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Stéphanie Deboeuf, Philippe Gondret, Marc Rabaud. Dynamics of grain ejection during impact cratering in a deep dense pile.. 2008. hal-00311419v1

HAL Id: hal-00311419

<https://hal.science/hal-00311419v1>

Preprint submitted on 15 Aug 2008 (v1), last revised 17 Dec 2008 (v3)

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Dynamics of grains ejection during impact cratering in a deep dense pile.

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(Dated: August 15, 2008)

We investigate experimentally the dynamics of grains ejection due to an impacting sphere on a granular material. The time evolution of the corona formed by the ejected grains is reported, mainly in terms of its diameter and height, and favourably compared with a simple ballistic model. A key characteristic of the granular corona is that the angle formed by its edge with the horizontal granular surface remains constant during the ejection process, which again can be reproduced by the ballistic model. The energy of the ejected grains is finally evaluated and allows for the calculation of an effective coefficient of restitution characterizing the complex collision process between the impacting sphere and the fine granular target. The effective restitution coefficient is found to be constant when varying the control parameters.

I. INTRODUCTION

Impact cratering has been recognized as an important geologic process for the last decades when the lunar craters have been finally attributed to impact structures rather than giant volcanoes as believed until 1950's [1]. The planetary impact craters such as the ones observed commonly on the Moon or the Earth result from very high energy impacts of meteorites and thus involve numerous and very complex phenomena such as shock and rarefaction wave propagation, melt and vaporization of the projectile and target materials, together with excavation by displacement and ejection of the target material [1]. From the beginning of the new millenium, physicists have conducted laboratory scale experiments with rather low impact energy on granular matter, interesting in the crater morphology and searching for scaling laws for the crater size [2, 3, 4, 5]. Even though their energies are typically many orders of magnitude smaller than those of meteor impacts, these small scale experiments on granular impacts may be relevant to planetary impact processes, as the progression of crater morphologies as a function of impact energy has been shown to mirror that seen in lunar craters [2, 5]. In these impact experiments, physicists have also been interested in the penetration of the impacting sphere in the granular target [6, 7, 8, 9, 10, 11]. Indeed, despite recent progress on the complex rheology of granular matter [12], the penetration dynamics of a solid sphere onto a granular medium is still hard to understand well as it involves both the complex drag resulting from frictional and collisional processes, and the final arrest involving the complex "liquid/solid" transition exhibited by granular matter. The penetration dynamics of the impact sphere and the grains ejection have been shown to be very different when the granular material is not dense but loose: a spectacular thin granular jet can raise very high after the impact as first demonstrated in Refs [13, 14]. The effects on this

granular jet of the interstitial fluid [15, 16] and of the initial packing fraction of the target [17] have then been studied. In the dense case, no granular jet but a growing granular corona is seen after the impact. These different kinds of grains ejection can be related to similar kinds of liquid ejection consecutive to the impact of a droplet into a deep or thin layer of liquid that have been first filmed by [18] and then studied extensively [19]. Much less studies focusing on the grains ejection have been performed in the dense granular case. If Ogale *et al.* [20] have looked at the mass of the spilled-over grains at low impact velocities (~ 1 m/s), Cintala *et al.* [21] measured the angle of the granular corona and the velocity distribution of the ejected grains at high impact velocities (~ 1 km/s). Such impact and grains ejection by an impacting projectile have been recently simulated in two limiting cases, where the projectile size is either larger than the grains size [22, 23] or equal to the grains size [24, 31]. This last case, where the projectile and target grains are identical, has been experimentally investigated [27, 28]. If the dynamics of the crater growth has been recently investigated experimentally in deep [25] or shallow [26] sand layers, we focus in the present paper on the dynamics of the granular corona formed by the ejected grains in low speed (~ 1 m/s) impact experiments. In section II, the experimental setup is described together with the measurements. A simple ballistic model is then presented in section III and compared to the experimental data. Section III ends this paper with a discussion.

II. EXPERIMENTS

Each experimental run consists of dropping a solid sphere into a granular medium. Four different steel spheres of density $\rho_s = 7800$ kg/m³ are used as impactors, with four different radius $R = 5.15, 6.75, 7.55, 9.50$ mm and masses m ranging thus from 4.5 g to 30 g. The steel sphere is

initially hold by a magnet through a semi-spherical hole, so that the sphere can be dropped without any translational nor rotational velocity by pulling up the magnet. The sphere is released directly above the center of a container and fall along its axis. The sphere is dropped from the height h above the granular surface which is varied between 8 cm and 60 cm, and the sphere thus impacts the granular material with the velocity $v_c = \sqrt{2gh}$ (g is the acceleration of gravity) varying from 1 m/s to 4 m/s and energy $e_c = mgh$ ranging from 3.10^{-3} J to 2.10^{-1} J. The target material consists in sieved glass beads of density $\rho_g = 2500$ kg/m³ ($\rho_s/\rho_g = 3.1$) and mean diameter $2r = 0.4 \pm 0.1$ mm ($R/r \sim 25 - 50$). The granular material fills the cylindrical container of diameter 19 cm and height 26 cm. Before each drop, the granular medium is prepared by gently stirring the grains with a thin rod. The container is then overfilled and the surface levelled using a straightedge. The typical value of the solid volume fraction of the packing is 60%, and the angle of repose of the pile is approximately 20° . The size ratio of the container diameter over the sphere diameter is always larger than 10, so that there is no influence of the radial confinement by the lateral walls of the container [29], neither of the bottom wall. Each impact experiment is lighted from the side to enhance contrast between grains and black background, while recorded by a high-speed camera at the rate of 500 images/s and resolution of 0.16 mm/pixel. The 256 gray levels images are thresholded to identify grains.

