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RESEARCH ARTICLE

Buffer capacity of granular matter to impact of spherical projectile based on discrete element method

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ABSTRACT Granular matter possesses impact-absorbing property due to its energy dissipation character. To investigate the impact-absorbing capacity of granular matter, the discrete element method (DEM) is adopted to simulate the impact of a spherical projectile on to a granular bed. The dynamic responses of the projectile are obtained for both thin and thick granular bed. The penetration depth of the projectile and the first impact peak are investigated with different bed thicknesses and impact velocities. Determining a suitable bed thickness is crucial to the buffering effect of granular matter. The first impact peak is independent of bed thickness when the thickness is larger than the critical thickness.

KEYWORDS granular matter, impact peak, buffer capacity, discrete element method, critical thickness

1 Introduction

Granular matter is a system composed of a large assembly of macroscopic grains, and behaves fundamentally different from solid and liquid. Recently, problems of projectile impact into granular media have become increasingly important in material engineering, soil mechanics and mechanical engineering, such as the formation of impact craters [1–4].

The dynamic behaviors of the projectile and granular matter were studied experimentally and numerically, respectively [5–9]. The shock induced load transfer in the granular layer was studied with discrete element method [10]. Recently, Kondic et al. [10] investigated the complex responses of the impact object under different object, grains and system properties, and the response of the granular system in terms of force networks for the impact of an intruder on a dense granular material.

The penetration of projectile into granular media has been experimentally measured and numerically simulated [1,11–15]. The influence of confinement on the penetration depth was also studied experimentally [16,17]. The exchange and propagation of impact energy during the impact process was studied [18,19].

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Granular matter performs impact-absorbing property due to the inelastic collision and frictional contacts between particles. However, little attention has been given to the buffer capacity of granular matter during the studies of projectile impact on a granular bed. This paper aims at investigating the buffer capacity of granular matter through the numerical simulation of a spherical projectile impacting on a granular bed using the discrete element method. The dynamic responses, penetration depth and the impact peak of the projectile are analyzed under different bed thicknesses and impact velocities.

2 Discrete element model for impact process of granular matter

The granular materials are filled in a cylinder container. The impact projectile and individual particles constituting the granular bed are modeled by regular spheres. The nonlinear contact model is adopted to calculate the contact force between particles, including elastic and viscous force. The sliding friction based on the Mohr-Coulomb criterion is also considered.

Granular particles are randomly generated and placed in the cylinder. The projectile is then free to fall into the granular bed from a certain height as shown in Fig. 1. The

Table 1 Main computational parameters in the DEM simulation

parameters	symbols	unit	values
particle diameter	d	cm	0.95–1.15
particle density	P	kg/m^3	2650
projectile mass	M	G	168
projectile diameter	D_s	cm	5
cylinder height	H	cm	30
cylinder diameter	D	cm	20
elastic modulus of particle	E	GPa	5.0
inter-particle friction coefficient	μ_p	–	0.5
wall-particle friction coefficient	μ_{pw}	–	0.15

main computational parameters in the calculation are listed in Table 1.

3 Buffer capacity of the granular matter under impact load

3.1 Dynamic response of the spherical projectile

During the impact, the impact force on the projectile reflects its energy attenuation. Two cases are considered here. One is for thin granular bed with a thickness of 0.5 cm, and the other is for thick granular bed with a thickness of 5 cm. Figure 2 shows the impact force-time curves with an impact velocity of 5.0 m/s. The impact velocity is obtained via setting a certain height of projectile above the granular bed surface then dropping down under gravity. For the thin granular bed case, more peaks appear presenting a gradual attenuation process, while only one peak appears and impact force decays sharply for the thick granular bed. In addition, the impact peak decreases as the granular layer thickness increases.

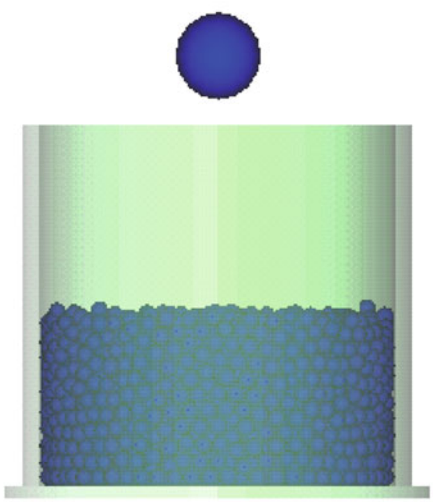

Fig. 1 DEM model of projectile impact on a cylindrical granular bed

Figure 3 shows the displacements of the projectile for the two cases. When the granular bed is thin, the projectile bounces several times until reaches final balance. When the granular bed is thick, no bouncing occurs and the projectile displacement decreases quickly to balance. The results indicate that the kinetic energy decays effectively and buffer capacity is good for granular bed case. This can be further illustrated by the velocity-time curve of the projectile. Figure 4 shows the velocity change of the projectile during impact. For the thin granular bed, the projectile velocity direction changes many times, indicating that the projectile collides with granular bed continuously and the energy dissipation is successive. For the thick granular bed, the projectile velocity direction does not change, the first collision dissipates most of the kinetic energy and an effective cushioning effect is achieved.

