IMPACT DYNAMICS IN "HARD" AND "SOFT" GRANULAR MATTER

DINÁMICA DE IMPACTO EN MATERIA GRANULAR "DURA" Y "BLANDA"

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Using a wireless accelerometer, we explore the dynamics of penetration of a sphere falling into very light granular matter prepared with different compactions. The duration of the penetration process until the sphere stops is ~30% bigger for less compacted granular matter, while the maximum penetration depth is ~40% bigger in that case. These outputs are quite remarkable, considering that the differences in the filling factors of the two granular media were smaller than 5%.

Utilizando un acelerómetro inalámbrico, exploramos la dinámica de penetración de una esfera que cae sobre material granular muy ligero, preparado con dos compactaciones diferentes. La duración del proceso de penetración hasta que la esfera se detiene es un ~30% mayor para el medio menos compacto, mientras que la penetración máxima para ese medio es un ~40% mayor. Estos resultados son notables, considerando que la diferencia entre ambos factores de llenado es menor del 5%.

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INTRODUCTION

Crater formation by impact in granular matter has been a subject of intense research in the last decade [1-7]. There is still debate about the form of the force law against penetration of the impactor, and how it depends on different experimental parameters, such as the density of the impacting object and the granular matter, the impact speed, the roughness and shape of the impactor, etc. Many of the existing reports concentrate in the study of the maximum penetration depth of the impacting object, and the diameter of the resulting crater. "Dynamical" studies, on the other hand, typically record the vertical position of the impactor during the penetration process [5], and only very few record *directly* its acceleration [6, 7].

In this paper, we use a wireless accelerometer to directly measure the acceleration of a sphere falling into extremely light granular matter, in order to find out how the penetration dynamics depend on the level of compaction of the granular medium.

EXPERIMENT

A cylindrical container of 30 *cm* diameter and 26 *cm* depth was filled with expanded polyestirene particles of density 0.014 ± 0.002 *g*/*cc* and diameter distributed between 2.0 and 6.5 *mm*, peaking at 5.8 *mm* [7]. Near the bottom of the container there was a fine horizontal mesh that allowed air to flow upwards injected by a compressor through a hole at the bottom of the system without loosing any granular material. This setup allowed us to prepare two types of granular matter:

Soft granular matter (SGM): Air was injected from the bottom from zero flow to a maximum, and then decreased back to zero flow (the maximum flow was selected in such a way that it produced visible "turbulence" at the free surface of the grains). The resulting granular medium, had a volume fraction of 0.64 ± 0.01. Using a rotating drum, we found that the maximum angle of stability for SGM was 29.52º ± 0.25º.

Hard granular matter (HGM): First, SGM was obtained. Then, the container was shaken horizontally for 5 seconds (the oscillations were approximately sinusoidal, with a period of 0.225 ± 0.004 *s* and acceleration amplitude of 1.9 ± 0.3 m/s^2). The resulting volume fraction was of 0.68 ± 0.01, and the maximum angle of stability was 30.29º ± 0.50º.

The impactor consisted in a 3-axis wireless accelerometer mounted into a 4-*cm* diameter ping-pong ball, in such a way that the *z*-axis of the accelerometer was pointing downwards along the vertical direction. The impactor weighted 23 grams (the lower hemisphere was more massive than the upper to guarantee minimal tilting when traveling through the granular media). The accelerometer had a resolution of 0.0001 *g*, and was able to transmit data in real time at 2.4 *GHz* to a USB node on an external PC, at a data point rate of 120 *Hz* [8].

A small magnet was glued to the top of the ping-pong ball, so the impactor could be "magnetically hanged", through a fixed, thin horizontal plastic plate, from the lower end of a vertical iron rod that initially touched the upper face of the fixed plate. When the rod was lifted up using a computer-controlled electro-mechanical device, the impactor was dropped onto the granular system with very small lateral tilting. The impactor was always released from a height where its lower end was just "touching" the free granular surface.

In the experiment, the vertical acceleration of the impactor was recorded in real time during its penetration into the granular medium (its horizontal acceleration was negligible compared to that along *z*).

RESULTS AND DISCUSSION

Fig. 1 shows the evolution of the vertical acceleration, velocity and position of the sphere as it penetrates the granular matter for HGM (left column) and SGM (right column). Velocity and position graphs were obtained after one and two integrations, respectively, of the acceleration vs. time graph -i.e., the direct output from the accelerometer. The insets have been constructed by plotting the acceleration vs. the calculated position. The positive direction is taken downwards.

