INTERMITTENT AND CONTINUOUS FLOWS IN GRANULAR PILES: EFFECTS OF CONTROLLING THE FEEDING HEIGHT

FLUJOS CONTINUOS E INTERMITENTES EN PILAS GRANULARES: EFECTOS DEL CONTROL DE LA ALTURA DE ALIMENTACIÓN

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Using a specially designed experimental set up, we have studied the so-called continuous to intermittent flow transition in sand piles confined in a Hele-Shaw cell where the deposition height of the sand can be controlled in addition to the input flow. Through systematic measurements varying the height and the input flow, we have established how the size of the pile at which the transition takes place depends on the two parameters studied. The results obtained allows to explain, at least semi-quantitatively, the observations commonly reported in the literature, carried out in experiments where the deposition height is not controlled.

Utilizando un conjunto experimental especialmente diseñado, hemos estudiado la llamada transición de flujo continuo a intermitente en pilas de arena confinadas en una celda de Hele-Shaw donde la altura de deposición de la arena puede ser controlada además del flujo de alimentación. A través de mediciones sistemáticas que varían la altura y el flujo de entrada, hemos establecido cómo el tamaño de la pila al que tiene lugar la transición depende de los dos parámetros estudiados. Los resultados obtenidos permiten explicar, al menos semi-cuantitativamente, las observaciones comúnmente reportadas en la literatura, realizadas en experimentos donde la altura de deposición no fue controlada.

PACS: Hele-Shaw flows, 47.15.gp; Avalanches (granular systems), 45.70.Ht; Avalanches, phase transitions in, 64.60.av; Granular systems, classical mechanics of, 45.70.-n

I. INTRODUCTION

Granular media are relevant to many human endeavors: for example, they play a central role in the construction, food and pharmaceutical industries, and also as an important component of the natural environment [1–3]. During the last years, granular matter has been increasingly studied from the fundamental point of view by physicists. It has been used, for example, to establish analogies that allow to understand certain phenomena in other areas of physics and engineering, ranging from superconducting avalanches, due to the sudden motion of magnetic flux lines to urban traffic [4, 5].

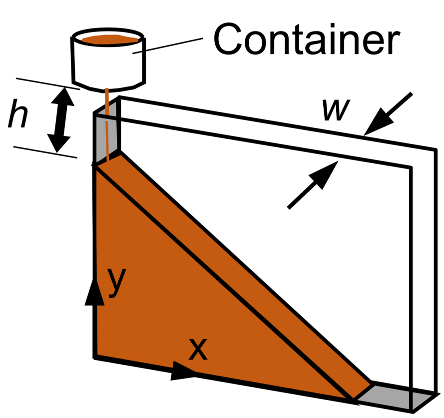

Figure 1. Sketch of the Hele-Shaw cell where the main parameters and coordinates are indicated.

Granular piles –that we will generically call sandpiles– have been used as a model for segreggation phenomena in geophysical scenarios, and also to illustrate the idea of self-organized criticality [1, 6–10]. Besides the well-known case of the sand down an inclined plane [11], a particularly attractive configuration of sandpiles is the Hele-Shaw cell: a pile of grains is grown confined between two vertical plates resting on an horizontal surface and separated by a distance w, where grains are poured from above, near a third vertical wall (see Figure 1) [9,12,13]. The height from which the grains are dropped to feed the pile has rarely been controlled in previous studies, and only by hand [12, 13]. Only recently has an automatic system been designed to fully control the dropping height [14].

A well known feature of surface flows in granular piles is the existence of continuous flows (where the grains flows uniformly down the slope within a certain depth from the free surface of the pile) and intermittent flows (where an avalanche suddely rolls down the surface of the pile, and accumulates at its lower edge, allowing a front to grow uphill until a new avalanche starts) [6, 7, 9]]. The transition between the two regimes as the pile grows is, however, poorly understood.

In this paper, we have used the system described in reference [14] to study the transition from the continuous to the intermittent regimes of granular flows on the surface of a quasi-2D pile as a function of the height, h, from which the granular matter is fed into the system (see Figure 1). We put special emphasis in unveiling the relation that exists between "conventional" experiments –i.e., those where the dropping height is not controlled– and those where it is kept constant in time.

II. RESULTS AND DISCUSSION

In every experiment, the behavior of the deposition height, h, and the area of the pile were measured as a function of time (the latter allows to compute the input flow, and make sure it is constant along the whole experiment). For the determination of the spatial-temporal coordinates of the transition, the evolution in time of a horizontal line of pixels located at a height equal to half the width of the input flow, from the bottom of the Hele-Shaw cell, was analyzed (Figure 2). The choice of vertical position of the line was taken based on the fact that it was important to leave out the "tail" at the base of the pile, which departs from the linear profile. On the other hand, since that "tail" increases in size with the input flow, it was reasonable to relate the position of the line with a characteristic length of it. In some cases where the end of the continuous regime (or the beginning of the intermittent one) is not so evident, it is necessary to use the curve of the angle of the pile versus time (which is also obtained from the image processing) as a complementary measurement to obtain the coordinates of the transition: the intermittent regime is then picked up where the angle of the pile starts a quasi-periodic oscillatory behavior.

