EFFECT OF GRAIN PROPIERTIES ON THE PENETRATION OF INTRUDERS NEAR A WALL INTO GRANULAR MATTER: A DEM STUDY

EFECTO DE LAS PROPIEDADES DE LOS GRANOS EN LA PENETRACIÓN DE INTRUSOS CERCA DE UNA FRONTERA EN UN MEDIO GRANULAR: UN ESTUDIO DEM

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Recibido 9/12/2021; Aceptado 23/02/2022

PACS: Granular system (sistema granular), 45.70.-n; Discrete element method (método de elementos discretos), 45.70.Mg; Numerical simulations (simulaciones numéricas), 79.20.Ap

I. INTRODUCTION

Due to the nature of inter-grain interactions –especially their dissipative character– granular materials show many unexpected phenomena [1–7]. However, analytical tools are often a difficult option to explain them, due to their complexity and the large number of degrees of freedom involved. The discrete element method (DEM) [8] has proven to be an excellent possibility for the purpose [9–12]. Here we use DEM simulations to study the sensitivity of a granular system to the change of the mechanical properties of the grains, applied to the penetration of a cylindrical intruder near a vertical wall, as described in [13].

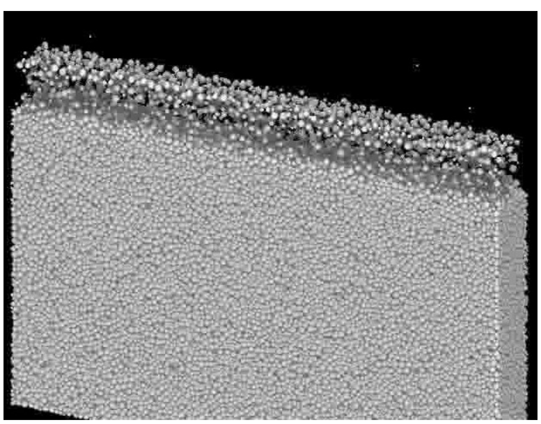

Figure 1. Preparation of the granular bed in the DEM simulations. A group of particles is poured periodically at an increasing height from the granular surface (particles moving down are seen as a less-dense layer on top of static grains in the snapshot shown above).

II. NUMERICAL SIMULATIONS

The experimental setup consists in a granular bed of expanded polystirene spheres confined into a Hele-Shaw cell, where a large cylindrical intruder is released from the free granular surface by means of an electromagnetic device that minimizes initial spurious vibrations and torques. Before its release, the cylinder is gently touching the left vertical wall of the cell.

The numerical simulations were performed using LAMMPS [14] reproducing the experimental conditions [13]. They were divided into two stages: preparation of the granular bed and the release of the intruder. In the first, the granular bed is prepared by pouring batches of particles with radius following a uniform random distribution within the range $1 - 3.25$ mm and a fixed density of 14×10^{-3} g/cm^3 Each pour generates particles at random positions within a limited space of the container, that moves up in the vertical direction as the container is filled (Fig. 1). The simulation ends when 10^5 particles are deposited and the total kinetic energy drops below 10^{-7} J.

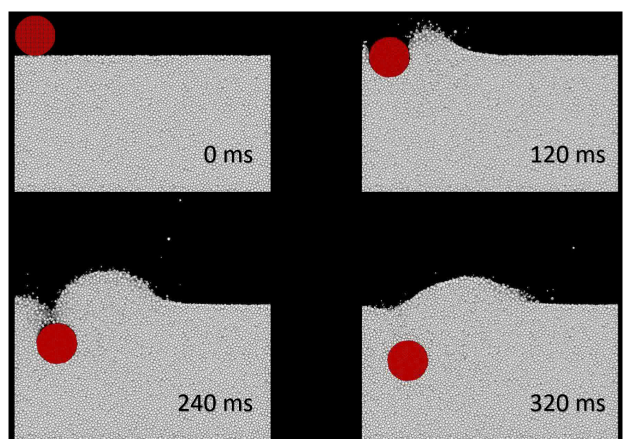

Figure 2. Rendered images of the DEM simulations describing the motion of the intruder as it penetrates into the granular bed near the wall.

