Influence of direction and rate of removal of confining gate in DEM based granular column simulations mimicking dry granular flows

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Abstract. Dry granular flows exhibit varied complex attributes based on the failure characteristics of natural slopes. However, for simplistic understanding of these flows, lab scale granular column collapse experiments are being widely followed, and while conducting the numerical simulation of the same, an instantaneous collapse of the whole granular mass resembling a dam break problem is usually considered. This differs from the real field scenarios, where flow either commences from the top or from the vicinity of the toe of slopes; and the failure of the slope is not instantaneous, but progressive or rate dependent. Thus, releasing the confining gate of granular column at a certain rate in upward and downward directions may simulate different failure mechanisms yielding greater insights for flow behaviour and depositional morphology of the dry granular flows. In this study, the influence of direction and rate of removal of confining gate has been examined for dry granular flows emanating from the collapse of granular column by implementing 3D – Discrete Element Method (DEM). Three different rates of gate removal, i.e., 0.05, 0.25 and 0.50 m/s have been considered for both upward and downward directions for different aspect ratios of the granular column and the results have been analysed.

1 Introduction

Geophysical flows, which are often characterized as granular flows, are very destructive in nature and cause immense losses to life and property. Understanding the attributes of these flows, even in dry state, is quite challenging due to complicated interactions between the flowing particles that significantly govern the flow dynamics and depositional morphology [1,2]. Experimentally, the granular flows are mimicked by conducting the sudden collapse of a column of particles under the effect of gravity. Such granular column collapse studies provide a fair understanding of the natural flow processes [3]. In such studies, the aim is to replicate a dam-break condition wherein the confining gate is removed almost instantaneously. Within the experiments, this is achieved by ensuring the duration of lift of confining gate is lesser than the time of free fall of particles present at the mid-height of the granular column [3,4]. Subsequently, the resulting flow is studied with respect to various mechanical parameters that affect the flow propagation.

Furthermore, while using the numerical tools, similar dam-break condition is generally mimicked by deactivating the confining gate in the numerical model at a certain time instant. This creates a rapid downward movement of the unconfined particles of the column in similitude to the experiments [1,4]. Although granular column collapse studies offer a simplistic approach for comprehending the devastating effects imparted by the natural geophysical flows idealized as dry granular flows, yet these studies are generally focussed on flow propagation rather than flow initiation. It would be worth to note the effects of flow initiation on granular flow propagation and subsequent dynamics. This could be achieved by introducing different removal rates of the confining gate yielding the granular column collapse and its subsequent flows. Further, direction of gate removal may highlight different failure mechanisms that actually exist in the real-field scenarios.

In the present work, the rates and direction of confining gate removal have been controlled in the 3D – Discrete Element Method (DEM) simulations of a granular column collapse. DEM is a numerical technique which helps in developing macro level responses using micro level interactions between the constituent particles [1]. By controlling the participation of particles in the flow emanating from the granular column collapse through varying rates of gate removal, the characteristics of the flow may be altered. It is also established that initial aspect ratio of the granular column (a), i.e., height/width ratio, is one of the most critical parameters that governs the flow features [3,4]. Hence, this approach of understanding flow initiation has been attempted for different aspect ratios of the granular column using DEM.

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2 Methodology

For this study, the effects of different types of flow initiation on the behavioural changes of a dry granular flow have been assessed by conducting simulations using LIGGGHTS, an open-source 3D-DEM software [5]. The granular flow emanates from the collapse of the granular column over a planar horizontal frictional bed by the controlled removal of confining gate as illustrated in Fig. 1.

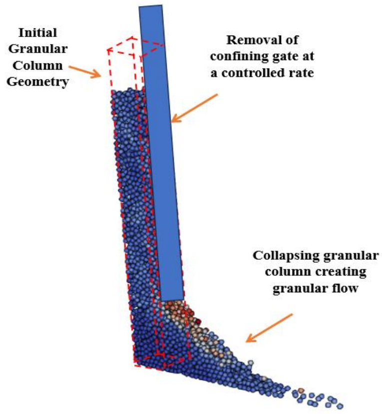

Fig. 1. Controlled removal of confining gate of the granular column creating granular flow.

Table 1. Micro-mechanical properties and the geometry details used in this study.