Fig. 1 shows a sequence of side view images separated by 30 ms illustrating the ejection dynamics of the grains after the sphere impact, defined as the time $t = 0$. One can see few isolated ejected grains above a corona of grains that expands radially and vertically before decreasing. The amount of ejected grains can be quantified by measuring the apparent surface area A_{tot} of all the grains in each image. The evolution of A_{tot} as a function of time is reported in Fig. 2 for different experiments corresponding to different dropping heights h of the same sphere. After the impact at $t = 0$, A_{tot} increases from zero up to a maximal value denoted $A_{tot\ max}$ at the time $t_{A_{tot\ max}}$, before decreasing and then vanishing. Each curve corresponds to a single impact experiment, thus without any ensemble averaging, but with a little smoothing by a slide-average over a time window of 10 ms so that no data appears in the reported figures before $t = 4$ ms. The global parameter $A_{tot}(t)$ appears thus as a non noisy measurement of the total number of ejected grains N_{ej} even if the exact relation between the two is not straightforward and will be discussed in the following. Increasing the dropping height h of a given sphere, the values $A_{tot\ max}$ and $t_{A_{tot\ max}}$ increase, accounting for the increase of both ejected grains and the dynamics duration. The same goes when keeping constant the dropping height h and increasing the mass m of the impacting sphere.

In impact experiments of a drop onto a liquid layer, a beautiful corona is classically observed [18, 19]. In such a liquid case, the corona is easy to define and extract as

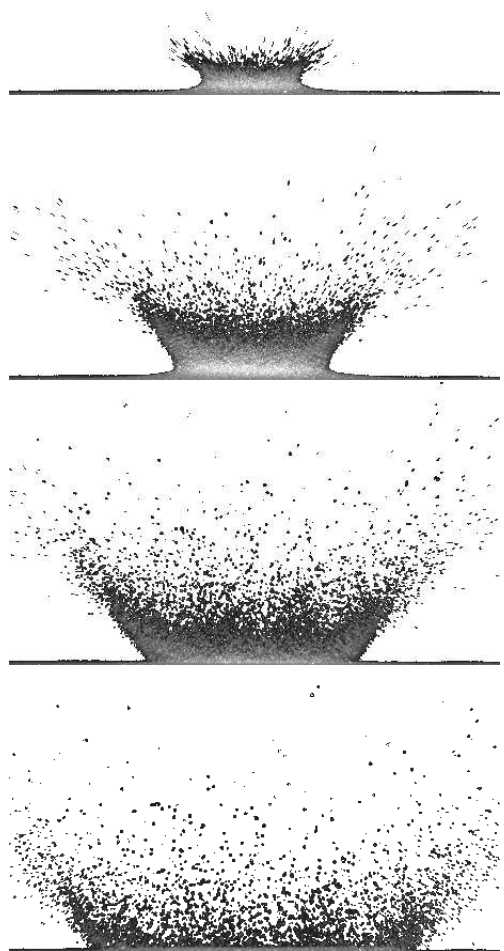


FIG. 1: Sequence of side view images separated by 30 ms, showing a typical temporal evolution of the ejected grains and the corona after the impact of the bead 2, dropped from the height $h = 30$ cm, with impact velocity $v_c = 2.45$ m/s and energy $e_c = 0.03$ J.

the liquid is a continuous medium. In the granular case, the corona is less easy to define as the ejected grains are more or less individual entities. We will see in the following that the evolution of the “observed” granular corona, in terms of its typical height, diameter and angle, will be interesting to follow as it describes well most of the ejection process. The granular corona is here defined as the largest connected part in the image. We have checked that the size of the corona does not depend significantly on the lighting and contrast of the images. To investigate the time evolution of the corona and characterize its shape which is basically axisymmetrical, its contour is extracted. An example of such a contour is drawn

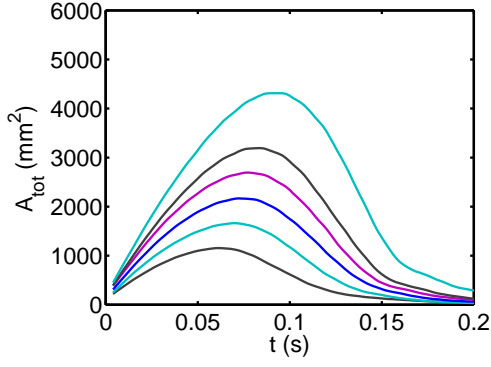


FIG. 2: Temporal evolution of the total apparent ejected grains A_{tot} for impact experiments of the sphere 3 dropped at different heights $h = 13, 23, 33, 43, 48$ and 58 cm, from bottom to top.

