INTRUDER PENETRATION IN GRANULAR MATTER STUDIED BY LOCK-IN ACCELEROMETRY

PENETRACIÓN DE INTRUSOS EN UN MEDIO GRANULAR ESTUDIADA MEDIANTE ACELEROMETRÍA LOCK-IN

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Understanding the penetration dynamics of intruders in granular beds is relevant not only for fundamental physics, but also for geophysical processes and construction on sediments or granular soils in areas potentially affected by earthquakes. In this work, we use Lock-in accelerometry to study the penetration of passive intruders into quasi-2D granular matter fluidized by lateral shaking. We observed that there are two well-defined stages in the penetration dynamics as the intruder sinks into the granular material.

La descripción de la dinámica de penetración de intrusos en medios granulares no solo es relevante para la Física sino también para procesos geofísicos y ramas de la industria, en particular la construcción en zonas de terremotos. En el presente trabajo utilizamos la técnica de Acelerometría Lock-in para estudiar la penetración de intrusos pasivos en un medio granular cuasi-bidimensional fluidizado mediante agitación lateral. Esta técnica demuestra que existen dos dinámicas de penetración bien definidas en la medida que el intruso se hunde en el medio granular.

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By applying an external oscilatory force it possible to find a transition from a solid phase to a liquid phase in a granular media [1]. Such effect produces the loss of solidity of the material and causes a passive object laying on its surface to sink, tilt, or shift laterally [1]. This fluidization has a destructive effect during earthquakes because the buildings loss stability and eventually collapse [2–4]. Due to that earthquakes are one of the most destructive natural hazards affecting the social and economic structures of man. Although they can not be forecasted, their magnitude and after-effects can be minimized [2]. In this paper we propose an experimental techinque aimed at understanding the effects of fluidization in order to reach that goal.

While in quasi-2D systems the penetration of an intruder can be followed by means of a video camera [5–7], in the case of 3D systems of non-transparent grains this is not possible. Wireless accelerometry has been used in a few ocasions to quantify, as far as we know, the sinking dynamics of an intruder [9–12]. In this note we use a method called Lock-in Accelerometry (LIA), previously reported by our group in order to study the penetration dynamics of a passive intruder into a laterally shaken Hele-Shaw cell. [8]. As a result, we are able to establish two well-defined stages in the dynamics of penetration of an intruder into shaken granular matter, as the penetration depth increases.

Figure 1 shows the experimental setup which consists in a Hele-Shaw cell with a gap of 21.4 ± 0.2 *mm* filled up with polidisperse spherical particles with 0.7 ± 0.1 *mm* of average size and effective density of 0.715 g/cm^3. At the bottom of the cell there is a horizontal hose with 30 holes of 0.5 *mm* diameter each, through which is possible inject air into the granular system. The cell is able to oscillate laterally using an electromagnetic shaker with an amplitude of 1.5 *cm* and a maximum frequency of $\nu = 6$ *Hz*. Released on the granular system there is an intruder, a squared parallelepiped of 40 ± 0.3 *mm* side, 17 ± 0.3 *mm* thickness, and a weight of 51 ± 1 *g*, whose sinking is followed by a digital camera *Hero2* that moves synchronously with the Hele-Shaw cell. Two 3-axis accelerometers MMA7456L are fixed to the Hele-Shaw cell (labeled Ref) and inside of the intruder (labeled Probe) [14].

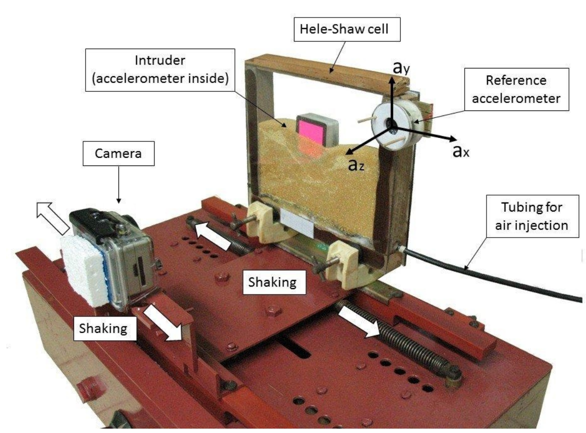

Figure 1. Experimental setup for quasi-2D measurements. Both the Hele-Shaw cell and the camera are synchronously shaken in the lateral direction. Accelerometers attached to the Hele-Shaw cell and the intruder bring the key information to quantify the sinking dynamics

A typical experiment consists in injecting air into the granular system for 10 seconds ensuring reproducible initial conditions. Later the intruder (with the Probe accelerometer inside) is released on the free surface of the bed. Then the data acquisition from the camera and accelerometers are activated and lastly the electromagnetic shaker and the air injection systems are started at the same time until the sinking process ends.

