Collapse of granular-liquid mixtures over rigid, inclined beds

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This work deals with the propagation of granular-liquid waves over rigid beds, originated by the sudden removal of a sluice gate in a rectangular, inclined flume. In particular, we experimentally investigate the role of the initial volume ratio of granular material—monodispersed plastic cylinders—to water, the flume width, and the bed roughness on the time evolution of the granular front. Due to the presence of the interstitial liquid, we observed previously unreported types of collapse: (i) discontinuous flows, where the granular material stops after an initial spreading, and then flows again when the liquid, initially slower than the particles, reaches the front and remobilizes it; (ii) flows evolving into uniformly progressive waves at an angle of inclination of the flume well below the angle of repose of the dry granular material. We also noticed an unusual influence of the lateral confinement on the wave propagation. Indeed, the constant front velocity in the uniformly progressive state decreases when the channel width increases. We claim that the latter observation and the presence of discontinuous flows, strongly support the idea that only two-phase, stratified mathematical models can predict the behavior of unsteady, granular-liquid mixtures at high concentration, such as debris flows.

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I. INTRODUCTION

One of the main mechanisms for the onset of a debris flow is the failure of a natural dam originated from a landslide in either a torrent or a canyon [1]. The prediction of the subsequent granular-liquid waves, which propagate along channels, has important practical applications in view of their possible interactions with the human environment. Laboratory experiments on the dam-break waves of granular-liquid mixtures can provide useful insight on the physical mechanisms acting on the flows. The experimental results may also serve to test mathematical models of granular-liquid flows [2,3].

Several works on the dam-break flow of clear water, turbulent or laminar, over rigid and erodible beds exist [4–6]. Conversely, the collapse of dry granular material over rigid and erodible beds has been experimentally investigated by Balmworth and Kerswell [7] and Mangeney *et al.* [8], among others. Also large-scale experiments on the collapse of fully saturated granular-liquid mixtures in an inclined, rectangular flume, either over a rigid or an erodible bed, have been performed [9,10]. Unlike those experiments, here we investigate the role of the initial degree of saturation of the mixture and the channel width on the dam-break waves of granular-liquid mixtures, moving in a rectangular, inclined channel over rigid beds. The paper is organized as follows. In Sec. II, we summarize the experimental setup and methods. Then, in Sec. III, we report the experimental results and analyze the influence of the control variables on the granular front propagation. Finally, we draw some conclusions in Sec. IV.

II. EXPERIMENTS

The sketch of the experimental setup and the typical initial configuration of a run is depicted in Fig. 1. The setup is composed of a 6-m-long, rectangular flume of adjustable width W and slope θ, with vertical sidewalls made of glass, located at the "Gaudenzio Fantoli" Hydraulic Lab of the Politecnico di Milano. The dam break is simulated by the pneumatic rising of a vertical sluice gate, whose opening time is roughly equal to 0.2 s, placed at the midsection of the flume. A mixture of water and plastic cylinders (density 1440 kg/m^3 and equivalent diameter $d = 3.9$ mm) is initially stored upstream of the gate. The initial fluid and particle depths are H_0 and h_0, respectively. We kept the maximum between H_0 and h_0, h_M, constant. We performed all the experiments at $\theta = 6.5^\circ$, i.e., well below the angle of repose of the dry granular material. We changed the initial degree of saturation, $\xi_0 = H_0/h_0$, of the mixture; the channel width, W; and the type of rigid bed. We employed either a "flat" bed, i.e., a metallic plate of roughness much smaller than the particle diameter, or a "bumpy" bed, meaning that we randomly glued a layer of the same plastic cylinders of the mixture at the channel bottom.

We filmed the propagation of the wave consequent to the opening of the sluice gate from above by means of a digital camera (at a frame rate of 25 Hz), mounted on top of the channel. We employed an edge-detection algorithm implemented in MATLAB to determine the temporal evolution of the position x_f of the granular front along the channel, averaged over the channel width (Fig. 2). The origin of the time coordinate t indicates the rising of the sluice gate. We also calculated the granular front velocity v_f by numerically differentiating the function $x_f(t)$. A summary of the characteristics of the experiments is reported in Table I. There, and in what follows, all quantities are made dimensionless using the particle diameter and the gravitational acceleration. All the experiments have been rerun up to three times to check the repeatability of the results. The repeatability was scarce only in the case of initially fully saturated mixtures, indicating an extreme sensitivity of the phenomenon to the initial degree of saturation, when the latter is around unity. Corresponding experimental results shown in the following plots must therefore be taken as only indicative.