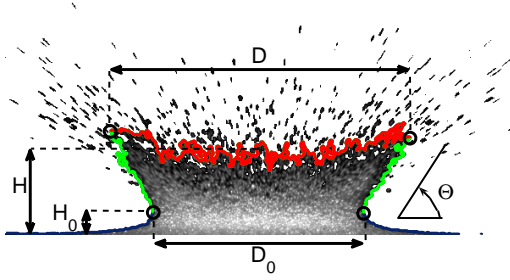


FIG. 3: Geometrical parameters characterizing the corona of ejected grains.

in Fig. 3. Note that this corresponds to the external contour of the ejecta curtain. This allows to detect two opposite points at the bottom (resp. at the top) of the corona as the nearest (resp. farthest) points in terms of horizontal distance. Their horizontal gap distance define respectively the minimal and maximal diameter D_0 and D of the corona. The height of the corona H is measured as the mean vertical position of the corona top contour delimited by the two top points and the height of its base H_0 corresponds to the height where the corona diameter is minimal and equal to D_0 . In all these height definitions, the zero is taken as the granular surface level before impact. As the corona lateral edge appears very straight except in a small zone at the base of the corona, we extract also the angle Θ formed by the corona edge with the horizontal, by a linear fit of the straight portions.

The time evolution of the corona, in terms of its height H , its maximal and minimal diameter D and D_0 , and its edge slope Θ , is displayed in Fig. 4 for the same experiments as in Fig. 2. The expansion of the corona is demonstrated in Fig. 4a by the increase of its height H up to a maximal value denoted H_{max} at time $t_{H_{max}}$. Then, H decreases with time until vanishing. For a given sphere, H_{max} and time $t_{H_{max}}$ increase monotonically with the dropping height h , so that the different curves of Fig. 4a ap-

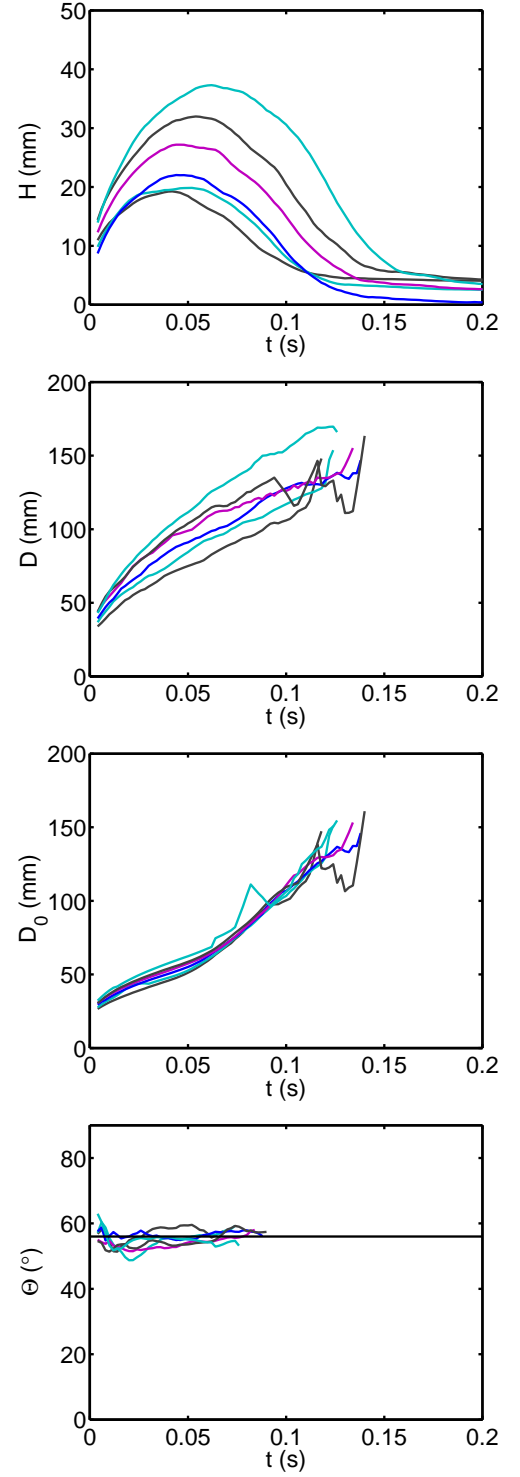


FIG. 4: Temporal evolution of (a) the height H , (b) the maximal diameter D , (c) the minimal diameter D_0 , and (d) the angle of the corona Θ for the same experimental parameters as in Fig. 2.

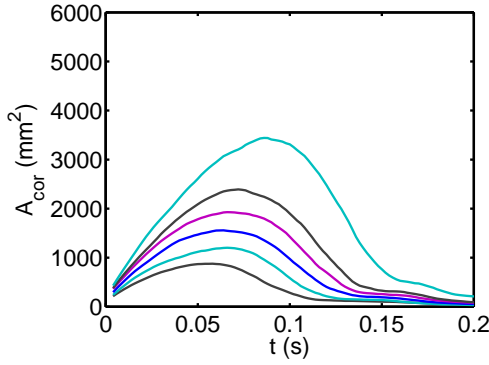


FIG. 5: Temporal evolution of the apparent surface area of the corona A_{cor} for the same experimental parameters as in Fig. 2.