Let us examine Figs 1 (a) and (d), as time increases. Initially, $a = 0$, which indicates that the impactor is hanging from the release system. The release process takes less than 70 *ms* both for HGM and SGM, and occurs before the impactor has dropped to a depth of 0.5 *cm* (as suggested by the insets). Then, the downward acceleration increases to average maximum values of 8 ± 1 m/s^2 for HGM and 9 ± 1 m/s^2 for SGM (ideally it should reach 9,8 m/s^2, but the ball is touching the granular surface before being released). After that, *a* increases in the upwards direction due to the action of granular resistance, reaching average minima of 8 ± 1 m/s^2 for HGM and 9 ± 1 m/s^2 SGM respectively. Finally, zero acceleration is reached, meaning that the sphere has stopped moving (in the case of SGM, $a = 0$ only after a few damped oscillations). The final stage of the stopping process occurs sharply within a few-*mm* distance. A major difference between the two media is the duration of the whole process from release to stop: 340 ± 10 *ms* for HDM, and 470 ± 20 *ms* for SGM.

Figs 1 (b) and (e) show the velocity records resulting from integrating in time the acceleration. In both cases, velocity starts at zero, and reaches maxima of 0.7 ± 0.1 *m*/*s* and 1.0 ± 0.1 *m*/*s* for HGM and SGM, respectively. Then, it goes back to zero quite symmetrically in time.

Figs 1 (c) and (f) show the *z*-position resulting from the integration of the velocity records. In the case of HGM, the depth inside the granular matter goes from zero (at the surface) to 0.14 ± 0.01 *m* (approximately in the middle of the granular column). In the case of the SGM, the final depth gives 0,22 ± 0,01 *m* (we checked both values using a thin thread attached to the sphere). Notice that, in the latter case, the ball stops only 4 *cm* from the bottom of the bucket. The damped oscillations of the acceleration at the end of the penetration process may be related to a jammed (more compacted) section of the granular material produced by the impactor itself immediately under it, which acts as a "solid wall". The process is probably enhanced by the proximity of the bottom wall in the case of SGM.

All in all, we have shown that, when a granular system is compacted in such a way that the filling factor decreases just to 94% of its original value, the total penetration time can be reduced to a 70%, the maximum velocity of the impactor can decreased to a 70%, and its maximum penetration depth can be reduced to a 60% of its initial value.

It has been shown before that the equation of motion for penetration of a spherical intruder into a larger system analogous to our SGM can be written as [7]

$$m\frac{d^2z}{dt^2} = mg - \eta\left(\frac{dz}{dt}\right)^2 - \kappa\lambda\left(1 - e^{-\frac{z}{\lambda}}\right), \quad (1)$$

where *m* and *z* are the mass of the sphere and the penetration depth from the free surface, respectively, λ is a characteristic length of the order of the diameter of the container, and the coefficients η and κ characterize the inertial drag, and a depth-dependent friction, respectively. This equation follows well most of the motion [7], but it cannot describe the release process at the very beginning and the final stopping stage (where the acceleration goes suddenly to zero when the ball stops in the bulk of the granular system).

In order to estimate parameters, we use two expressions associated to the motion far from its ends. From (1), it is not difficult to see that

$$\kappa = m\left|s_{a\to 0}\right| e^{z_{a\to 0}/\lambda}, \quad (2)$$

where $s_{a\to 0}$ and $z_{a\to 0}$ are the slope of the *a* vs. *z* graph (see insets), and the depth of the impactor when the acceleration approaches zero, respectively. Assuming $\lambda \sim 0.3$ *m* the resulting values for HGM and SGM cannot be clearly differentiated, and give a value of $\kappa = 1.9 \pm 0.3$ kg/s^2, which is near the value reported in [7] for a 6-*m* long cylinder with SGM. Additionally,

$$\eta = \frac{1}{v_{\max}^2}\left[mg - \kappa\lambda\left(1 - e^{-z_{v_{\max}}/\lambda}\right)\right], \quad (3)$$

where $v_{\max}$ is the maximum speed of the impactor during penetration, and $z_{\max}$ is the depth at which the ball experiences that speed. Equation (3) gives $\eta_{\mathrm{HGM}} = 0.16 \pm 0.02$ *kg*/*m* for HGM and $\eta_{\mathrm{SGM}} = 0.05 \pm 0.02$ *kg*/*m* for SGM. The latter value is close to that estimated in [7].