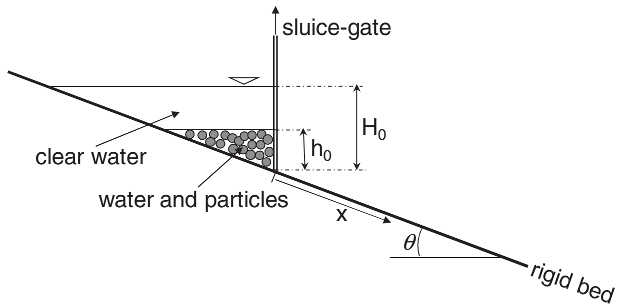

FIG. 1. Sketch of the experimental setup and the initial configuration.

TABLE I. Characteristics of the experiments.

Run	h_M	ξ_0	W	Bed
pw01	64	0.75	18	Flat
pw02	64	1.00	18	Flat
pw03	64	1.25	18	Flat
pw04	64	0.75	37	Flat
pw05	64	1.00	37	Flat
pw06	64	1.25	37	Flat
pw07	64	0.75	62	Flat
pw08	64	1.00	62	Flat
pw09	64	1.25	62	Flat
pw10	64	0.75	123	Flat
pw11	64	1.00	123	Flat
pw12	64	1.25	123	Flat
pw30	64	0.25	18	Bumpy
pw32	64	0.50	18	Bumpy
pw33	64	0.75	18	Bumpy
pw13	64	0.85	18	Bumpy
pw14	64	1.00	18	Bumpy
pw15	64	1.07	18	Bumpy
pw36	64	1.25	18	Bumpy
pw22	64	0.25	123	Bumpy
pw24	64	0.50	123	Bumpy
pw19	64	0.75	123	Bumpy
pw16	64	0.85	123	Bumpy
pw28	64	1.00	123	Bumpy
pw18	64	1.07	123	Bumpy
pw20	64	1.25	123	Bumpy

III. RESULTS

Figure 3 shows the influence of the initial degree of saturation on the granular front position and velocity when $W = 18$ and the rigid bed is bumpy. The experimental data are normalized in the way suggested by Mangeney *et al.* [8]. There is an initial acceleration phase dominated by the inertia, where all the curves substantially coincide. Indeed, the initial bulk density of the mixture barely changes in the experiments, ranging from 960 kg/m^3, when $\xi_0 = 0.25$, to 1200 kg/m^3, when $\xi_0 = 1.25$. Then, the front propagation is strongly influenced by the initial degree of saturation. Intuitively, increasing the initial content of water encourages the mobility. For $\xi_0 = 0.25$, the flow stops after a spreading that resembles the dry case [8]. For $\xi_0 = 0.5$, the flow is discontinuous; after a first spreading and an intermediate arrest—corresponding to an intermediate run-out—the granular front starts to flow again. It eventually reaches a constant velocity state, as in the case of the uniformly progressive waves [3,11,12]. Visual observation of the wave propagation allows one to ascribe this behavior to the phase separation between the particles and the liquid, as suggested by Berzi and Jenkins [12]. The granular front is always initially faster than the liquid front; at the lowest initial degrees of saturation, the difference in the two velocities is sufficient for the granular front to stop, given that the angle of inclination of the channel is less than the angle of repose of the granular material. When the liquid front reaches and overcomes the granular front [Fig. 2(b)], it transmits drag and buoyancy to the particles [13,14], causing the remobilization observed in Fig. 3. At $\xi_0 = 0.75$, a substantial slowing down of the front replaces the above described intermediate arrest. Even when the mixture is initially oversaturated ($\xi_0 = 1.25$), the presence of two peaks in the temporal evolution of the front velocity [Fig. 3(b)] reveals the intrinsic two-phase nature of the phenomenon. Figure 3(b) also shows that the channel is not long enough for the granular front to reach the constant velocity state at the highest initial degrees of saturation.