pear in order. Note that for large impact energies (large impact heights h), H decreases eventually to a non-zero value, because of the final crater rims lying above the initial free surface [2]. In the same time, the maximal diameter D and the minimal diameter D_0 increase with time, as shown in Fig. 4b and c, up to their maximal values $D_{H_{max}}$ and $D_{0_{max}}$, when the corona disappears and its height vanishes. The evolutions of D and D_0 seem quite different, about linear for D and parabolic for D_0 : when D increases significantly with the dropping height h , D_0 does not vary so much. Note that at the nearly end of the corona life, for vanishing height H , the values of D and D_0 become very noisy (not shown). The angle Θ the corona edge forms with the horizontal, shown in Fig. 4d, is roughly constant as a function of time and whatever the dropping height h , and equal to about 56° with relative variations of $\sim 5\%$. The same kind of evolutions of all these parameters are observed for the four different tested spheres. The corona evolution reported here for granular impacts can be now compared to the corona evolution for the liquid case [19]. For the liquid case, the corona spreads radially as the square root of time whereas it seems more close to a quadratic evolution for the granular case (see $D_0(t)$ in Fig. 4c). The scaling law of spreading is thus very different in the two granular and liquid cases, with inverse curvatures in the $D_0(t)$ plot. Besides, the angle of a liquid corona is found independent of the drop impact velocities, as found for the granular corona. But, a big difference is that the angle of the corona depends crucially on the initial liquid thickness δ for the liquid case, as it varies from 90° for a film thickness δ larger than the drop radius R towards smaller values for smaller film thickness, e.g. $\Theta \simeq 40^\circ$ for $\delta/R = 0.1$ [30]. The fact that the angle of a granular corona does not seem to depend on the depth of the granular layer may be related to the collisional chains that redirected the impact velocity within a few grains layer only [31]. Note the value of the edge angle $\Theta \simeq 56^\circ$ in the granular case obtained here for $\delta/R \gg 1$, by contrast with the liquid case.

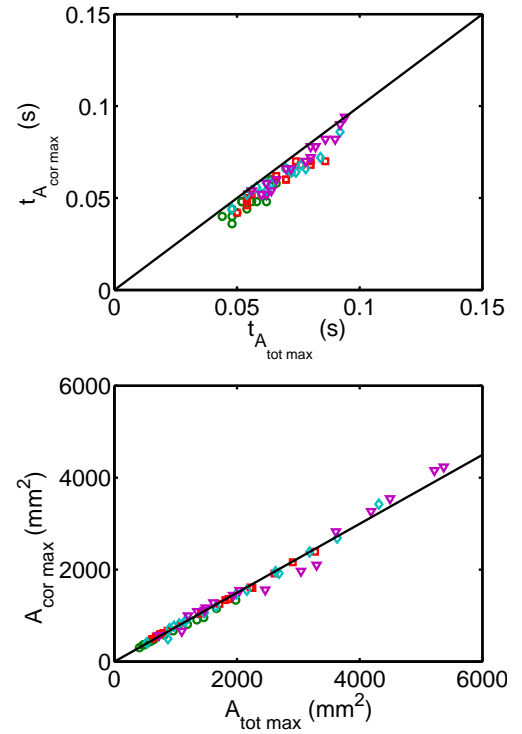


FIG. 6: Time $t_{A_{cor\ max}}$ for maximal value of the corona apparent area A_{cor} as a function of time $t_{A_{tot\ max}}$ for maximal value of the total apparent area A_{tot} . Maximal values $A_{cor\ max}$ of A_{cor} as a function of maximal values $A_{tot\ max}$ of A_{tot} . For all of the 65 experiments, with different dropping heights h and four different beads, by increasing radius: \circ , \square , \diamond and ∇ .

With the measurements of the geometrical parameters of the corona presented above, we can now define the apparent area of the corona, denoted A_{cor} , that is related to the amount of ejected grains contained in the corona, and compare it to the total apparent area of ejected grains, A_{tot} , presented previously and related to the total amount of the ejected grains, both in the corona and isolated. A_{cor} is measured as the area included inside the corona contour, which is not far from the area $H(D + D_0)/2$ corresponding to the approximate corona trapezium shape. The time evolution of A_{cor} is reported in Fig. 5 for the same experimental parameters as in Figs. 2 and 4. If A_{cor} is always smaller than A_{tot} as expected, the evolution of A_{cor} is qualitatively the same as the one of A_{tot} (Fig. 2). This is confirmed by the quantitative comparison of the corresponding coordinates of the curve maxima, $(t_{A_{tot\ max}}, A_{tot\ max})$ and $(t_{A_{cor\ max}}, A_{cor\ max})$, that are reported in Fig. 6 for all the experiments (all dropping heights, all four different spheres). The evolutions of A_{cor} and A_{tot} are synchronized in time as illustrated by the equality $t_{A_{cor\ max}} \simeq t_{A_{tot\ max}}$ (Fig. 6a). Besides, $A_{cor\ max}$ is found proportional to $A_{tot\ max}$ with the same ratio for all experiments: $A_{cor\ max} \simeq 0.75 A_{tot\ max}$ (Fig. 6b). All this suggests that the investigation of the corona dynamics is a good first order for the study of

the dynamics of grains ejection due to an impact. Here is a summary of our main results from the evolution of the observed corona: whereas some properties, such as the dynamics duration, the maximal expansion of the corona, the number of ejected grains, depend quantitatively on the experimental parameters, some other geometrical parameters, such as the corona edge angle, its minimal diameter at its base, keep constant for all experiments and as a function of time. How interpret these seemingly contrasting observations?

