Experimental simulation of mass flow characteristics for evaluation of the role of flow-bed roughness

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ABSTRACT: One of the significant geohazards associated with rock slopes is the avalanche. The mechanisms associated with such events are commonly studied under controlled settings of a laboratory scale analog as typical field conditions are inherently complex and uncertain. Accordingly, in this study, experiments on a novel laboratory-scale avalanche simulating system were performed to examine the flow and deposit characteristics of dry granular silica sand with the help of high-speed camera. The model consists of a fully regulated rigid flow-bed (0.6 m), on which the tests were performed at 36°, 42° and 47° angles of inclination, with frictionless (mica) and rough (P120 sandpaper) surfaces. The results showed that: (i) runout and deposit length on a smooth bed were greater than those on a rough surface, (ii) the height and width of deposit were greater on rough surfaces, and (iii) deposit width was not significantly affected by changes in the inclination angle.

Keywords: Avalanche, bed friction, dry granular flow, granular mass deposit characteristics.

1 INTRODUCTION

Avalanches, which belong to a category of landslides, pose a significant threat as they involve extremely rapid movement of debris resulting from the fragmentation of soil or rocks, typically through rock falls or rockslides (Hsü 1975). In the last two decades, landslides have led to almost 18,000 fatalities with economic losses amounting to 6.2 billion US dollars globally (CRED 2022). The destructive nature of landslides is attributed to the large extent of rock and debris they deposit. To understand the granular flow behaviour and the nature of its deposition, experiments with different configurations have been conducted, with the dam break problem being one of the most popular (Ahmadipur et al. 2019; Bahman Sheikh 2021; Bryant et al. 2015; Crosta et al. 2017; Fei et al. 2020). One notable aspect of these studies is that the flow was directed through an inclined flume with enclosed side walls, which restricted the flow and limited its sideways spread. While the results of these studies may be useful in certain scenarios, caution should be exercised when applying them to situations where the avalanche is not confined before reaching the horizontal runout zone. However, there have been very few experiments conducted on an unconfined flow over an inclined section (Crosta et al. 2017; Davies & McSaveney 1999; Manzella 2008). To better replicate and rigorously analyse the unconfined flow behaviour of granular materials, a laboratory-scale avalanche simulating experimental setup (ASES) has been designed for this work to observe the flow and deposition characteristics of dry silica sand under different bed roughness conditions.

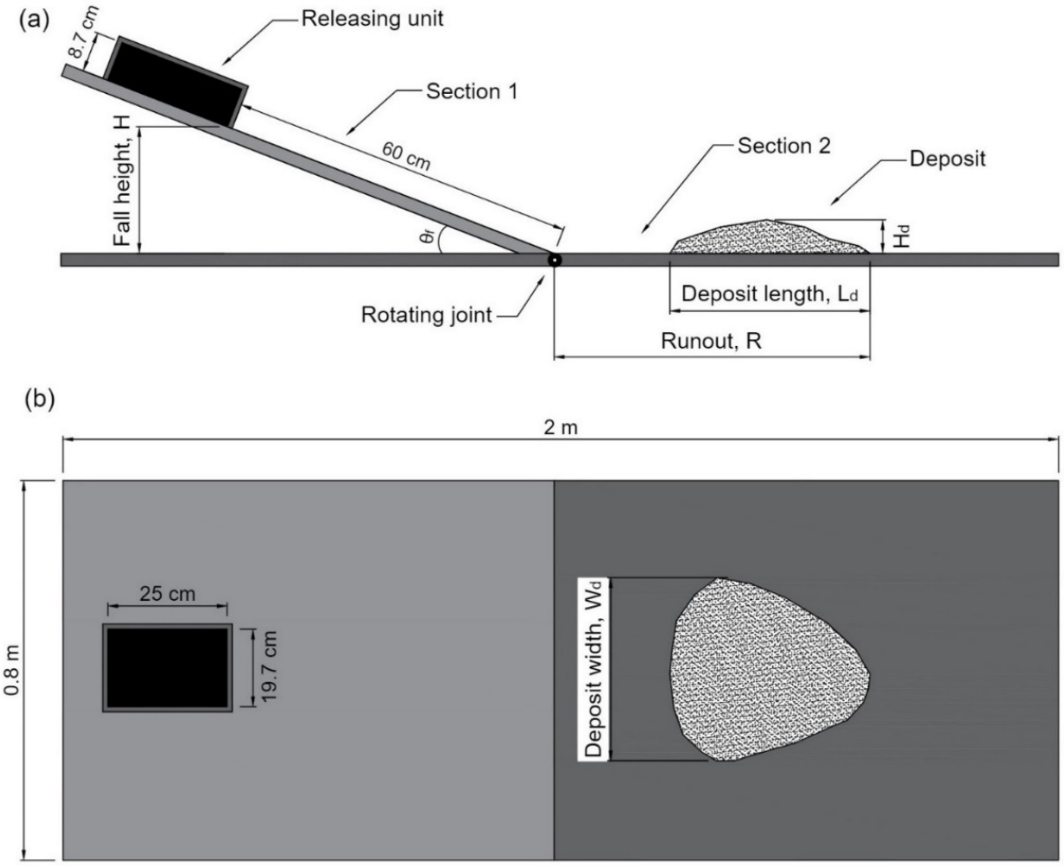

Figure 1. Schematic diagram of the experimental setup (a) side view and (b) top view.