Parameters	Values
Geometrical details of the granular column	
Column width (L_i) (m)	0.06
Column thickness (m)	0.03
Aspect ratio (a)	0.85, 6.4
Details of the confining gate	
Width of the confining gate (b) (m)	0.03
Gate removal velocity (V_r) (m/s)	0.05, 0.25, 0.50
Direction of gate removal	Upwards & Downwards
Micro-mechanical properties of particles	
Diameter (d) (m)	0.006
Density (ρ_s) (kg/m^3)	2700
Modulus of Elasticity (E) (N/m^2)	5×10^7
Coefficient of friction for interaction between column particles (μ)	0.6
Coefficient of friction for particle-wall and particle-gate interactions (μ')	0.6
Poisson's ratio (v)	0.3
Coefficient of restitution (e)	0.7
Packing porosity (n)	0.43
Bulk density (ρ) (kg/m^3)	1539
Contact Model	Hertz-Mindlin

The granular column collapse model has been validated with the experimental results of Shi et al. [4,6]. The geometrical properties of the granular column and micro-mechanical properties of its particles that have been used in this study are mentioned in Table 1. Different rates of confining gate removal (V_r) have been considered in both the upward and downward direction. The resulting flow characteristics have been compared with that of the flow emanating from instantaneous gate removal.

In order to compare the results developed for different scenarios, the output parameters such as run-out distance, residual column height, velocity and kinetic energy of particles have been normalized as per the standard equations mentioned in [4,6].

3 Results and Inferences

3.1 Mechanism of column failure and flow initiation

For the emanating granular flows, the velocity vectors at the flow initiation have been analysed in case of the upward and downward gate removal and compared with the same developed for instantaneous gate removal at the same time instant. Fig. 3 shows the comparison of the velocity vectors for granular column of a = 6.4.

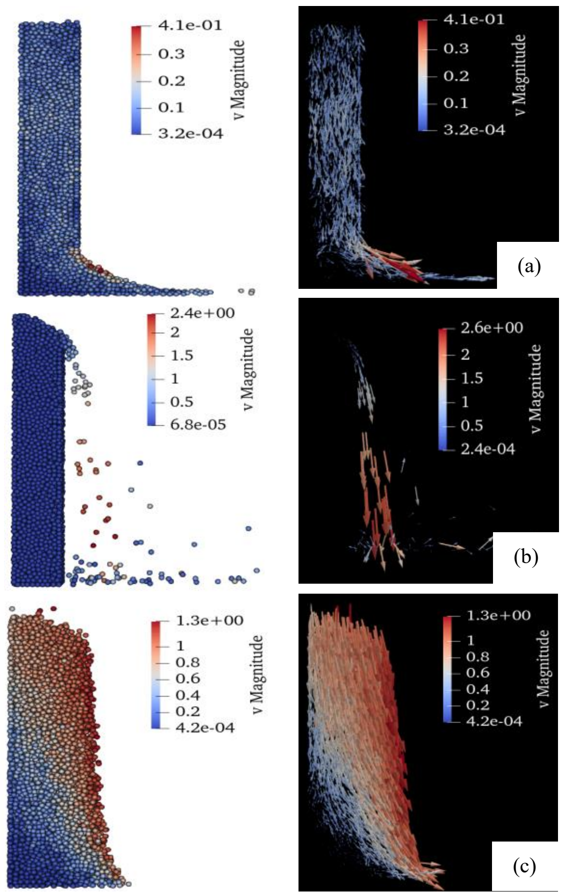

Fig. 2. Comparison of velocity vectors at flow initiation when the confining gate is removed (a) upwards and (b) downwards at a controlled rate, and (c) instantaneously.

It can be observed from the velocity vectors of Fig. 2(a) that when the gate is removed in the upward direction, the unconfined particles present at the bottom of the column tend to move forth steadily but with lesser velocities owing to the lower initial potential energies associated with such particles. In addition, other particles of the column move vertically down until they reach the unconfined region of the column. On the contrary, when the gate is removed in the downward direction, the particles present at the top of the column commence the flow by falling freely towards the bed. The velocity attained by such particles is higher owing to their elevated positions and higher potential energies. Furthermore, in this condition, the flow initiates with irregular movement of column particles including falling freely, bouncing and striking against each other. However, when the gate is removed instantaneously, no particle specific behaviour in flow initiation is observed; rather, the entire mass falls together inclined towards the bed and the whole granular mass starts contributing towards the flow. Therefore, it could be inferred that the direction of confining gate removal relates with different column failure mechanisms that may occur during granular flow initiation. When the flow starts from the top of the granular column, this may lead to higher flow velocities clubbed with irregular particle movements, which is more damaging since its commencement provides least time for evacuation or transit. Such are the cases that appear naturally during rockfalls. Conversely, any removal of support near the toe of the granular column produces slow mobilization of particles, thereby providing greater chances for evacuation of resources in the affected region.