The essence of the technique *LIA* (Lock-In Accelerometry) [8] is the combined use of the information from the accelerometer fixed to the Hele-Shaw cell (Ref) and from the accelerometer inside of the intruder (Probe). Then, the experimental parameter used to study the sinking process is the correlation between the horizontal accelerations from both accelerometers. To calculate the correlation it is used a modification of the Pearson's correlation coefficient aimed at decreasing the noise in the output that consist in calculating the evolution of the Pearson's coefficient within time intervals of size D, each one starting at moment k, as follows:

$$r(k) = \frac{\sum_{i=k}^{k+D} a_{x,R}(i)\, a_{x,P}(i)}{\left[\sum_{i=k}^{k+D} (a_{x,R}(i))^2 \sum_{i=k}^{k+D} (a_{x,P}(i))^2\right]^{\frac{1}{2}}} \tag{1}$$

where $a_{x,R}$ and $a_{x,P}$ represent the horizontal accelerations of the Reference and the Probe, respectively. i represents the sampled time index and N is the total number of experimental data points (k runs from 1 to $N - D$).

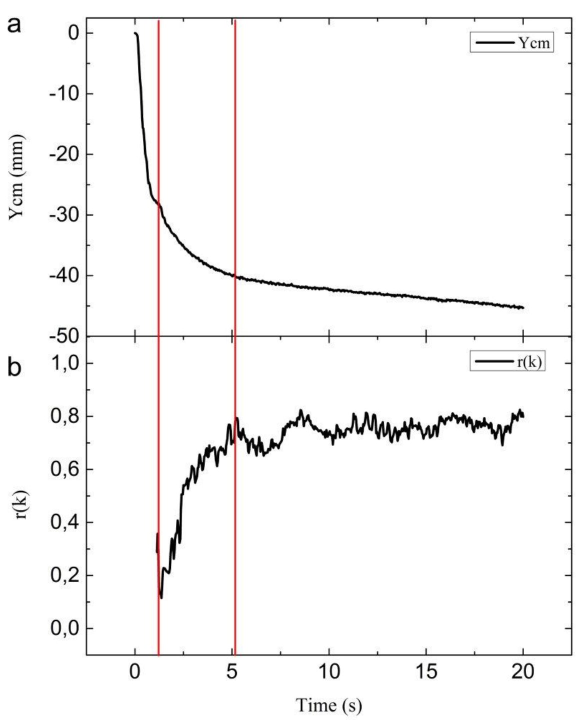

Figure 2. a) Penetration depth of the center of mass of the intruder (Ycm) versus time obtained from the video processing. b) Correlation coefficient versus time (the small oscillations seen in the curve correspond to a small "wobbling."of the intruder as its bottom touches the jammed phase, but its upper part is in a partially fluidized region). With the help of the vertical guide lines it is easy to see that the changes in the correlation curve correspond to the changes in the sinking velocity of the intruder.

The key idea behind the LIA technique is that when the intruder is sinking, it will be a delay between $a_{x,R}$ and $a_{x,P}$ and the correlation coefficient will be smaller than one. As depth increases the correlation increases because the probe is finishing its passage through the fluidized granular phase, and reaches a jammed phase into the granular system. Finally the value of the correlation must reach a plateau close to 1 indicating the end of the sinking process, where the intruder is moving almost synchronously with the reference.