2 EXPERIMENTAL SYSTEM AND METHODS

The avalanche simulating experimental setup (ASES) specifically consists of two sections (1×0.8 m) made of generic wood (Figure 1). The section-1 is an inclined rectangular panel, which represents the transportation zone, while the section-2 represents the horizontal runout zone. The test setup also consists of a cuboidal releasing unit (25 cm x 19.7 cm x 8.7 cm), to enable a controlled and sudden release of the flow material (silica sand in this study). The releasing unit is attached to section-1, which allows 0.6-meter length for the material to move along before reaching the section-2. The releasing unit was made from frictionless material and has an automated shutter opening system through which the flow material can be constrained (or allowed to flow) as per the user requirements. The novelty of the ASES lies in its ability to allow inclination of section-1 at any angle between 0 and 80 degrees, enabling its application in generating uninterrupted flow even on a highly rough bed surface. Furthermore, the sidewalls were not attached at inclined section of the ASES to allow the flow to expand laterally in this section to simulate realistic field-scale unconfined condition where the flow occurs without any channelization during transportation zone.

Silica sand with a uniform size of 0.6 - 1 mm (d_{50} = 0.8 mm) was used as the flow material, as it can be closely matched to the angular rock particles (Davies & McSaveney 1999; Li et al. 2021). Two sets of friction beds were used during the testing. In the first set, a smooth mica bed was employed, and in the second phase, a high friction sandpaper having grit size P120 was used as bed. The basal friction angle of the target sand over the two bed materials was measured using a tilting plane apparatus (Ahmadipur et al. 2019; Chu et al. 1995; Manzella 2008; Pudasaini & Hutter 2007), which was designed to accurately measure both static friction angle (the angle at which a thin layer of material remains in a pseudo-static state) and dynamic friction angles (the friction offered by the base to the moving mass). For this, the procedure as outlined by Manzella (2008) was used. The material properties are summarized in Table 1.

Table 1. Properties of silica sand and ASES.

Sand characteristics		Experimental setup characteristics			
Property	Value	Property	Value		
Mass (kg)	2.0	Length of inclined plane (m)	0.6		
Bulk density (Kg/m^3)	1250.0	Angle of inclination (°)	36	42	47
Specific gravity	2.66	Fall height (m)	0.35	0.40	0.44
Size of particle, d_{50} (mm)	0.8				
Static friction angle (°)	31 (with mica) 40 (with sandpaper)				
Dynamic friction angle (°)	29 (with mica) 38 (with sandpaper)				
Angle of repose (°)	34				

During the tests, 2 kg of dry silica sand was carefully placed inside the releasing unit making a shape of triangular prism, which was rigorously maintained throughout the experimental program. Experiments were conducted at three different angles of inclination, 36°, 42° and 47°, on a smooth mica surface. For the rough sandpaper surface, the inclinations were 42° and 47° as the static and dynamic friction angle for the silica sand and sandpaper was greater than 36°, causing most of the silica sand to be deposited on the section-1 when the experiment was conducted at 36°. For both the bed surfaces, repeatability was ensured by performing the same experiment multiple times at the same inclination angle. After the deposition of the material, the deposit length, deposit width, deposit height and runout, were measured manually. The boundary of the deposit was determined to be the point where the grains were no longer connected to the main accumulation (Manzella & Labiouse 2009).

To document the granular flow, a Baumer VLXT-17M.I high speed camera with a 486-fps frame rate and a 1600×1100-pixel resolution was used to capture the formation of sectional profile and the software named Baumer camera explorer was used to analyze the images.

3 RESULTS AND DISCUSSION

Based on analysis of flow morphology, it can be noticed that a rough bed surface provides a wider extent to the flow (Figure 2b) than that of smooth bed (Figure 2a). When the grains move onto a rough inclined surface, the flow is retarded from the bed, resulting in a lower velocity and more time for the top grains to move sideways. This wider flow on the inclined rough bed surface translates into a wider deposit width on section-2 (Table 2).

Table 2. The depositional characteristics of the silica sand during the flume experiments.