After the first stage of the simulation ends, the intruder is generated as a 3.75 cm radius, 5.2 cm height and 0.255 kg mass cylinder, modeled as a many-particle-rigid-body, using a 1 mm-spacing simple cubic lattice, formed by spherical particles with a diameter of 1 mm. The intruder is released from the surface of the granular bed with zero initial velocity as shown at the upper left snapshot in Fig. 2 (initially, the left border of the intruder is 0.5 mm from the wall). The interaction between particles is ruled by a Hertzian contact model [15–17] where the parameters are calculated based on the material properties: Young Modulus $E = 5\,GPa$, restitution coefficient $e = 0.1$, Poisson's ratio $\nu = 2/7$ and friction coefficient $\mu = 0.5$, as described in [18, 19]. Both the particles and the intruder interact with the vertical wall following the same contact model. Fig. 2 shows the typical motion of the intruder: as it penetrates it suffers a horizontal repulsion due to the effect of the wall. In this work, we will describe the impact of μ, E and e in the penetration process, that is, the time evolution of the vertical and horizontal displacements of the intruder (although rotation was also observed [13], it will not be discussed here). μ and e are studied in the range 0.05−0.90, while E moves within the span 10−200 GPA. When a parameter is changed, the rest remain constant (experimental values).

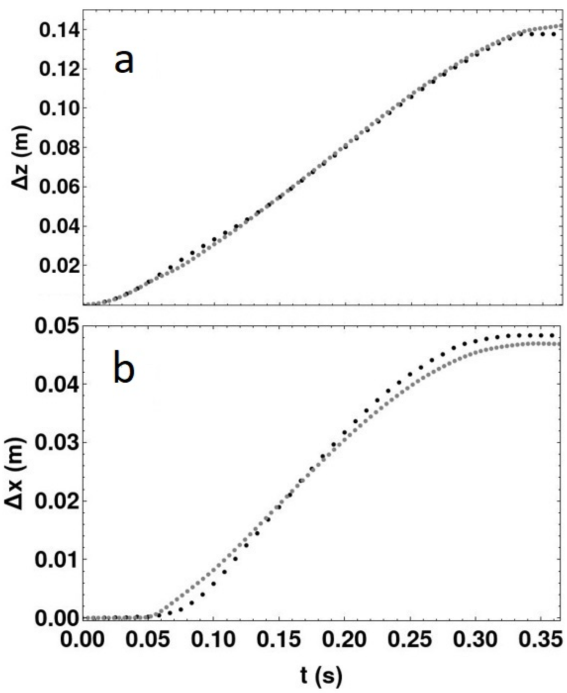

Figure 3. DEM simulation vs experimental results. (a) Vertical penetration of the intruder (experiment:black, simulation:gray) as an average over 10 numerical simulations/experiments. (b) Horizontal displacement of the intruder (Experimental data was taken from [13]).

III. RESULTS AND DISCUSSION

The first step is to check if the simulations are able to reproduce the experimental results. In Fig. 3 we observe a good fit between experiment and simulation, within root-mean-square errors of 0.0554 and 0.0347 (normalized to the maximum value of each experimental curve), for the horizontal and vertical motion, respectively. This confirms the possibility of using DEM simulations to investigate further experimental situations by changing the material properties of the granular system. Each of the following results were obtained from a single simulation, and as such no error bars are included. Note that the intruder release simulations are deterministic i.e., there are no deviations, given a fixed preparation of the granular bed.

In granular materials, the external stress acting on the system is transmitted by relatively rigid, heavily stressed chains of particles forming a sparse network of contact forces known as "force chains". The bigger μ the more rigid and stable are the force chains. In Fig. 4 we observe the effect of the value of μ on the motion of the cylindrical intruder. For low values (i.e. $\mu \leq 0.1$) the intruder hits the bottom of the cell as the force chains are never "stronger" than the gravity acting on the intruder. For $\mu \geq 0.25$ the motion stops before reaching the floor; the higher the value of μ the lesser the vertical penetration.

