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Steady state behavior of spherical intruder impaction in vertically vibrated granular beds

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Abstract. This study explores the dynamics of a spherical intruder impacting a vertically vibrated granular bed using discrete element method (DEM) simulations. The system consists of 25,000 particles contained in a box with sinusoidal bottom wall vibrations ranging from 25 to 500 Hz. The intruder is dropped from a fixed height with varying initial velocities. Results show that the vibration frequency and initial velocity significantly influence the intruder's penetration depth and hence the final resting position. Lower vibration frequencies allow deeper penetration due to reduced granular agitation, while higher impact velocities enhance penetration through increased momentum.

1 Introduction

Granular materials are ubiquitous in nature and industry, ranging from soil and sand to pharmaceutical powders and agricultural grains. Understanding how objects (intruders) move through these materials has significant implications for numerous applications, including planetary science, civil engineering, and manufacturing processes.

The impact of an intruder on a granular bed is a rich problem with applications ranging from asteroid impacts to industrial granular dampers [1, 2].

In a static bed, the impact energy is primarily dissipated through particle collisions, friction, and the reorganization of force chains [3–5]. The resulting drag force on the intruder typically follows two phases: a rapid deceleration due to inertial forces, followed by a slower phase dominated by friction as the bed particles rearrange. This resistance arises from the formation of a dense packing zone ahead of the intruder, with drag increasing as the intruder penetrates deeper into the bed [6].

Since the continuous energy input from vibration can significantly alter the bed's response to the impact [7], an intruder impacting a vibrated granular medium introduces additional complexities in the behaviour of the system. While the impaction on static granular beds is well studied, the influence of bed vibrations on the dynamics of intruder impacts remains largely unexplored to the best of our knowledge, presenting a key area for investigation in this study.

This paper explores the dynamics of intruders impacting vibrated granular media at various velocities, focusing on how vibration parameters and impact velocities affect the motion of an intruder through the granular media.

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Table 1. Configuration specific simulation parameters.

Parameters	Value
System dimensions (L x B x H)	12.5 cm x 12.5 cm x 300 cm
Wall types along X, Y, Z direction	periodic, periodic, rigid
Total simulation time	40 s
Bed particle diameter (d_p)	0.5 cm
Bed particle material density (ρ_p)	2.5 g / cc
Bed particle count	25 000
Intruder diameter (d_I)	2.5 cm
Intruder density (ρ_I)	2.5 g / cc
Acceleration due to gravity (g)	981 cm/s^2
Bottom wall vibration frequency	25 Hz to 500 Hz
Bottom wall vibration amplitude	0.1 cm
Initial velocity of the intruder while dropping	0 cm/sec to 800 cm/sec

2 Methodology

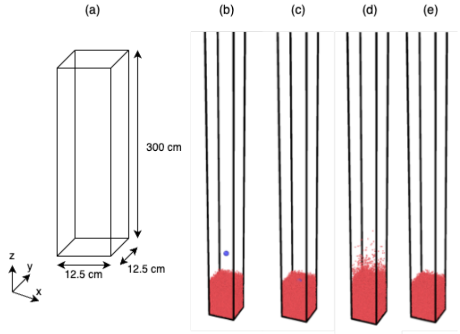

Figure 1. (a) System dimensions, (b) Intruder incidence on the vibrated granular bed, (c) The instance of intruder impaction on the bed, (d) Ejection of bed particles during the impact and (e) Bed settled to a steady state after the impact

The simulated system consists of a 3D bed with 25,000 particles in a container with a bottom wall vibrating sinusoidally at a set frequency and amplitude. At $t = 0$ s, bed particles are initialized in a sub-region at the bottom. The intruder is kept fixed at the top of the system until the bed reaches a steady state. The material density of the intruder is kept same as that of the bed particles while the intruder size ratio is $5d_p$. The intruder is then dropped from the top from a height of $600d_p$ under gravity. The drop velocity is varied between 0 and $800/\sqrt{2gd_p}$ to achieve varying intruder impaction velocities. The intruder penetrates into the bed during the impaction and eventually settles to a steady position.

The simulations are conducted using Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS) software. The simulation parameters used in the study are summarised in the and Table 1.

3 Results and discussion

As shown in the Figure 2, the volume fraction profile of the bed remains close to packing for lower vibration frequencies [8].

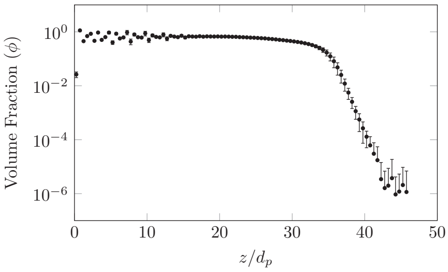

Figure 2. Steady state bed volume fraction profile for the bed after the impaction for vibration frequency of 25 Hz and intruder initial velocity of 0.

