0.62 m wide has the 0.03 m high Perspex sides so that all activity within it is visible. The slope inclination can be adjusted to cover a range of angles between 0 and 90º to the horizontal. The setup is equipped with a Perspex release box with a hinged door at the top of the slope. During the test, the river pebbles are released through the hinged door and allowed to travel freely down the slope and runout onto a flat base. A high-speed camera (Canon T3i) that can take 30 frames per second at a maximum resolution of 1280 x 720 pixels was used to track the position of the marked pebble.

Two tactile sensing pads with pressure capacity of 20 psi were fixed at the particle landing location and similar pads were fixed directly on the vertical wall. These pads were connected to a data acquisition system to monitor the impact forces on the ground (horizontal plane) and on the wall (vertical plane) as a result particle movement. The layout of these sensors can be seen in Figure 3.

3. DEM SIMULATION

The Discrete element method is known to consider the interaction among distinct particles at their contact points. It is generally a dynamic process that reaches static equilibrium when the internal and external forces are balanced (Tran et al., 2014). The numerical simulations are performed in this study using the discrete element program, PFC^{3D}. A detailed description of the code can be found in the relevant manual (ICG, 2014).

The numerical simulations are carried out as depicted in Figure 4. A discrete element sample that consists of 53 spherical particles is generated to follow the particle size distribution of the material used in the experiment, as shown in Figure 2. Spherical particles are used in this preliminary analysis to reduce computational cost and at the same time capture the mechanical response associated with particle flow. The micromechanical parameters used in the analysis are listed in the Table 1.

The sloped section is simulated using bonded particles arranged in a hexagonal pattern with an average particle diameter of 5.5 cm (see Figure 2). This procedure captures to a reasonable extent the characteristics of the perforated sheet used in the experiment, and reproduces a bumpy surface that allows for the rolling resistance to be automatically considered.

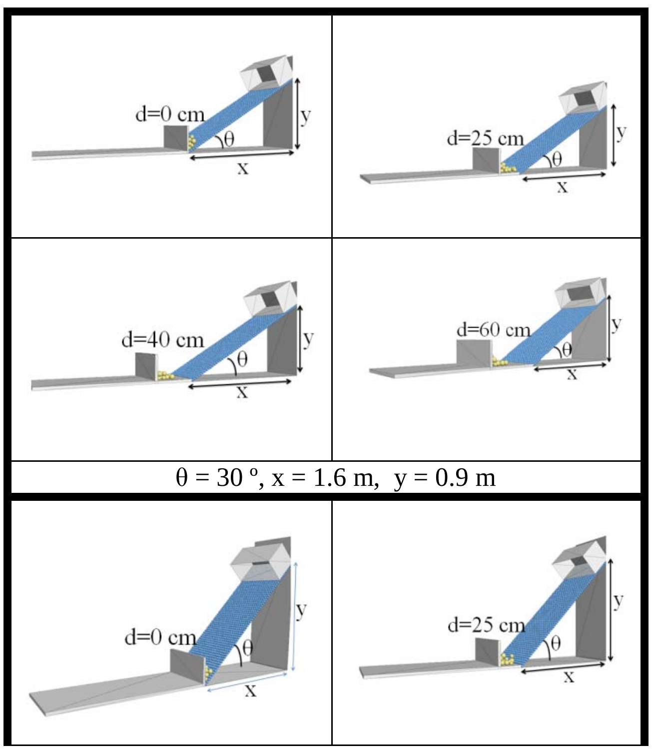
Once the generated particles have reached an equilibrium state in the release box, particle flow is initiated by removing the wall facets of the release box allowing the particles to freely flow down the slope.

A total of 12 particle flow simulations are performed in this study using various slope inclination angles (30º, 45º and 60º) and wall location with respect to the toe of the slope (0 cm, 25 cm, 40 cm, and 60 cm).

The particle friction coefficient was determined using the repose angle test. It is worth noting that friction coefficients that range from 0.37 to 0.5 were used by other authors (e.g. The reference paper written by the McDowell et al., 2011 & Lo et al., 2010).

Table 1: Particle properties used in DEM tests.