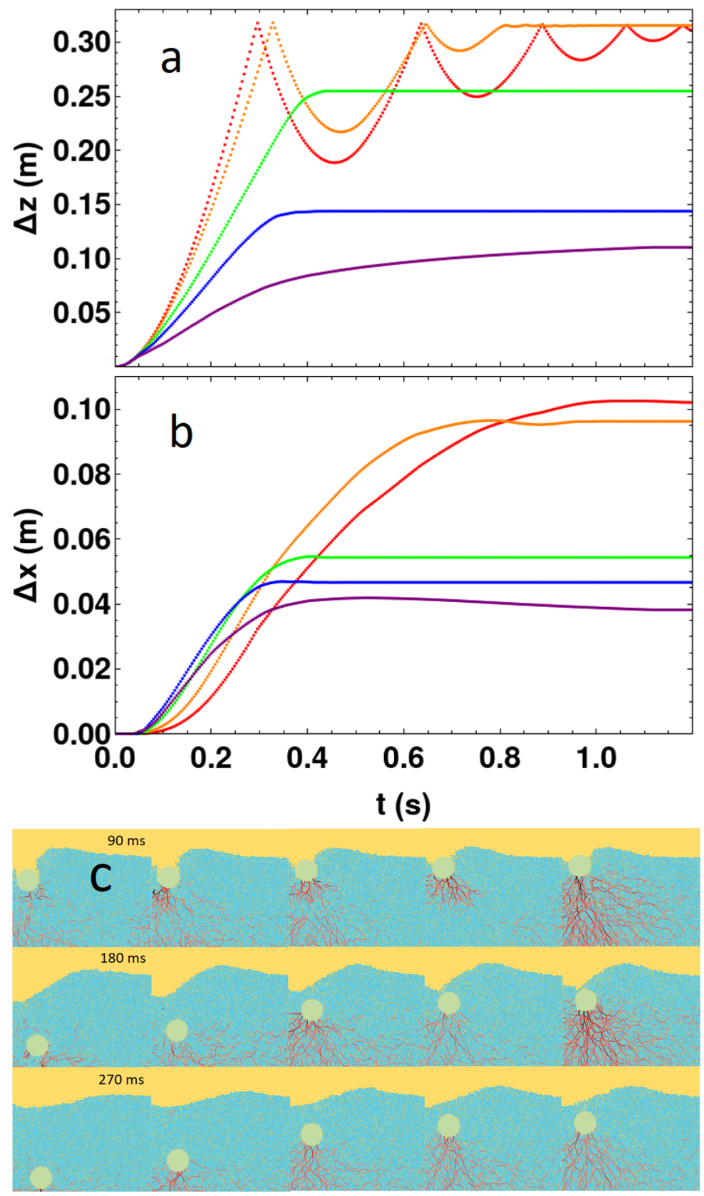

Figure 4. Sensitivity of the penetration process to changes in the friction coefficient. (a) Time evolution of the vertical motion of the intruder for $\mu = 0.05$ (red), 0.10 (orange), 0.25 (green), 0.50 (blue), 0.90 (purple). (b) Same as (a) but for the case of the horizontal motion. (c) Representation of force chains (strength proportional to red intensity) for different moments of the penetration process, obtained from 2D DEM simulations: $\mu = 0.05, 0.10, 0.25, 0.50, 0.90$, correspond to columns from left to right.

Comparing Fig. 4 (a) and (b) shows an interesting phenomenon: while the difference in the vertical penetration for μ = 0.25, 0.50 and 0.90 is rather large, the difference in the horizontal repulsion is much smaller. We speculate that the initial force chains, i.e. those ”charged” after the initial vertical free-fall plunge of the intruder [13], could be the ones with the largest component in the x-axis, repelling the intruder from the wall (this is consistent with the experiment and model predictions in [13]). Although higher values of μ lead to smaller penetration, they also increase the initial ”push” caused by the force chains formed between the intruder and the vertical wall, offsetting the difference in the horizontal displacement.

To visualize the force chains acting on the intruder during the penetration process, 2D simulations were implemented (As in [20], we first checked out that our 2D simulations resulted in penetration results qualitatively similar to key 3D outputs, like those shown in Fig. 4 (a) and (b)). The results shown in Fig. 4 (c), illustrate the expected increase in the strength and density of force chains as μ increases. Checking the speculation included in the previous paragraph turns out to be more difficult based on the images shown in Fig. 4(c), and will be further analyzed elsewhere.