3.2 Variation in flow propagation and depositional characteristics: Influence of rate of confining gate removal and aspect ratio of granular column

The rate of confining gate removal controls the participation of the particles in the emanating flow. As the rate of removal increases, more particles tend to contribute and move along the flow. Fig. 3(a) shows the variation of normalized run-out distance [L] for different V_r values for two aspect ratios, i.e., $a = 0.85$ and 6.4. The results have been compared for the case of instantaneous removal of gate. Run-out distance has been calculated as per particle velocity-based approach by identifying the reach of such particles having velocity less than 1% of maximum average particle velocity at a significantly larger time scale [6].

It is apparent from the plot that the run-out distance increases with the increase in V_r and achieves its maximum value for instantaneous removal of the gate. Further, this effect is dominant for the granular column of higher aspect ratio. It can also be inferred from Fig. 3(a) that there is no appreciable effect of direction of gate removal on the final run-out distance attained by the resulting flow. Thus, the mechanism of column failure does not affect the reach of the flow on a horizontal bed. Also, from the plots of normalized residual column height [H] with respect to V_r as shown in Fig. 3(b), it could be concluded that the direction and rate of confining gate removal has no significant effect on the final depositional height of the flow. As expected, [L] and [H] are higher for higher aspect ratio.

In order to assess the effect of controlled gate removal on the flow behaviour, a plot for normalized maximum particle velocity [V_{max}] attained during the flow has been presented at Fig. 3(c). It can be observed that the particle velocity is higher when the confining gate is removed in the downward direction. Also, for the granular flow emanating from the column of $a = 6.4$, V_{max} is higher when the gate is removed downwards when compared with that of $a = 0.85$; however, this trend becomes opposite when the gate is removed in upward direction. This indicates that mechanism of granular column failure has a role in controlling the effect of a on the particle velocity. Though, for upward gate removal, V_{max} increases with increase in V_r but the trend is slightly opposite for downward gate removal.

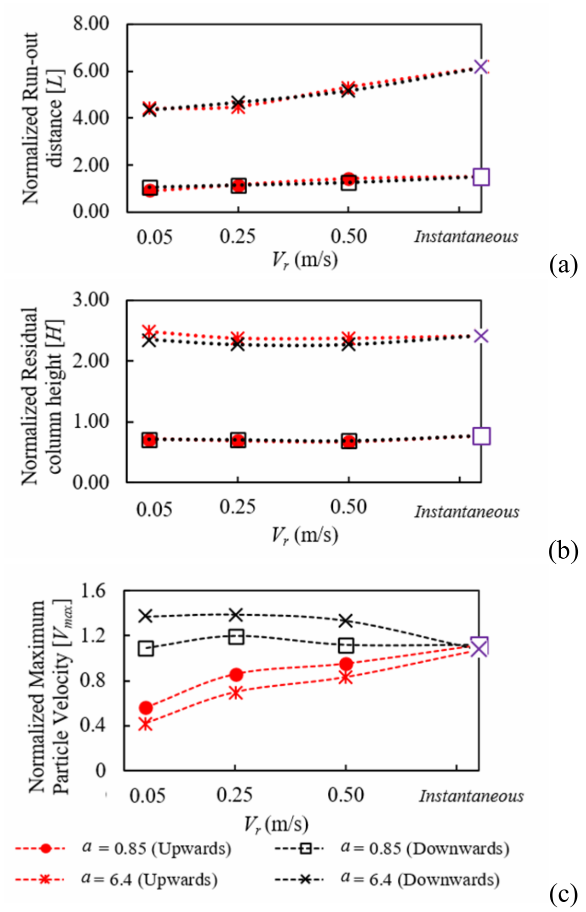

Fig. 3. Variation in (a) [L] (b) [H] and (c) [V_{max}] for different V_r values for both upward and downward removal of confining gate for the granular column of $a = 0.85$ & 6.4

Figure 4 represents the final deposited state of the granular mass, which is vital in understanding the particle-level response of the granular flows resulting from controlled gate removal of the granular column. It can be inferred from the coloured shadings that the particles present at the apex of the column remain at the top of deposition for instantaneous and upward gate removal (similar deposition profiles for both); however, the situation reverses for the case of downward gate removal. Furthermore, in the latter case, particles present at the bottom of the granular column do not contribute to the flow and remain predominantly intact. Additionally, reach of bottom level particles is highest for the case of upward gate removal. However, as V_r increases, both the cases shown in Fig. 4(a) & 4(b) would converge with that of the instantaneous gate removal case (Fig. 4c), as illustrated in Fig. 3(a).