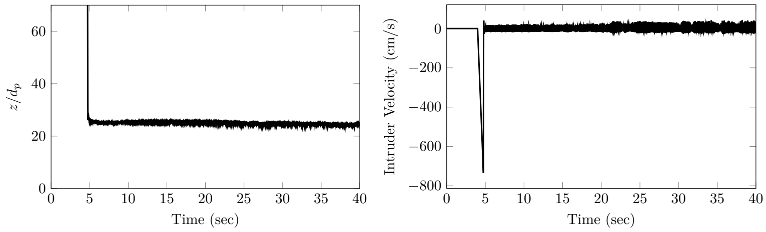

Figure 3. Intruder position and velocity with time for vibration frequency of 25 Hz and intruder initial velocity of 0.

The streaming or kinetic stress tensor arises from the fluctuating motion of particles and is given by:

$$\sigma_{ij}^{\text{str}}(z) = \frac{1}{V(z)} \sum_{V(z)} m\, v_i'(z)\, v_j'(z) \tag{1}$$

where m is the mass of particle i, $v_i'(z)$ is the fluctuating velocity component of the particle in direction i at height z, $V(z)$ is the volume of the bin at height z and the sum is taken over all particles in that volume.

The corresponding pressure due to streaming component defined as follows:

$$P_{\text{str}}(z) = \frac{1}{3} \sum_{\text{i=1}}^{3} \sigma_{ii}^{\text{str}}(z) = \rho_p \phi(z) T(z) \tag{2}$$

where ρ_p is the material density of the bed particles in the system. $\phi(z)$ is the volume fraction of the bed at height z. $T(z)$ represents the granular temperature at height z.

The collisional stress tensor arises from momentum transfer during particle collisions and is given by

$$\sigma_{ij}^{\text{coll}}(z) = \frac{1}{V(z)} \sum_{V(z)} F_i^{(c)}\, r_j^{(c)} \tag{3}$$

where $F_i^{(c)}$ is the force component in direction i during a collision, $r_i^{(c)}$ is the component of inter-particle vector at contact in direction i, and $V(z)$ is the volume of the bin at height z and the sum is taken over all the contacts in that volume.

The collisional pressure is again defined as one-third of the trace of the collisional stress tensor:

$$P_{\text{coll}}(z) = \frac{1}{3} \sum_{\text{i=1}}^{3} \sigma_{ii}^{\text{coll}}(z) = \frac{-N(z)}{3L_x L_y \Delta z} \sum_{\text{i=1}}^{3} \tau_{ii}(z) \tag{4}$$

where $N(z)$ denotes the number of particles in the vertical bin at height z. The dimensions $L_x L_y \Delta z$ represent the volume of the of the vertical bin at height z. $\tau_{ii}(z)$ is stress energy per particle for the bin at height z computed from LAMMPS in the x, y, and z directions, respectively for $i = 1, 2, 3$.

Figure 4 highlights that the collisional component of the pressure dominates the streaming component for the system. The steady-state, time-averaged, and spatially binned collisional and streaming components of pressure [9] are determined as shown in Equation (4) and Equation (2).

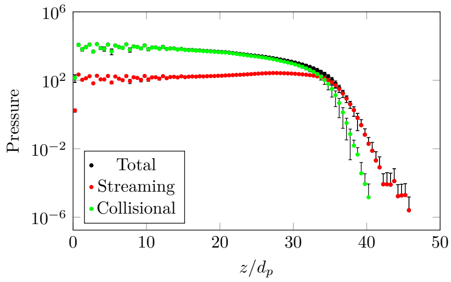

Figure 4. Steady state bed pressure profile for the bed after the impaction for vibration frequency of 25 Hz and intruder initial velocity of 0.

Figure 3 shows the intruder reaching a steady position after the impaction. The intruder position and velocity w.r.t. time is obtained from the output data from LAMMPS simulations. The instant of impaction can be seen in the velocity profile where the velocity of the intruder reaches a maximum after the intruder falls and then hits the bed. The impact velocity changes based on the initial velocity provided to the intruder at the instant when it it dropped.

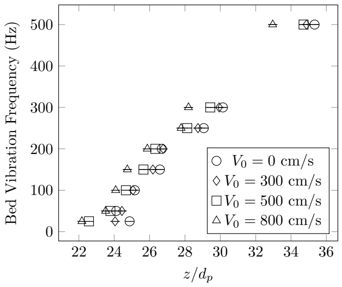

Figure 5. Vibration frequency of the bed plotted against the intruder steady state position after the impaction. The steady state position after impact also depends on the initial intruder velocity.

Figure 5 reveals that the penetration depth increases with decreasing vibration frequency and increasing initial impact velocity. At higher vibration frequencies, the bed offers greater resistance to penetration due to increased particle rearrangements and transient force chains. Conversely, at lower frequencies, the denser packing provides less resistance once disrupted, allowing the intruder to settle deeper. The higher kinetic energy for increased impact velocity enables the intruder to overcome inter-particle resistance and penetrate further into the bed.

These results highlight the interplay between external energy input (via vibration) and momentum transfer (via impact), showing how vibration can modulate the behaviour of granular materials upon intruder impaction.

4 Conclusion

The impact dynamics of a spherical intruder in a vibrated granular bed depend critically on both the vibration frequency and the intruder's initial velocity. The system consistently reaches a steady state post-impact, characterized by a stable intruder position and bed structure. These results underscore the role of external energy input on the resistance experienced by the intruder in vibrated granular systems and offer a foundation for further exploration into impact dynamics in driven granular media.

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