III. BALLISTIC MODEL FOR GRAINS EJECTION

We will attempt to analyse the evolution of the corona, representing an ensemble of grains, by using a simple ballistic model, defined at the scale of one grain constituent. The dimensions $\{D, H\}$ of the corona are thought to be approximately controlled by the coordinates $\{x, z\}$ of the “speediest” grain, with (the largest) initial velocity $\{v_{x0}, v_{z0}\}$ at the initial position $\{D(0), H(0)\}$ and following a ballistic trajectory. This hints at one grain submitted to its own weight but not any other interaction force, *e.g.* inter-grains interactions. In this case, the temporal evolutions of D and H are expected to follow the equations:

$$H(t) = v_{z0}t - gt^2/2 + H(0); \quad (1)$$

$$D(t) = D(0) + 2v_{x0}t. \quad (2)$$

In section II, experiments have shown us that the corona of the ejected grains is axisymmetrical with straight edges, *i.e.* has a trapezium shape of height H , maximal width D and constant angle Θ , so that its minimal width D_0 is equal to $D - 2H/\tan\Theta$. Using the previous equations (1) and (2) for H and D give for D_0 the relation $D(0) - 2H(0)/\tan\Theta + gt^2/\tan\Theta + 2v_{x0}t(1 - \tan\theta_0/\tan\Theta)$, with $\tan\theta_0 = v_{z0}/v_{x0}$. In the case where $\Theta = \theta_0$, as it will be discussed later, this leads to :

$$D_0(t) = D_0(0) + gt^2/\tan\Theta, \quad (3)$$

with $D_0(0) = D(0) - 2H(0)/\tan\Theta$.

For each experiment, $H(t)$ and $D(t)$ are fitted by eqs. (1) and (2) with two free parameters: v_{z0} and $H(0)$ for $H(t)$, and v_{x0} and $D(0)$ for $D(t)$. Then coefficients of eq. (3) for $D_0(t)$ are deduced. The velocities v_{z0} and v_{x0} , extracted from the evolution of the corona, are characteristic of the process of grains ejection induced by the impact, and allow for the computation of the characteristic angle of ejection θ_0 according to:

$$\tan\theta_0 = v_{z0}/v_{x0}. \quad (4)$$

Fig. 7 shows the rescaled height (a), top (b) and bottom (c) diameters of the corona, by using the fit parameters, for the 65 experiments with different dropping heights

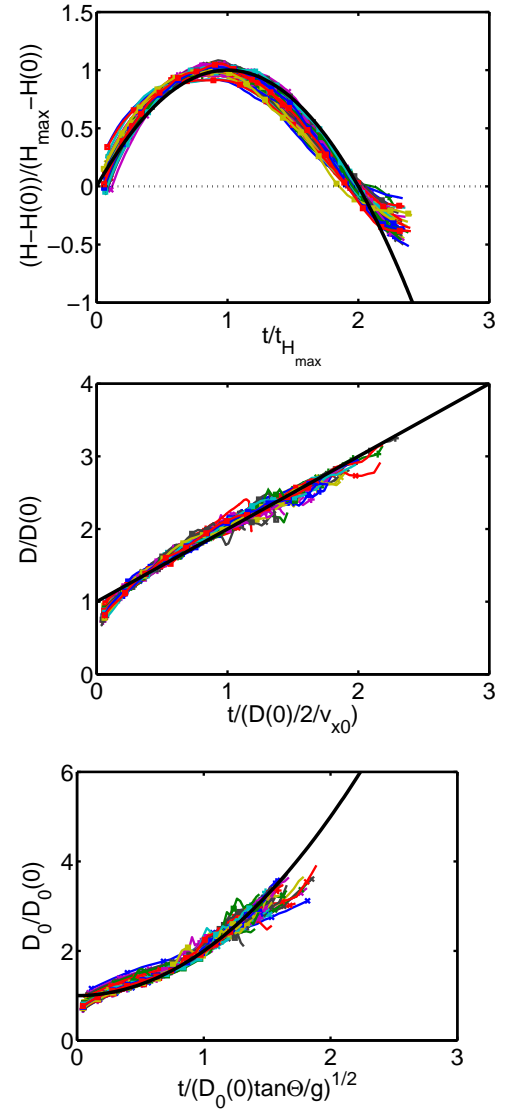


FIG. 7: Rescaled data of heights $(H - H(0))/(H_{max} - H(0))$, top and bottom diameters $D/D(0)$ and $D_0/D_0(0)$ as a function of rescaled time $t/t_{H_{max}}$, $t/(D(0)/2/v_{x0})$ and $t/\sqrt{D_0(0)\tan\Theta/g}$ for all of the 65 experiments, with four different beads and different dropping heights.