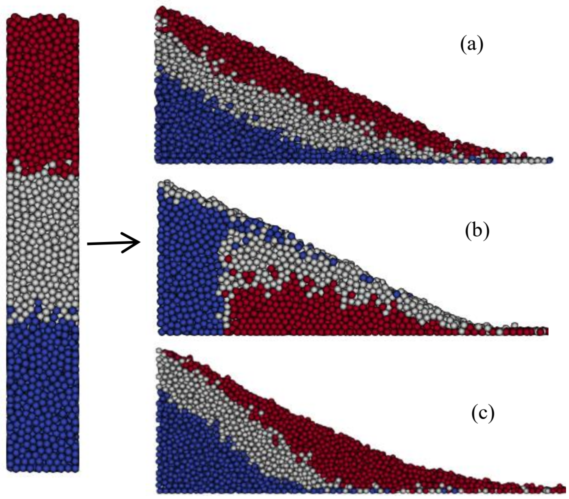

Fig. 4. Deposition profile of the granular column of a = 6.4 when the confining gate is removed (a) upwards and (b) downwards at V_r = 0.05 m/s, and (c) instantaneously.

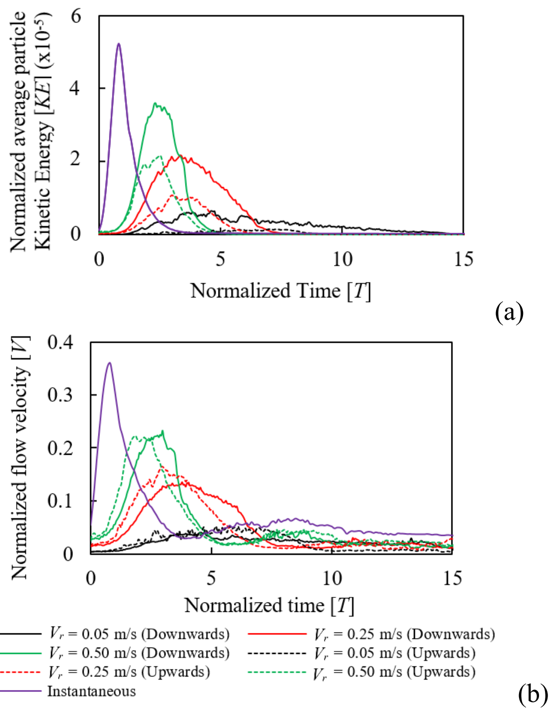

Fig. 5. Variation of (a) [*KE*] and (b) [*V*] with [*T*] for different V_r values with a = 6.4 in case of both upward and downward removal of confining gate.

Similar micro-level insights can be developed from Fig. 5(a), which represents the variation of normalized particle kinetic energy [*KE*] (which is a measure of destructive power of the flow) at different normalized time instants [*T*] for the column of a = 6.4 with different V_r values. Due to reduced rates of the confining gate removal, the granular flows exhibit reduced magnitude of particle kinetic energy indicating that the destructive behaviour of the flow lessens. Kinetic energies developed due to upward gate removal is lesser than that for downward removal. Interestingly, in comparison to the occurrence of the peak particle kinetic energy for the instantaneous gate removal case, the sustained and delayed peaks of the same for lesser V_r showcases that the participation of particles towards the flow is delayed and movement of the particles is slow. This is further substantiated from the normalized average flow velocity plots (Fig. 5b), which represents a macro-level response of the resulting flow. Not only the peak flow velocities are affected by V_r values, but more is the delay in involvement of column particles towards the flow and greater is the time taken for achieving the maximum flow velocity. Furthermore, the reduced but sustained peak velocities for lesser V_r values explain the marginal variations in run-out distance for all the cases.

4 Conclusion

In this work, different scenarios for initiation of granular flow have been developed by inducing different rates (V_r) of removal of confining gate in upward as well as downward direction for the collapse of granular column, and the findings are compared with that for instantaneous gate removal using DEM simulations. Distinct mechanisms of column failure and flow initiation are observed for the two different directions of gate removal, wherein, downward removal of gate causes higher initial particle velocities and irregular movements of particles along with reversal of deposition profile. Further, as V_r increases, more particles tend to contribute towards the flow and the magnitude of flow parameters such as velocity and kinetic energy have been notice to increase. Additionally, flow characteristics appear to converge with the case of instantaneous gate removal with an increase in V_r. Furthermore, it has been observed that there are only marginal effects of kinds of flow initiation on final depositional parameters.

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