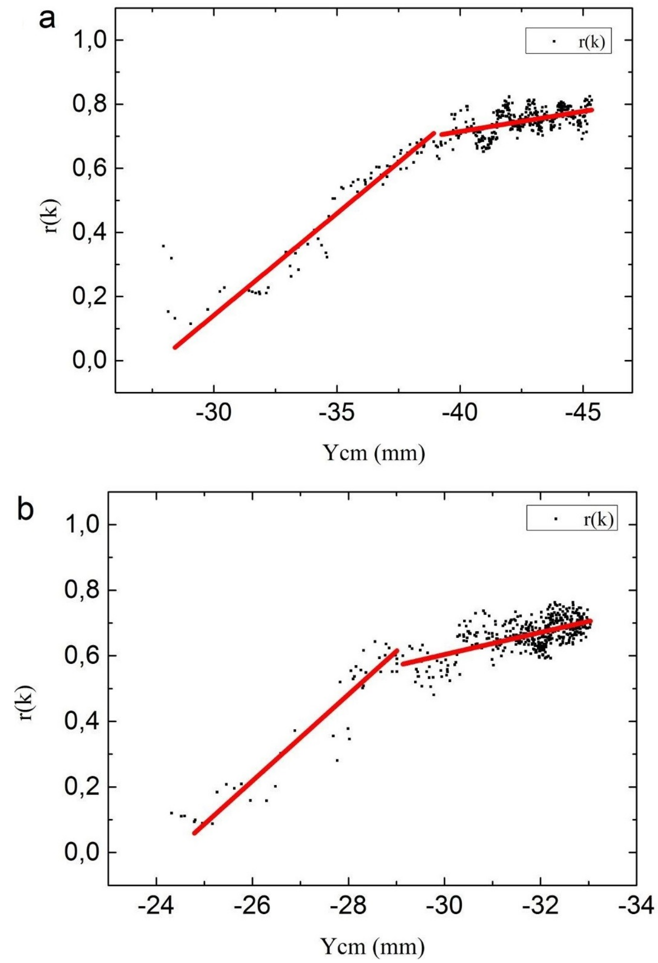

Figure 3. Correlation coefficient versus penetration depth of the center of mass (Ycm) a) for 2.5 Hz and 800 cm^3/h b) for 2.5 Hz and 700 cm^3/h.

Figure 2 shows the representative curves of a) the penetration depth of the center of mass (Ycm) and b) correlation coefficient versus time for an experiment with frequency of 2.5 Hz and air flux of 800 cm^3/h. Figure 2a shows the penetration depth of the center of mass in time obtained by the image processing from the videos taken by the digital camera. The general behavior of the sinking may be characterized, fundamentally, by three stages: initially there is a fast sinking process, that takes around 1 s, then a decrease in the sinking velocity and after 5 s a creep process takes place until the final stop. Figure 2b shows the time evolution of the correlation coefficient calculated using Eq. (1) with $D = 30$. The first region in the correlation curve could not be measured due to technical limitations of the accelerometers. At $t = 0$, as reported in [8] for the case of the 3D experiment, the correlation should be 1 because both accelerometers are at rest relative to the Hele-Shaw cell. Then, we will have an initial fast-decrease in the correlation because in the initial moments, probe and reference have a delay in their horizontal accelerations as briefly discussed above. Later on, there is an increase of the correlation as a result of the arrival of the intruder to a region in the system in which it starts to move together with the granular mass. Finally the correlation remains at a saturation value until the end of the experiment.

Figure 3 shows the correlation coefficient as a function of the penetration depth of the center of mass (Ycm) for experiments with a) frequency of 2.5 Hz and air flux of 800 cm^3/h and b) frequency of 2.5Hz and air flux of 700 cm^3/h where it is visible the influence of the air flux in the granular system. With the help of the guide lines it is possible to identify two main regions in each experiment, one between 29 *mm* and 39 *mm* of depth and the other from 39 *mm* to 45 *mm* of depth in Figure 3a. In Figure 3b, there is one between 25 *mm* and 29 *mm* of depth and the other from 29 *mm* to 33 *mm* of depth. In the case of Figure 3a those regions match with the two regions after the first guide line in Figure 2. The previous curves may be useful as a calibration function to characterize the variation of the penetration depth of the center of mass of the intruder in the time from the temporal dependence of the correlation.

In the present contribution we have studied dry materials, but the technique can also be used for wet granular matter. Finally, substituting the intruder by a solid rock and the granular bed by actual soil may expand the technique to measure, in situ, the rheological response of a soil during an earthquake.

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