and different impacting spheres. Experimental data are rescaled according to the following equations:

$$\frac{H(t) - H(0)}{H_{max} - H(0)} = 2 \left(\frac{t}{t_{H_{max}}} \right) - \left(\frac{t}{t_{H_{max}}} \right)^2; \quad (5)$$

$$\frac{D(t)}{D(0)} = 1 + \frac{t}{D(0)/(2v_{x0})}; \quad (6)$$

$$\frac{D_0(t)}{D_0(0)} = 1 + \left(\frac{t}{\sqrt{D_0(0)\tan\Theta/g}} \right)^2. \quad (7)$$

The quantities H_{max} and $t_{H_{max}}$ are related to $H(0)$ and

v_{z0} through the following relations:

$$H_{max} = v_{z0}^2/(2g) + H(0) ; \quad (8)$$

$$t_{H_{max}} = v_{z0}/g. \quad (9)$$

We clearly see that when rescaled, $H(t)$ in Fig. 7a, $D(t)$ in Fig. 7b and $D_0(t)$ in Fig. 7c, collapse for all experiments, corresponding to different dropping heights and different impacting spheres. These collapses confirm that the evolutions of height is of parabola-type, of the top diameter is linear with time and of the bottom diameter is quadratic. The characteristic time-scales τ_H , τ_D and τ_{D_0} , of the evolutions of H , D and D_0 have different expressions, respectively:

- $\tau_H = v_{z0}/g$,
- $\tau_D = D(0)/(2v_{x0})$ and
- $\tau_{D_0} = \sqrt{D_0(0) \tan \Theta / g}$,

but are approximately equal: $\tau_{D_0} \simeq 1.1\tau_D \simeq 1.5\tau_H$.

Whereas the horizontal position of ejection $D(0)$ is obviously attributed to steric hindrance between grains and the impacting bead, the non-zero altitude of ejection $H(0)$ may be related to the apparent swelling of the granular free surface, visible on the transient and slight increase of the height of the corona base H_0 , just after the impact. This is corroborated by the proportionality between the initial corona height $H(0)$ and the typical values of the corona base H_0 . When the impactor starts to penetrate in the granular target, neighbouring grains (the same volume than the bead), have to move towards the free granular surface, resulting in a global vertical displacement of this later.

All these results suggest to propose the following scenario for grains ejection: grains are ejected instantaneously in the same direction -with the same ejection angle θ with the horizontal-, but with any distribution of velocities. In this case, at each time, all grains align along a straight line, forming the corona wall of angle θ with the horizontal, as sketched in Fig. 8a. The velocity of the corona wall is equal to $gt/\tan\theta$, predicting a quadratic spreading of the wall and giving eq. (3) for the evolution of the minimal diameter D_0 . The size of the corona is obviously given by the trajectory of the speediest grain, leading to the ballistic eqs. (1)-(2) for the evolutions of its height H and its top diameter D . The slope angle of the corona wall Θ , the angle of ejection θ_0 and the angle present in the corona wall velocity are equal. If grains are ejected within a finite time δt instead of instantaneously, with decreasing velocities defining thus a velocity distribution, but still in the constant direction θ , the slope angle Θ of the corona wall decreases slightly at very first times, but then remains essentially constant as a function of time, with $\Theta \leq \theta$, as shown in Fig. 8b, for $\delta t = 5$ ms and $\theta = 53^\circ$. Three laws for the temporal decrease of the grains ejection velocity v (linear, quadratic and exponential) have been plotted with $v(0) = 1000$ mm/s.

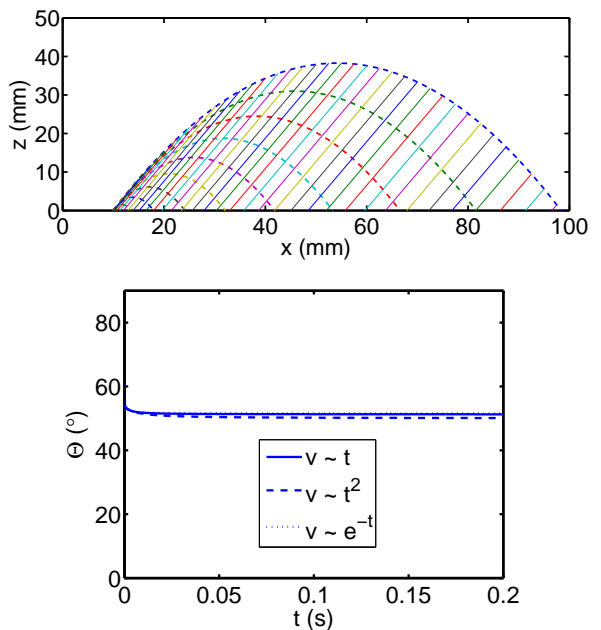


FIG. 8: a) Ballistic model for grains ejection: grains are ejected instantaneously in the same direction of angle θ with the horizontal, with different velocity amplitudes, which trajectories are drawn in dashed lines. In this case, at each time grains align along a straight line, forming the corona edge, drawn in continuous lines, of angle θ , and of velocity $gt/\tan\theta$. b) Temporal evolution of the angle Θ of the corona edge, if grains are ejected within a finite time $\delta t = 5$ ms in the direction $\theta_0 = 53^\circ$, with a linear, quadratic or exponential decrease of ejection velocity with $v(0) = 1000$ mm/s.