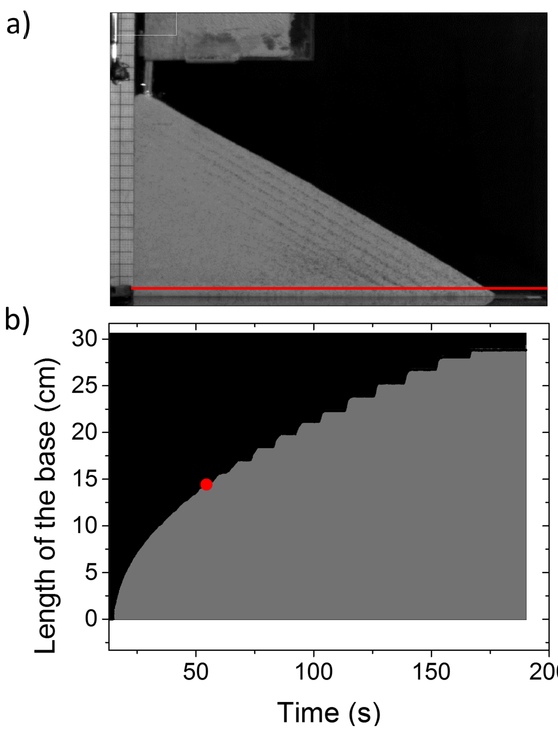

Figure 2. a) Snapshot taken from a video of a typical experiment. The horizontal red line is used to construct the spatial-temporal diagram. b) Spatial-temporal diagram based on the horizontal red line of a). The red dot indicates the coordinate of the continuous to intermittent flow transition.

Two types of experiments were performed. In the first group, we kept the feeding height constant in time, as well as the input flow. In the second, the input flow was kept constant, but the feeding height decreased as the pile height increased, since the pile grew up while the dropping altitude was kept fixed at a height equal to 23 cm. In all experiments, the horizontal size of the pile where the transition from continuous to intermittent flow occurred, X_c , was determined, as shown in Figure 3 (illustrating with the case where the feeding heigth is kept constant). Notice that the continuous lines shown in Fig. 3 are just the best mathematical fits, waiting for a proper physical interpretation in the future.

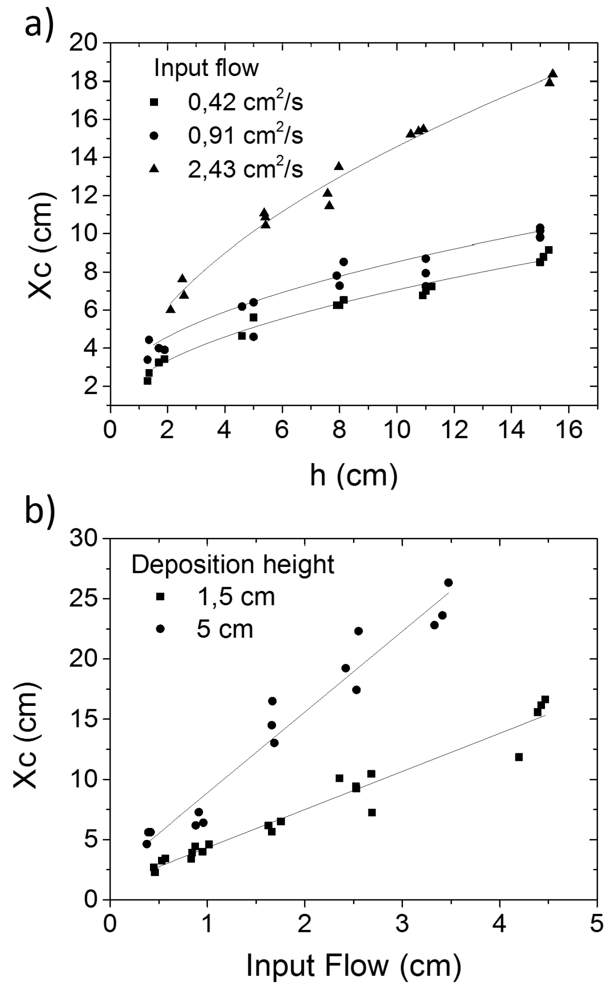

Figure 3. Dependence of the transition spatial coordinate X_c as a function of a) the deposition height for different input flows and b) the input flow F for different deposition heights. The continuous lines follow the law a) $X_c \propto h^{0.5}$ with values of R-squared of 0.98, 0.92 and 0.97 respectively and b) $X_c \propto F$ with values of R-squared of 0.95 for each one. The data was taken from experiments where h was kept constant. We repeated at least three times the experiments for each pair of values of deposition height and input flow. Differences of the values of the parameters, deposition height and input flow, are due to the nature of the initial conditions in each experiment, which were tuned manually.