Bed surface	Angle of inclination, θ_f (°)	Deposit length, L_d (cm)	Runout, R (cm)	Deposit width, W_d (cm)	Deposit height, H_d (cm)
Smooth	36	28.8	25.4	60.5	3.3
	42	33.0	33.9	61.5	1.7
	47	37.7	44.4	59.4	1.3
Rough	42	26.3	20.0	64.3	5.7
	47	27.2	22.9	63.8	2.9

Figure 2. Flow and deposit morphology of silica sand on smooth mica bed (a1, a2, and a3) and rough sandpaper bed (b1, b2, and b3).

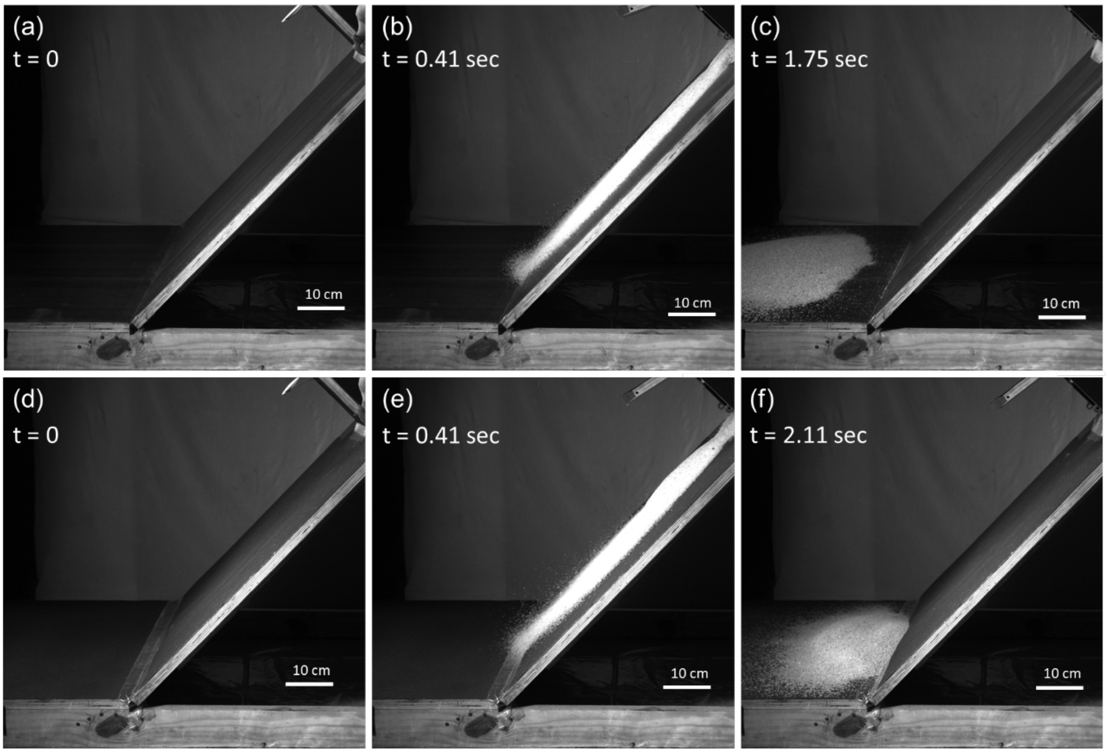

Figure 3. Profile view of the flow and deposit morphology of silica sand at 47^o on smooth mica bed (a, b, and c) and rough sandpaper bed (d, e, and f).

The distinction between the deposits of smooth and rough bed surfaces is evident from profile view (Figure 3). On section-2, the deposit profile has a distinct boundary in case of smooth bed, suggesting that the granular mass moved with insignificant shearing on its upper sand layers indicating a sliding-dominant flow. On the other hand, the deposit pattern on a rough bed appears more dispersed, suggesting that the lower layer was captured by the high frictional horizontal surface, and the upper layers could slide over each other due to the lower internal friction compared to the bed friction angle, resulting in a flow dominated by spreading as also noted by Bahman Sheikh (2021).

The Figure 4 illustrates the quantitative characteristics of silica sand deposits on both smooth and rough surfaces. When deposited on a rough surface, the length and runout of the deposit were shorter compared to those on a smooth surface (Figure 4a,b). However, the width and height of the deposit were greater on a rough surface (Figure 4c,d). The trend of deposit characteristics was similar on both surfaces with changes in inclination angle. As the angle of inclination increased, the deposit length and runout also increased (Figure 4a,b), due to higher kinetic energy of the silica sand at the bottom of the panel. This resulted in a decrease in the height of the deposit (Figure 4d), while the deposit width was invariable with the inclination angle (Figure 4c). These findings are consistent with those observed by Crosta et al. (2017), Fei et al. (2020), and Manzella (2008).