Property	Unit	Value
Contact model		Linear (no-tension)
Density	kg/m³	2620
Effective Modulus	(Pa)	20E8
Stiffness ratio		1.5
Friction coefficient		0.45
Viscous damping ratio Normal Shear		 0.5 0.5
Number of particles		53



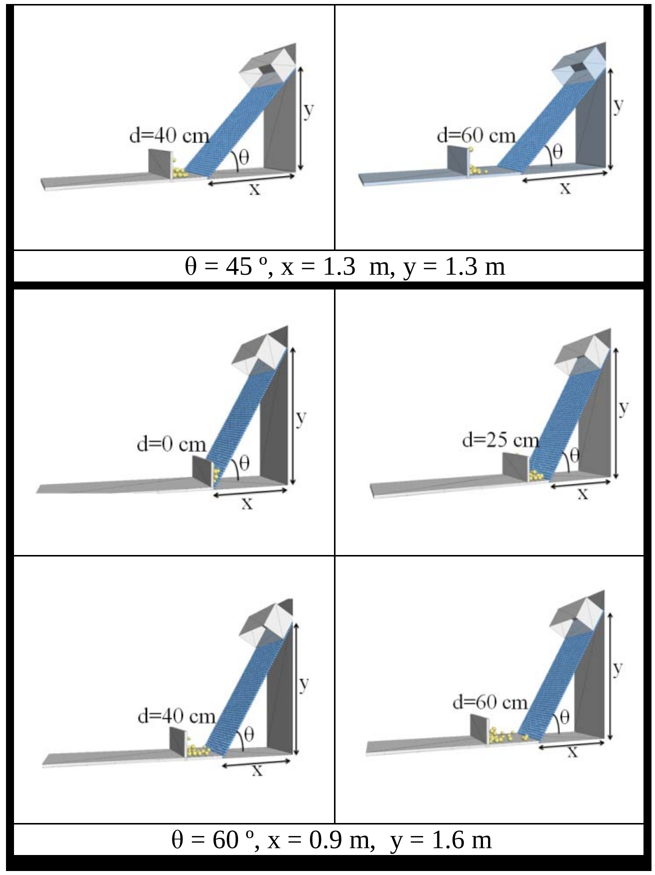


Figure 4: DEM setups of particle flow for different inclination angles and separation distance from the wall.

4. RESULTS

4.1 Particle mobility

The recorded and calculated results for the three investigated slope inclination angles (30º, 45º and 60º) are summarized in this section.

Displacement profiles with time are shown in Figure 5. Results reveal that for a given elapsed time from the beginning of the test, particle displacement increased with the increase in slope inclination. For example, when the elapsed time reached 0.6 sec. particles had moved 0.7 m, 1.2 m, and 1.5 m for slope angles 30º, 45º, and 60º, respectively. In all investigated cases, the rate of change in displacement was found to increase up to a maximum maintained value. The flowing particles started to slow down as they approach the toe of the slope. Calculated displacements are generally found to be in good agreement with the measured values for different inclination angles.

The velocity profiles obtained from the experiments and the DEM simulations are presented in Figure 6. Results show that, the maximum measured velocity increased from 3 m/s to 6 m/s when the slope angle increased from 30° to 60°. The time required to reach the maximum velocity decreased from about 0.7 seconds to 0.3 seconds when the slope angle increased from 30° to 60°. It was also found that the maximum calculated velocity is slightly smaller compared with the measured one, particularly for a slope angle of 60°. On the other hand, particle acceleration (defined by the slope of the velocity-time relationship) calculated using DE analysis is slightly higher compared with the values measured in the experiments. In addition, a significant deceleration response was calculated (see Figure 6) after the maximum velocity was reached. The difference in acceleration responses between the calculated and measured values can be attributed to the simplified spherical shaped particles used in the analysis.

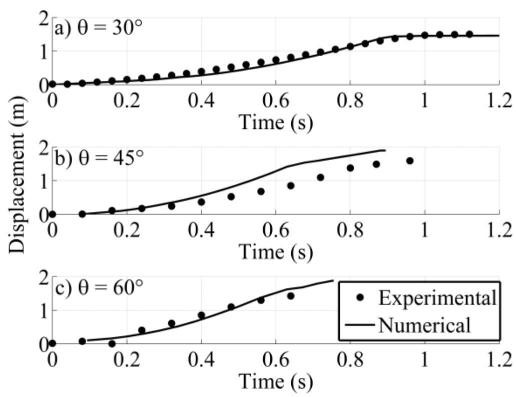


Figure 5: Displacement profiles for different inclination angles with the wall located at the toe of the slope.

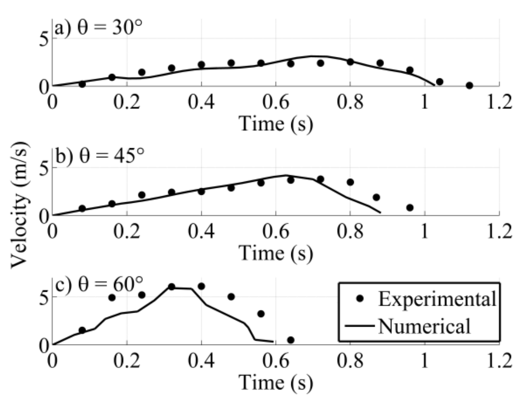


Figure 6: Velocity profiles for different inclination angles with wall located at the toe of the slope.