Using the obtained temporal coordinates of the transition, it is possible to establish a link between controlled h and non-controlled h experiments. We do that by constructing a "phase diagram" based on the experimental data of the time at which transition occurs. The resulting "phase diagram", illustrated in Fig. 4 for two values of the input flow, allows to predict the time at which the continuous to intermittent transition occurs for piles without controlling deposition height, based on the data obtained from piles with controlled deposition height, as we will explain below in detail. Moreover our diagrams allows to find, for any experiment with fixed deposition height, h, an equivalent experiment with non-controlled h where continuous to intermittent transition take place at the same time, being equal the input flows.

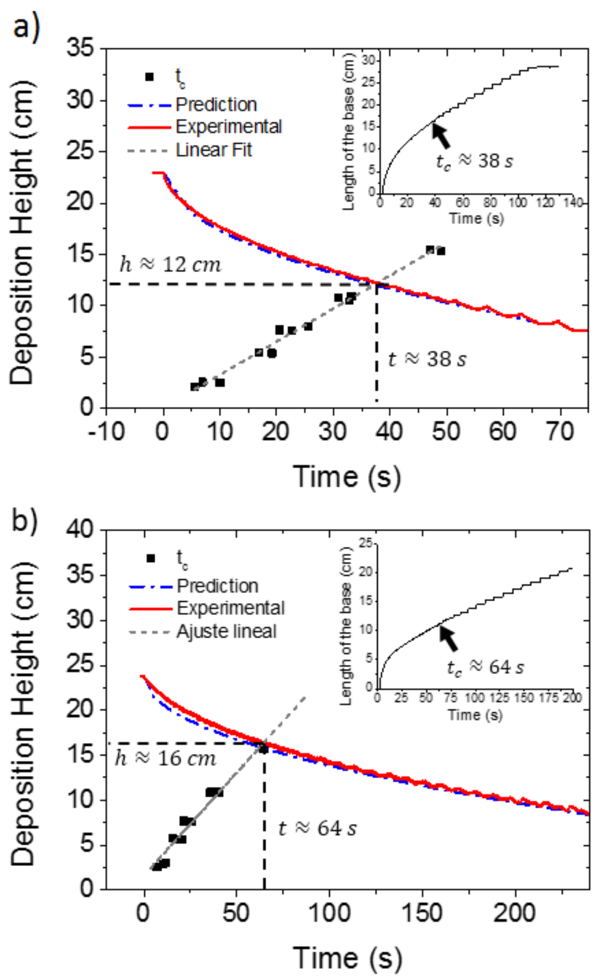

Figure 4. Connection between fixed and variable h experiments. Dots represent the temporal coordinates of the transition measured in our experiments for different values of h, where it is kept constant for each experiment. The solid lines are the variation of the deposition height measured for non-controlled experiments –i.e., where h decreases in time as the pile grows. The lines with dashes and dots are predictions (see text). Inset: Evolution of the horizontal size of the pile obtained from the spatial-temporal diagram for the non-controlled experiment (red line). The experiments illustrated have an input flux of a) 2.43 cm^2/s and b) 0.75 cm^2/s.

Figure 4 shows, for one input flow, the temporal coordinates t_c of the transition for experiments with different fixed deposition heights, as well as the dependence of the deposition height with time for an experiment where it was non-controlled. The black dots follow a linear dependence with h that delimitates, from left to right, the end of the continuous phase and the beginning of the intermittent one. Prediction curves were made applying the mass conservation principle. It was obtained that the deposition height for a non-controlled experiment varies as $h_0 - \sqrt{2tFtan\theta_c}$, where h_0 is the initial height of the container over the bottom of the Hele-Shaw cell, F the input flow in cm^2/s and θ_c the critical angle of the pile's surface.

III. CONCLUSIONS

In summary, we have performed the first systematic study of the transition from the continuous to the intermittent regimes of granular flows on a sand heap, including both conventional experiments, as well as those where the deposition height is controlled to be constant in time. We have demonstrated the relation between the two situations, in such a way that we are able to predict at what time the transition will take place for a non-controlled deposition height, based on the data taken from experiments with controlled deposition heights. This constitutes a first and necessary step to fully understand the physical nature of the transition.

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