3.2 Penetration depth of the projectile in granular bed

The projectile leaves impact crater on the granular bed during impact process, and many parameters influence the crater size and penetration depth. Here only the effect of different impact velocities on the penetration depth is discussed. Figure 5 plots the relationship between granular bed thickness H and penetration depth H_P under different impact velocities.

Here, an effective thickness of granular bed is defined by the granular mass over the section area of container when the container is filled only by one layer granular matter. We also call this effective thickness as the granular thickness when it is less than the particle mean diameter, $D = 1.0$ cm. When the thickness of granular bed is less than 1.0 cm, the projectile penetrates through the granular bed and contacts the cylinder bottom, exhibiting no obvious buffering effect. When the bed thickness is in the range of 1.0 – 3.0 cm, the penetration depth increases with the increasing granular bed thickness, and is independent of impact velocity for each thickness. The penetration depth equals the thickness of granular bed. This means the project can

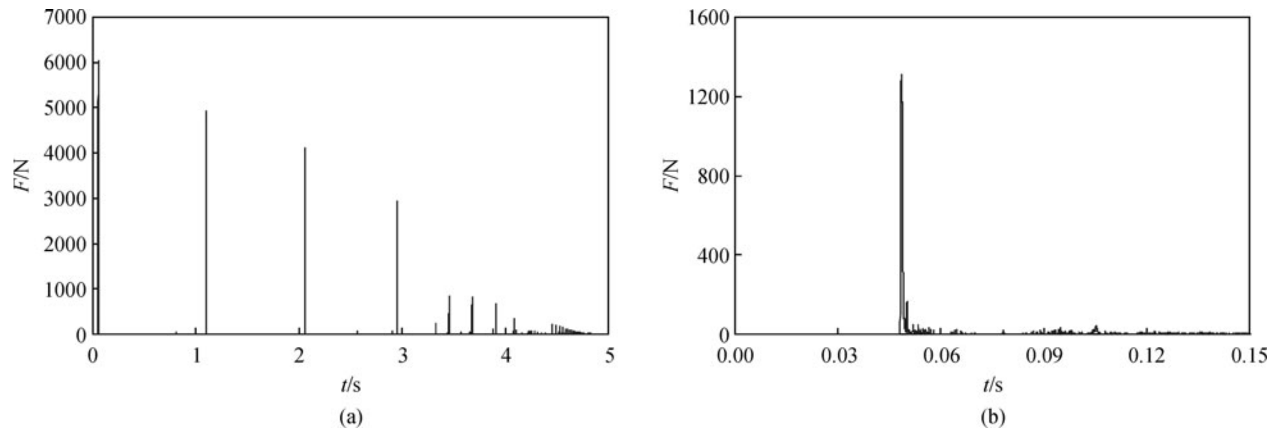

Fig. 2 Impact force-time curves of the projectile during impact process on granular bed. (a) Thin granular bed with $H = 0.5$ cm; (b) thick granular bed with $H = 5.0$ cm