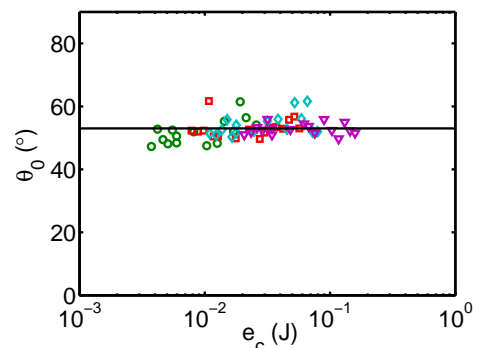


FIG. 9: Variations of the characteristic angle of ejection θ_0 with the impact energy e_c , for the 65 experiments (same symbols as in Fig. 6).

This scenario for grains ejection is supported by the well description of the corona dimensions as a function of time by eqs. (1)-(2)-(3) or rescaled eqs. (5)-(6)-(7), and especially by the quantitative comparison of the different angles obtained by different means. First, the slope angle Θ of the corona wall has been directly measured and shown to be constant as a function of time (Fig. 4d): $\langle \Theta \rangle \simeq 56^\circ$. Second, the angle of ejection θ_0 , computed from eq. (4),

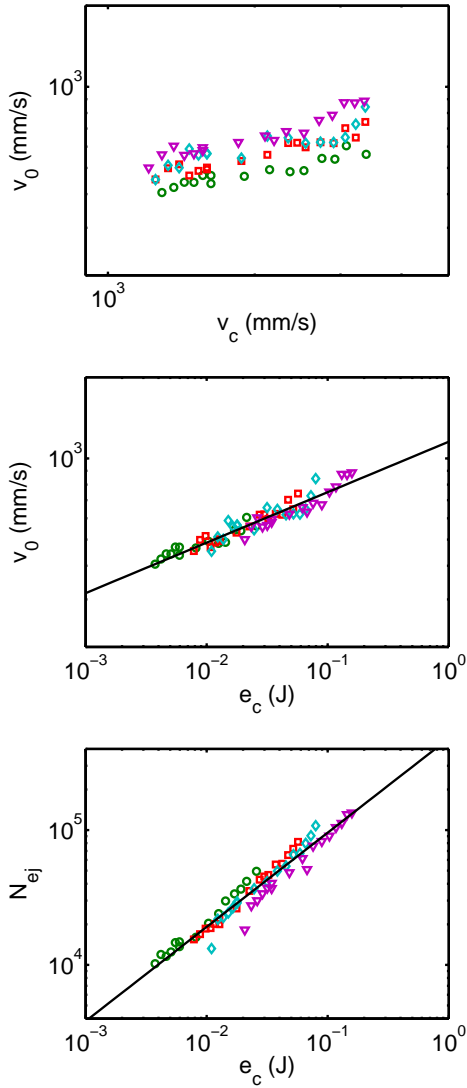


FIG. 10: Variations of some ejection parameters as a function of some impact parameters: a) $v_0(v_c)$, b) $v_0(e_c)$ and the best power law fit eq. (10), c) $N_{ej}(e_c)$ and the best power law fit eq. (12), for all experiments (same symbols as in Fig. 6).

is constant among all experiments and equal to the wall angle: $\theta_0 \simeq 53^\circ \simeq \Theta$. We have checked that these angles are robustly constant for all experiments and do not depend on any impact parameter, as shown by the clear absence of any correlation of θ_0 with the impact energy e_c in Fig. 9. Note that the simple ejection model presented here is quasi-instantaneous, in contrast with the one in [26].

To summarize, except at the time of impact, when a slight global displacement of the granular surface layer occurs, the geometrical parameters of the corona of the ejected grains are well described by considering the present simple ballistic model, that does not appeal to any inter-grains interactions, and thus despite the seemingly collective motion in the form of the corona.

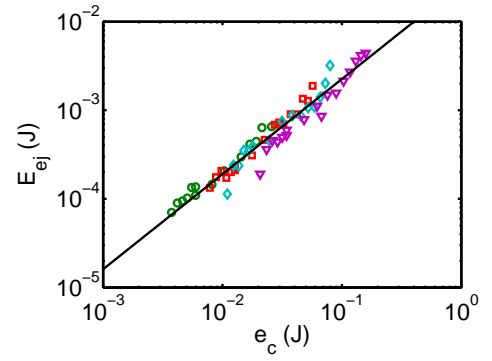


FIG. 11: Energy distributed to ejecta E_{ej} as a function of impact energy e_c . This allows to define an effective coefficient of restitution, constant when impact energy and impactor radius is varied (same symbols as in Fig. 6).