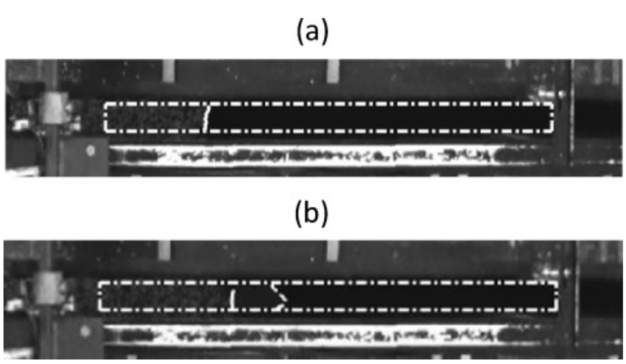

FIG. 2. (a) Wave evolution as seen from above in the channel of width equal to 18 diameters and bumpy bed, for $\xi_0 = 0.5$, after 1.1 s from the opening of the sluice gate (during the intermediate arrest; see the text for more details). The image shows the granular front (solid line) as determined by the edge-detection algorithm (the dot-dashed line indicates the extension of the area searched by the algorithm to find edges). (b) Same as in (a), but after 3.7 s from the opening of the sluice gate (at the onset of the second spreading of the granular material). The dashed line indicates the liquid front as determined by visual observation.

Figure 4 shows the effect of the type of rigid bed on the granular front propagation when $W = 18$. For $\xi_0 = 1.25$, the propagation of the granular front is independent of the channel bed. A longer channel is probably required to observe the influence of this parameter. On the other hand, for $\xi_0 = 0.75$, the bottom resistance plays a role on the wave propagation almost immediately. Given that the resistance encountered by the granular front is less when the bed is flat, the intermediate arrest, or slowing down, is delayed with respect to the case of a bumpy bed. Figure 4(b) also indicates that the presence of a flat bed when $\xi_0 = 0.75$ intensifies the intermittency of the front propagation, that proceeds as two consecutive pulses rather than a single pulse followed by a more continuous flowing.

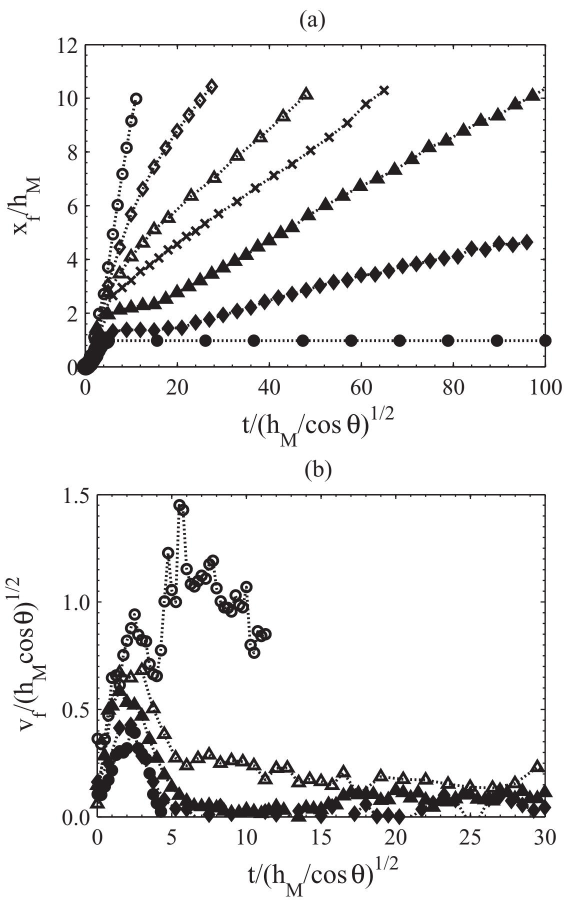

FIG. 3. Influence of the degree of saturation on (a) the normalized granular front position and (b) the normalized granular front velocity as functions of the normalized time. Experimental measurements refer to the case of waves over rigid, bumpy beds, with $W = 18$, for $\xi_0 = 0.25$ (filled circles), $\xi_0 = 0.50$ (filled diamonds), $\xi_0 = 0.75$ (filled triangles), $\xi_0 = 0.85$ (crosses); $\xi_0 = 1.00$ (open triangles), $\xi_0 = 1.07$ (open diamonds), and $\xi_0 = 1.25$ (open circles).