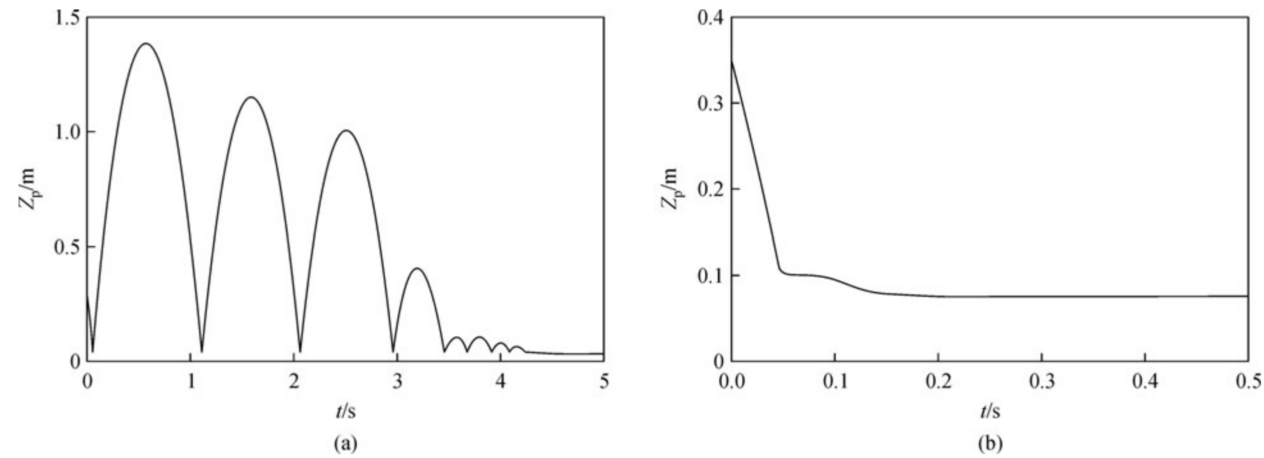

Fig. 3 Displacement of the projectile during impact process. (a) Thin granular bed with $H = 0.5$ cm; (b) thick granular bed with $H = 5.0$ cm

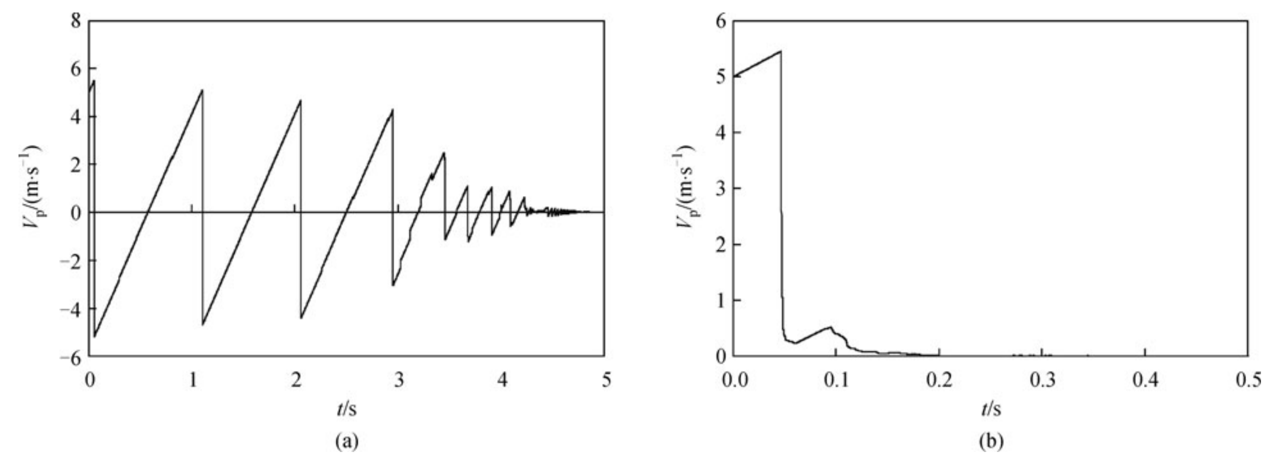

Fig. 4 Velocity–time curve of the projectile during impact process. (a) Thin granular bed with $H = 0.5$ cm; (b) thick granular bed with $H = 5.0$ cm

penetrate through the granular bed and contact with the container bottom during the impact. When the bed thickness is larger than 3.0 cm, the larger the impact velocity, the deeper the penetration depth; and penetration depth does not change much as bed thickness increases for each impact velocity. The results indicate that the granular bed in this thickness range possesses a certain degree of buffer capacity. Therefore, finding a suitable granular bed