4.2 Impact pressure onto the vertical wall

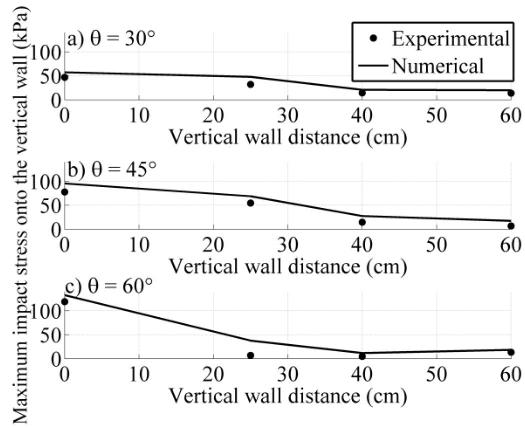


Figure 7: Impact stress onto the vertical wall considering the different conditions.

Figure 7 shows the relationship between the maximum impact stress measured on the vertical wall and the inclination angle of the slope. It can be seen that the location of the vertical wall has a significant impact on the impact pressure. The largest impact pressure was reached at an inclination of 60º and was found to be approximately 35% higher than that measured for 30º and 45º slope angles. Figure 6 also shows that, at wall distances of 25 cm and 40 cm, higher impact pressure was recorded for slope angle of 45º as compared to those measured at angles of 60º. It is also evident from the results that with the increase in vertical wall distance from the toe of the slope, the impact pressure for inclination angle of 60º, significantly dropped to a very small value. This can be attributed to the fast dissipation of energy in the moving particles for such a steep slope.

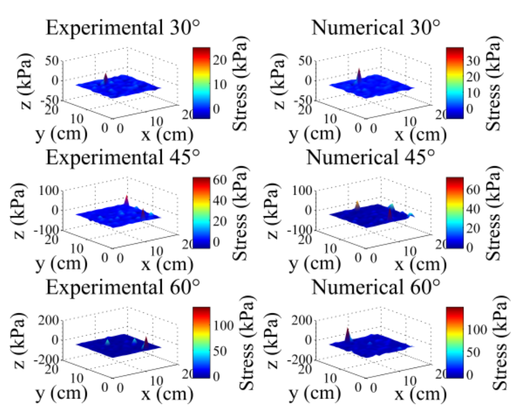


Figure 8: Contour of impact pressure on the vertical wall considering different inclination angles.

Figure 8 illustrates contours of the impact pressure on the vertical wall when placed right at the toe of the slope. It is apparent that the distribution of impact pressure on the vertical wall was irregular as observed in the experiments and as confirmed using the numerical simulations. It has been found that for the investigated slope inclination angles, the calculated pressure was consistently larger than that measured in the experiments. Additional numerical simulations are needed to investigate the role of particle shape on particle movement pattern and the impact forces on the barrier wall.

5. DISCUSSION

The above results suggest that a simplified DEM simulation using spherical shaped particles was able to capture some of the important features of particle flow on different inclined slopes. Reasonable agreement was found between the measured and calculated particle velocities as well as the impact pressure on a vertical wall located near toe of the slope. The numerical simulation provided slightly higher impact pressure in most of the investigated cases as compared to those measured in the experiments with a difference of about 10%.

The maximum velocity calculated from the DEM analysis was found to be slightly higher than the measured value. It was also found that observed pebble movement during the experiments is sensitive to the particle geometry. Further analyses will be needed to explore the role of particle geometry on the micro-scale response and the sensitivity of the solution to the contact model used in the DEM simulations.

6. SUMMARY AND CONCLUSIONS

Laboratory experiments were conducted to investigate particle flow on a rough incline for three different slope angles. Particle velocity and displacement patterns are measured and the results are used to validate a discrete element model. Impact pressure induced by the flowing particles on a vertical wall located at some distance from the toe is also measured. The suitability of discrete element methods to realistically simulate the observed behaviour is evaluated. Despite the complexity of particle flow behaviour observed in each test, DEM was able to reasonably produce a response that is consistent with that found in the experiments. The model was to some extent able to capture the interaction between particles and the perforated sheet as well as the vertical wall where particle flow is dominated by coupled sliding and rolling movement.

7. ACKNOWLEDGEMENT

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