Despite the lack of direct measurements of grains velocity, we deduced a characteristic ejection velocity $v_0 = \sqrt{v_{z0}^2 + v_{x0}^2}$ from geometric measurements. The typical values of v_0 increase only by a factor of 2 (between 400 mm/s and 800 mm/s), when the impact velocity v_c increases by a factor of 3 (between 1000 mm/s and 3000 mm/s). Fig. 10a shows the slow increase of v_0 with v_c , and its dependence on the impacting sphere, meaning that v_c is not the relevant parameter to account for the variations of v_0 . Whereas neither impact velocity v_c nor impact momentum mv_c does not describe well the variations of v_0 , the impact energy e_c do, as shown by Fig. 10b in log-log scales, with the best power law fit:

$$v_0 \simeq 1.2 \cdot 10^3 e_c^{0.19}. \quad (10)$$

The impact energy of the impacting sphere appears to be the relevant parameter for the description of the variations of ejection properties, as well as for the crater size scaling laws, studied by [2, 5]. Note that the prefactor has not simple units, but eq. (10) can be better understood by considering the kinetic energy transmitted to the ejected grains at time of impact. In section II, we wrote that the characteristic number of ejected grains N_{ej} could be estimated from the total apparent surface of all of the ejected grains. Assuming that the whole real surface of the corona (in 3d) is composed of grains (compacity of approximately 1) and the corona wall thickness is approximately of 1 grain, this gives:

$$N_{ej} = A_{tot max}/r^2. \quad (11)$$

The number of ejected grains N_{ej} is plotted in Fig. 10c in log-log scales. We see that all the experiments made with 4 different spheres collapse when plotted as a function of impact energy e_c . N_{ej} increases with e_c according to the best power law fit:

$$N_{ej} \simeq 4.8 \cdot 10^5 e_c^{0.70}. \quad (12)$$

These observations can be compared with the experiments [27, 28] on the impact of one bead on a granular target composed of the same beads ($\rho_s/\rho_g = 1$,

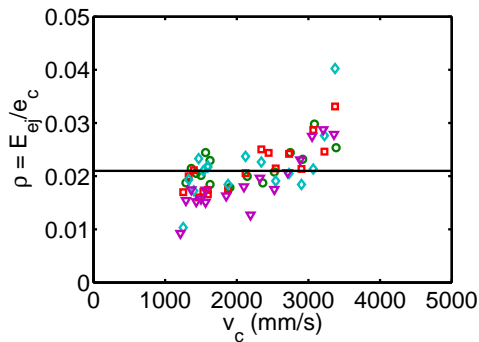


FIG. 12: Coefficient of restitution $\rho = E_{ej}/e_c$ characterizing the energy balance between the impacting sphere and ejected grains, as a function of impact velocity v_c (same symbols as in Fig. 6).

$R/r = 1$). Whereas the typical ejection velocity do not change a lot with impact energy, the number of ejected grains do. A similar result holds here: v_0 slowly increases and N_{ej} increases more strongly with e_c . We can now estimate the kinetic energy transmitted to the ejected grains as $E_{ej} \simeq mN_{ej}v_0^2/2$. Fig. 11 shows E_{ej} as a function of e_c in log-log scales, showing again that the influence of impact parameters on ejection properties is encoded properly in the parameter e_c . The best power law fit gives:

$$E_{ej} \simeq 2.7 \cdot 10^{-2} e_c^{1.07}, \quad (13)$$

that is approximately a linear relation, with a non-dimensionalized prefactor. This surprising and unexpected result allows to define a coefficient of restitution $\rho = E_{ej}/e_c$, characterizing the energy balance between the impacting sphere and ejected grains, that appears to be constant and estimated to $2.7 \cdot 10^{-2}$. Even a finer examination of ρ among all experiments, as shown in Fig. 12 where ρ is plotted as a function of impact velocity v_c (as usually done), confirms its constant value.

IV. DISCUSSION.

The dynamics of grains ejection due to an impacting sphere on a granular material has been experimentally

investigated through the time evolution of the corona formed by the ejected grains, in terms of its geometrical evolution. Whereas the dimensions of the corona - its height, top and bottom diameters - change with time, the angle formed by its edge with the horizontal granular surface remains constant during the ejection process. All these geometrical properties are well described by a simple ballistic model, suggesting that grains are (quasi-)instantaneously ejected at time of impact in a constant direction.

This direction appears to be constant when varying the dropping height of the impacting sphere and its radius, and equal to 56° . This independence and this value are the same as observed both in the case of high speed impacts, for which experiments of sphere/sand impacts [21] and simulations of sphere/spheres impacts [23] found values between 40° and 60° ; and in the case of low-speed impact of a sphere with identical spheres, for which experiments found on average 60° [27, 31]. However in the later case, the ejection angles are widely distributed between 0° and 180° . By contrast, the typical ejection velocities and number of ejected grains change when varying experimental parameters. As qualitatively observed in [20], more energetic is the impact and more grains are ejected. Moreover these are ejected with higher velocities, even if the later dependence with impact energy is lower than the former. These observations hold again for sphere/same spheres impact experiments [27]

By varying some experimental parameters, it has been shown that the relevant parameter to describe the variations of ejection properties is the impact energy, as well as for the crater size scaling laws studied by [2, 5]. The energy of the ejected grains is finally evaluated and allows for the calculation of an effective coefficient of restitution characterizing the complex collision process between the impacting sphere and the fine granular target. An important result is that the effective restitution coefficient is constant when varying the control parameters, estimated to $2.7 \cdot 10^{-2}$. This allows to discuss the transfer of energy between the impacting bead and the different processes happened upon impact: penetration of the bead, ejection of grains, excavation of the crater. Whereas a few fraction (of the order of 1%) of the initial energy is transmitted to grain through their ejection, only a tiny fraction (of the order of 0.1%) is required to excavate the crater according to [5].

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