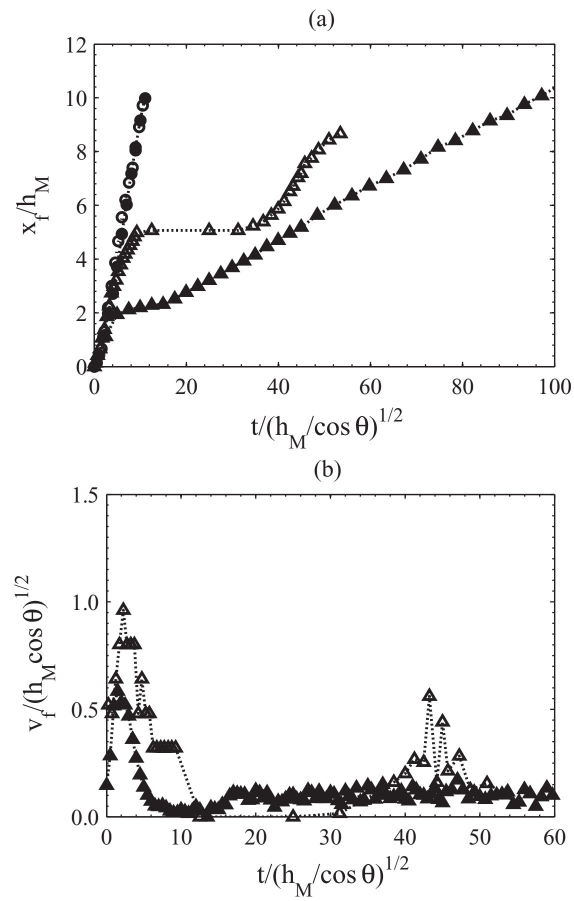

FIG. 4. Influence of the channel bed on (a) the normalized granular front position and (b) the normalized granular front velocity as functions of the normalized time. Experimental measurements refer to the case of waves in a channel of $W = 18$, for $\xi_0 = 0.75$ and flat bed (open triangles), $\xi_0 = 0.75$ and bumpy bed (filled triangles), $\xi_0 = 1.25$ and flat bed (open circles), and $\xi_0 = 1.25$ and bumpy bed (filled circles).

Figures 5 and 6 show the influence of the channel width on the granular front propagation. This influence is negligible if $\xi_0 \geqslant 1$ (once again, this could be due to the limited length of our apparatus). On the other hand, the channel width plays an important role in the granular front propagation when $\xi_0 < 1$. There is an initial inertial phase, where the curves collapse onto a single one, with the latter different for either flat or bumpy beds. Then, an increase of the channel width encourages the mobility of the granular front, at least during the first spreading. Indeed, the intermediate—or final—runout of the granular front increases, if the channel width increases (Figs. 4 and 5). This is not surprising, given that the sidewalls exert a frictional force on the particles which is proportional to the inverse of the channel width [15].

Figure 7 shows the constant granular front velocity v_u at the uniformly progressive state [11,12], as a function of the initial degree of saturation for flows over rigid, bumpy beds. As expected, v_u is a monotonic increasing function of ξ_0. It is possible to define four different types of flow on the basis of the behavior in terms of v_u, and the experimental observation of the discontinuity. The boundaries between the flow types indicated

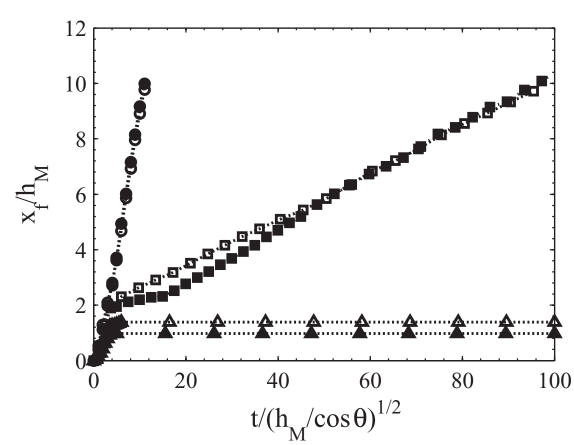

FIG. 5. Influence of the channel width on the normalized granular front position as a function of the normalized time. Experimental measurements refer to the case of waves over rigid, bumpy beds, for $\xi_0 = 0.25$ and $W = 18$ (filled triangles), $\xi_0 = 0.25$ and $W = 123$ (open triangles), $\xi_0 = 0.75$ and $W = 18$ (filled squares), $\xi_0 = 0.75$ and $W = 123$ (open squares), $\xi_0 = 1.25$ and $W = 18$ (filled circles), and $\xi_0 = 1.25$ and $W = 123$ (open circles).