CONCLUSION

We have shown that, when a granular system is compacted, a small increase in compaction produces an increase in the penetration time, a decrease in the total penetration depth, and a sizable increase in the inertial drag coefficient.

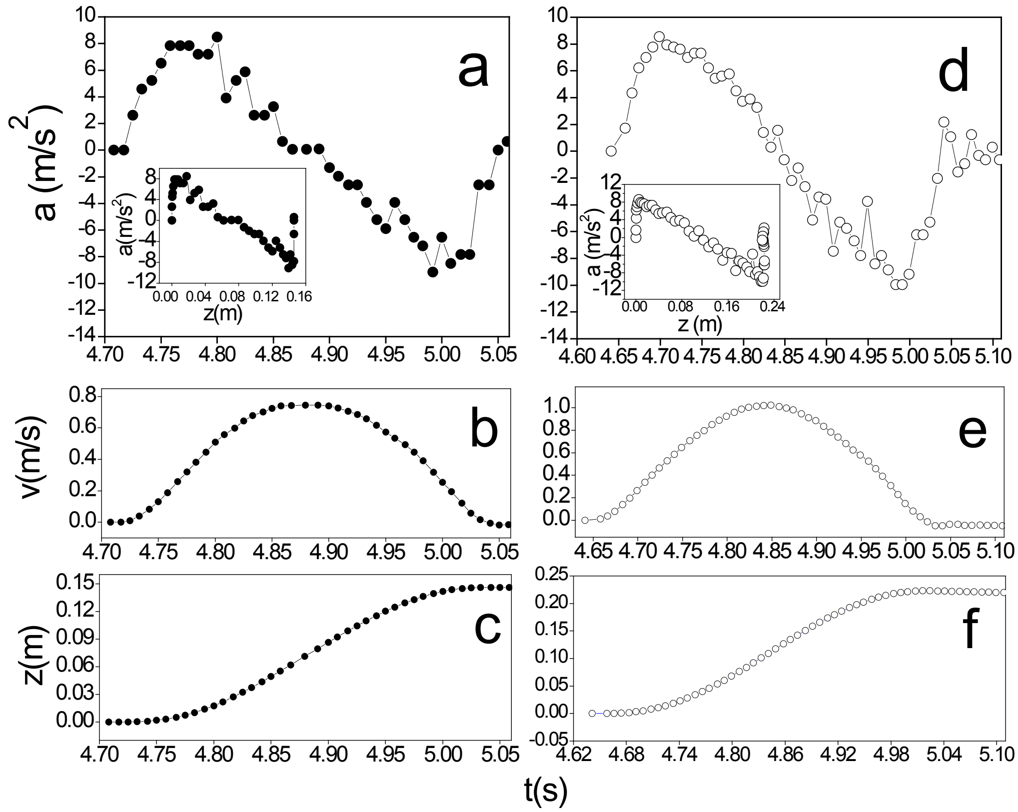

Figure 1: Experimental results. (a) - (c) Vertical acceleration, velocity and position of the impactor vs. time graphs, respectively, for Hard Granular Matter (inset is Acceleration vs. position). (d) - (f) Analogous graphs for Soft Granular Matter. Positive reference points downward.

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[1] J. S. Uehara, M. A. Ambroso, R. P. Ohja and D. J. Durian, Phys. Rev. Lett. **90**, 194301 (2003).
[2] A. M. Walsh, K. E. Holloway, P. Habdas and J. R. de Bruyn, Phys. Rev. Lett. **91**, 104301 (2003).
[3] S. J. de Vet and J. R. de Bruyn, Phys. Rev. E. **76**, 041306 (2007).
[4] J. F. Boudet, Y. Amarouchene, and H. Kellay, Phys. Rev. Lett. **96**, 158001 (2006).
[5] H. Katsuragi and D. Durian, Nat. Phys. **3**, 420 (2007).
[6] D. I. Goldman and P. Umbanhowar, Phys Rev. E **77**, 021308 (2008).
[7] F. Pacheco-Vázquez, G. A. Caballero-Robledo, J. M. Solano-Altamirano, E. Altshuler, A. J. Batista-Leyva and J. C. Ruiz-Suárez, Phys. Rev. Lett. **106**, 218001 (2011).
[8] See MMA7660FC ZSTAR3 accelerometer details at www.freescale.com/zstar
[9] T. Brzinski and D. J. Durian, Soft Matter **6**, 3038 (2011).
[10] D. J. Constantino, J. Bartell, K. Scheidler and P. Schiffer, Phys. Rev. E **83**, 0011305 (2011).