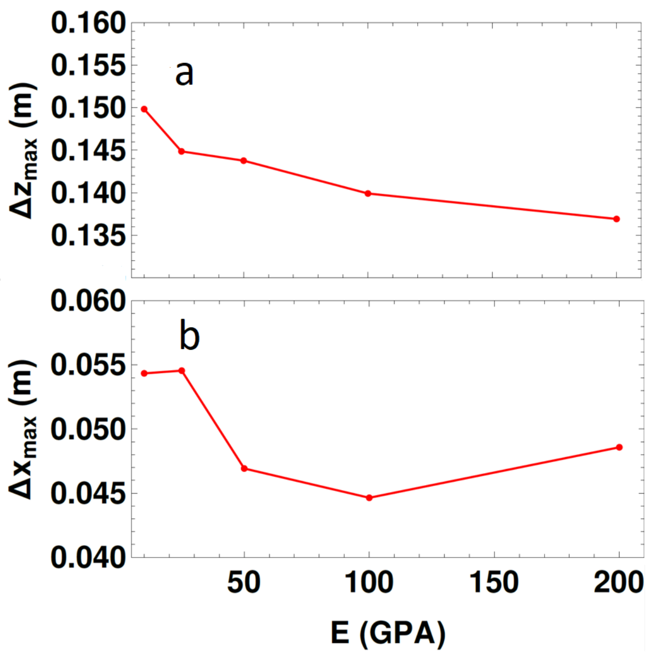

Figure 5. Sensibility of the penetration dynamic to changes in the Young Modulus. (a) Final penetration depth as a function of E. (b) Maximum lateral displacement.

The Young Modulus E describes the relation between the compressive stress and the axial strain of a solid material. The greater E the less deformation of the solid under the same force per unit area. Fig. 5 shows the sensibility of the studied granular system to changes in the Young Modulus of the grains. As can be observed, the impact, for the studied range of values, is less important than that caused by changes in friction. In Fig. 5 (b) a slight decrease in the vertical penetration of the intruder is observed as E increases. This could be related to the increase in the resistance of the particles to deformation (i.e. stronger force chains). In any case, the relatively small effect of Young's modulus (for the studied range of values) indicates that our granular system is, as a whole, more plastic than elastic: the building and destruction of force chains depends more on friction than on the bulk elastic properties of the grains.

The restitution coefficient is defined as the ratio between the final to initial relative speeds between two colliding particles, that is, the ratio of translational kinetic energy converted to other forms of energy (heat, deformation) during the process.

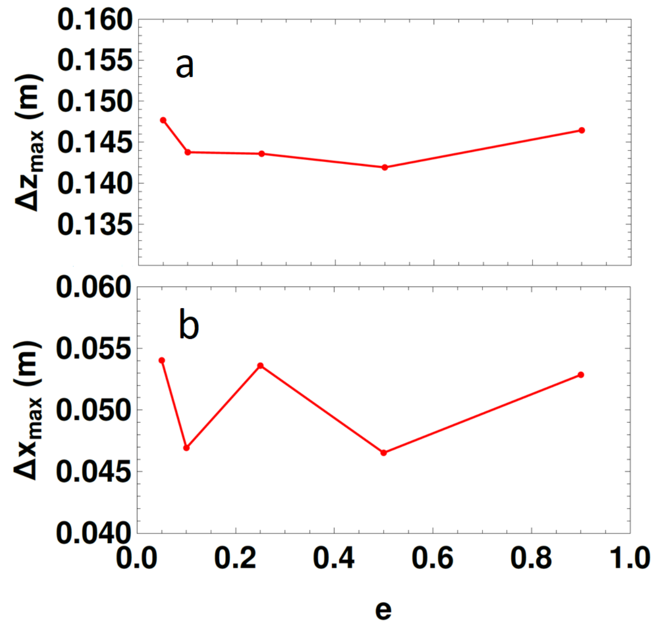

Figure 6. Sensibility of the penetration process to changes in the restitution coefficient. (a) Final penetration depth as a function of e. (b) Maximum lateral displacement.

In Fig. 6 we observe that changes in e cause negligible effect in the motion of the intruder. This could be related to two factors: one, a large part of the kinetic energy dissipates due to tangential dynamic (friction); and two, the large network of force chains allows for a sparse distribution of the force and dissipation of the kinetic energy of the intruder. The second reason is consistent with the relatively higher value of penetration observed for $e = 0.05$ in Fig. 6 (a) which suggests that values of e closer to zero offer less resistance to the motion of the intruder, as the only way to dissipate the kinetic energy would be through the friction between particles.

IV. CONCLUSION

In summary, we have studied a granular system where a large and massive cylindrical intruder penetrates from the free granular surface with zero initial velocity near a wall, using DEM simulations. The sensibility of the system to different grain properties was analyzed, observing the strong effect of the friction coefficient on the motion of the intruder. Higher values of μ allow the creation of stronger force chains that reduce the vertical penetration of the intruder, yet they also increase the initial horizontal repulsion form the lateral wall.

However, the influence of the Young modulus and the restitution coefficient of the grains have a negligible impact in the penetration process, suggesting that they play a less important role in the formation and strength of force chains.

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