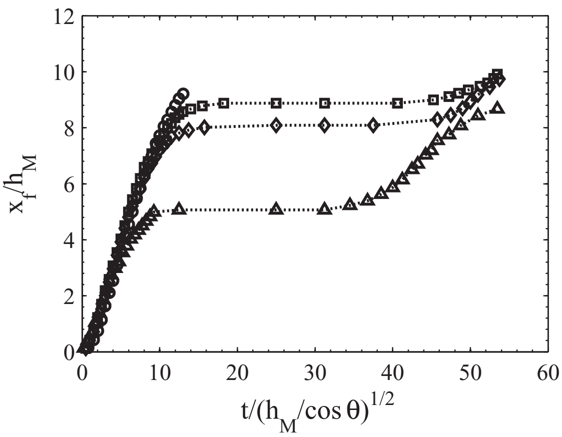

FIG. 6. Influence of the channel width on the normalized granular front position as a function of the normalized time. Experimental measurements refer to the case of waves over rigid, flat beds, when $\xi_0 = 0.75$, for $W = 18$ (open triangles), $W = 37$ (open diamonds), $W = 62$ (open squares), and $W = 123$ (open circles).

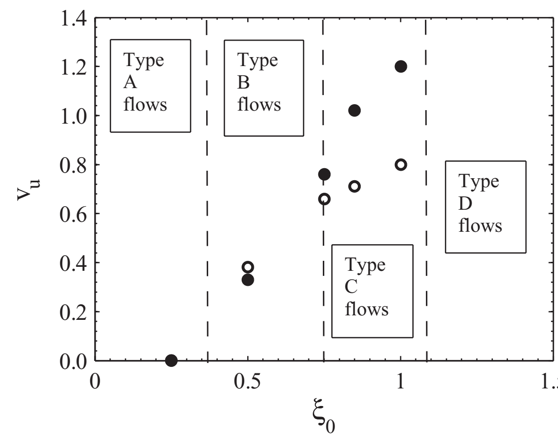

FIG. 7. Granular front velocity at the uniformly progressive state as a function of the initial degree of saturation for flows over bumpy beds, when $W = 18$ (filled circles) and $W = 123$ (open circles).

in Fig. 7 are only qualitative, and we do not expect any sharp transition between them. Type A flows are characterized by a single spreading of the granular material with a final runout, i.e., $v_u = 0$, as in the experiments of Mangeney *et al.* [8] on dry particles at angles of inclination of the bed less than the angle of repose. Type B flows are the already mentioned discontinuous flows: there are two consecutive spreadings of the granular material, separated by a quiescent interval, with nonzero final v_u. Type C flows reach the nonzero value of v_u in a continuous way, without intermediate arrest, as in the experiments of Pouliquen [16,17] on dry granular material at angles of inclination of the bed greater than the angle of repose. Finally, type D flows do not reach the uniformly progressive state, probably because the experimental channel is not long enough. Figure 7 indicates that v_u increases, if the channel width decreases, at least for type C flows. A plausible explanation of this apparent counterintuitive result relies, once again, on the two-phase nature of the flow. When $W = 18$, the granular front slows down more than when $W = 123$, while the liquid front follows at a seemingly unchanged velocity (systematic measurements of the liquid front position are required, though, to assess the validity of this statement). Hence, in the narrower channel, the liquid front reaches the particle front, thus increasing the local degree of saturation of the head of the granular wave and leading to greater values of v_u.

IV. CONCLUSIONS

We experimentally investigated the propagation of granular-liquid waves over rigid, flat or bumpy beds originated from the almost instantaneous opening of a sluice gate in a rectangular channel. We kept the angle of inclination of the latter constant, and less than the angle of repose of the granular material. Unlike previous works, we analyzed the influence of the initial degree of saturation and the channel width on the position and velocity of the granular front as functions of time. The main results of the paper are as follows: (i) there is a range of initial degrees of saturation less than unity where the granular wave is discontinuous, i.e., characterized by an intermediate quiescence, never reported in the case of dry granular material; (ii) above a certain threshold of the initial degree of saturation, the granular waves evolve towards a uniformly progressive state, if the channel is long enough; and (iii) the granular front velocity at the uniformly progressive state increases with the initial degree of saturation and decreases with the channel width.

The experimental results clearly show the intrinsic, two-phase nature of unsteady, high-concentrated granular-liquid waves, and the fact that the particle and the liquid front evolves differently during the flow. Hence, two-phase mathematical models that allow for a difference in the particle and liquid height over the bed [3,12] are probably the most suitable to simulate the propagation of those flows.

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