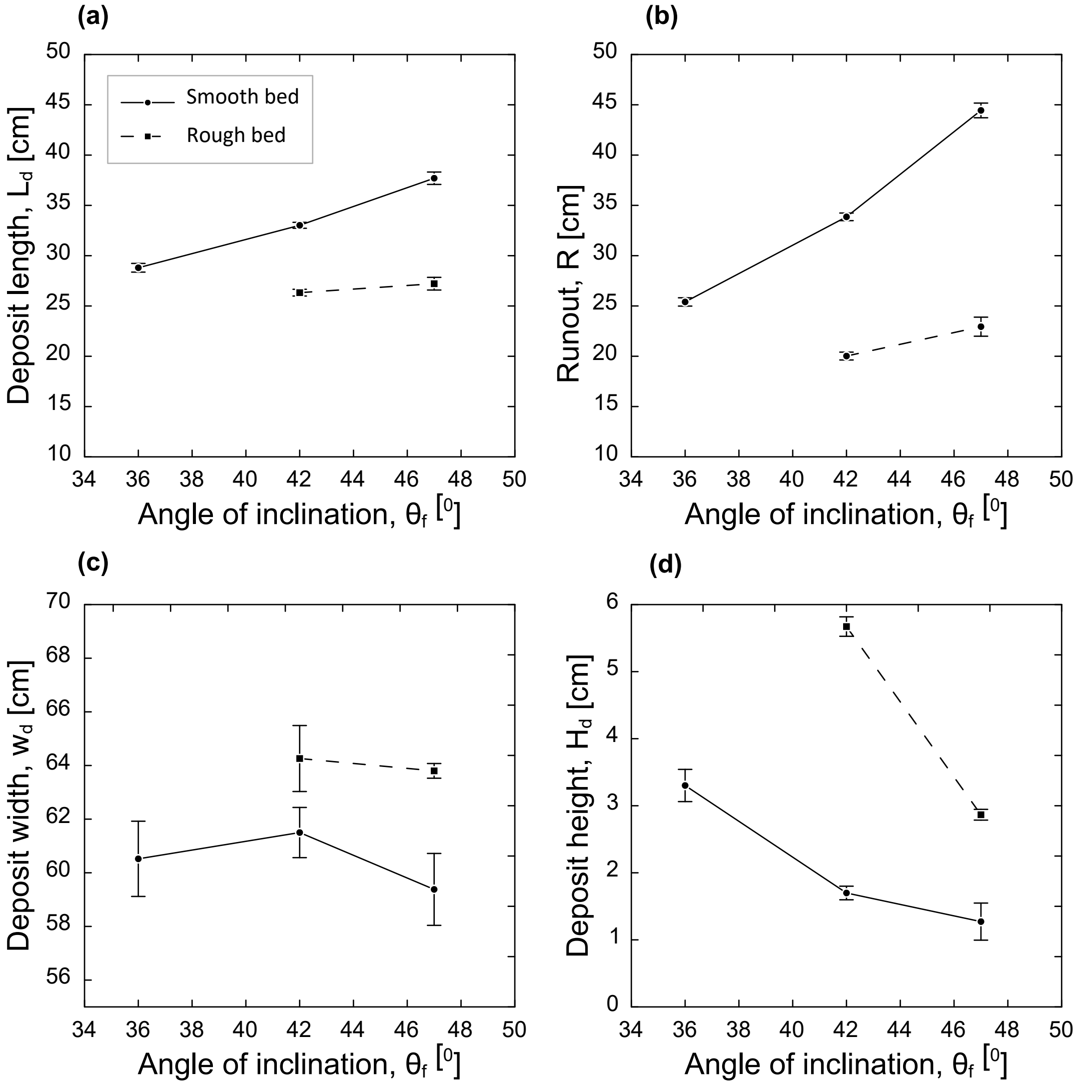

Figure 4. Effect of angle of inclination and bed roughness on (a) deposit length, (b) runout, (c) deposit width, (d) deposit height.

4 CONCLUSION

The primary goal of conducting laboratory experiments is to determine the effect of bed roughness and inclination angle on the flow and deposition of dry silica sand. The main findings from this research are as follows:

- The roughness of the bed affects the width of the flow, as evidenced by the increased sideways spread of the flow on the section-1 of ASES.
- The varied deposit characteristics, such as the spreading of silica sand on rough bed surfaces, suggest that the flow mechanisms at the upper layers differ depending on the roughness of the bed.
- The considerable contrast in deposit features on different bed surfaces indicates that not only the internal friction angle but also the frictional properties of the bed surface can influence the deposition of silica sand on horizontal runout section.

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