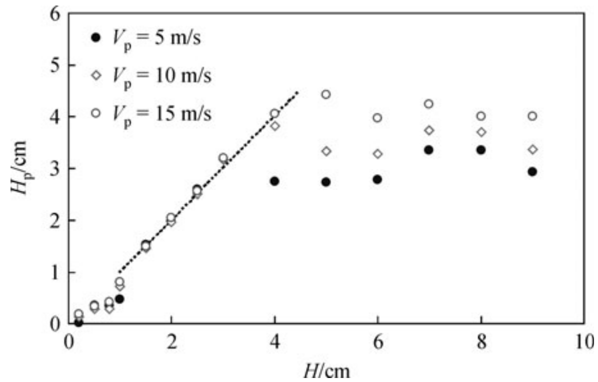

Fig. 5 Relationship between penetration depth and granular bed thickness

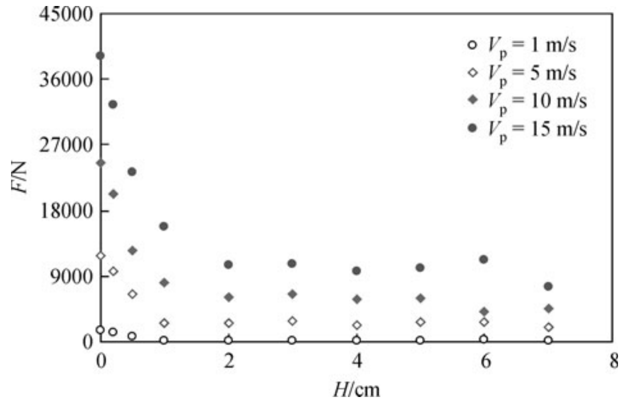

Fig. 6 Relationship between impact load peak and granular thickness

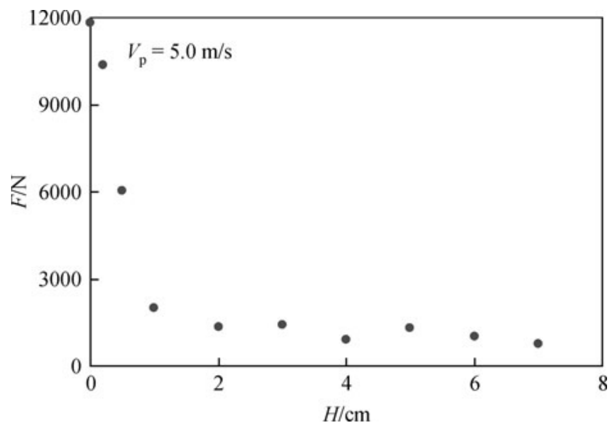

Fig. 7 The impact force peak F_1 under different impact velocities and granular bed thicknesses

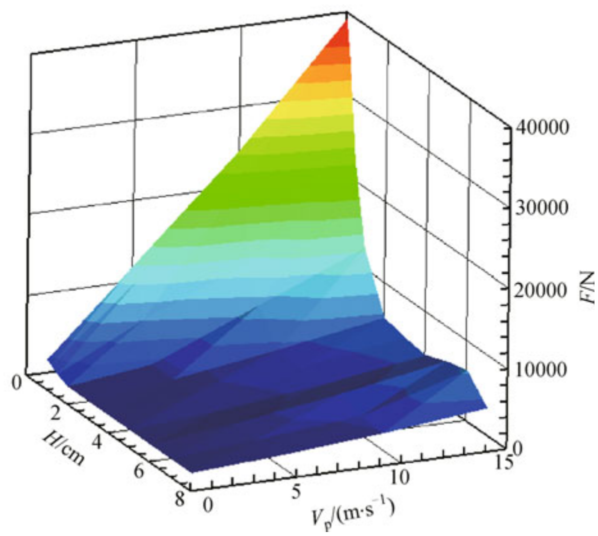

Fig. 8 Distribution of impact force peak under different impact velocities and granular thicknesses

thickness, which is defined as critical thickness H_c, is very important for the buffering effect of granular materials.

3.3 Influences of impact velocity and bed thickness on the impact load

The granular cushioning effect can be reflected by the first impact load. Figure 6 shows the first impact peak F_1 at different impact velocities. With increasing impact velocity, the impact peak F_1 increases. For lower velocity (v = 1.0 m/s, v = 5.0 m/s), the impact peak F_1 decreases sharply when the thickness is less than 1.0 cm, and stabilizes when the thickness is larger than 1.0 cm, the critical thickness is about 1.0 cm. While for higher velocity (v = 10.0 m/s, v = 15.0 m/s), the critical thickness is 2.0 cm.

Figure 7 shows the first impact peak F_1 under different granular bed thicknesses. The results show both the impact peak F_1 decreases sharply when the thickness is less than the critical thickness, and tends to be stable as the granular bed thickness increases. Figure 8 reflects the change of impact peak F_1 with different granular bed thicknesses and impact velocities comprehensively. The impact peak decreases with the increasing granular bed thickness, and stabilizes as reaching the critical thickness H_c. Before reaching the critical thickness H_c, the impact peak increases relatively large as impact velocity increases. After reaching the critical thickness H_c, the increase of impact peak becomes obviously slow.

4 Conclusions

Buffer capacity of granular matter is investigated through the simulation of a spherical projectile impacting on a granular bed using the discrete element method. The changes of impact force, displacement and velocity of the projectile versus time are compared under thin and thick granular bed. The penetration depth of the projectile and the first impact peak are investigated under different bed thicknesses and impact velocities. Simulation results show that the critical thickness of granular bed is particularly important for the buffering effect of granular matter during impact. The behavior of the granular is associated with force chain formation and breaking at the micro-scale. In the next study, force chain structures will be investigated to reveal the inherent mechanism of the exhibited buffering effect of granular matter.

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