Experimental study of the collision process of a grain on a two-dimensional granular bed

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(Received 28 January 2000)

We report an experimental study on the collision of a bead on a two-dimensional hexagonal granular packing. This collision process is of crucial importance in aeolian transport of grains. We have investigated the kinematic properties of the incident bead before and after the collision, and the resulting deformation of the packing. A typical collision is characterized by the rebound of the impacting bead and the ejection of a few beads of the packing. We have shown that the properties of the rebound bead depend weakly on the impact speed and that the rebound process involves only a few bead layers of the packing. On the contrary, the ejection mechanism depends strongly on the impact speed. In particular, it is found that the number of ejected grains increases with the impact speed whereas the most likely value of their energy is practically independent of the impact speed. Furthermore, we have given evidences that the ejection process involves a great number of packing layers and therefore is extremely sensitive to the height of the packing. For small packing heights, one observes additional ejected grains which can be interpreted as being produced by the reflection of the shock wave on the bottom of the pile.

PACS number(s): 45.70.−n, 62.20.−x, 81.05.Rm

I. INTRODUCTION

Flows of granular materials occur in a lot of industrial processes involving transport of grains or powders and also in natural phenomena. One of the major problems in granular flows is to model correctly the collisions between grains. The collision processes are of paramount importance because they are responsible for the transfer and dissipation of energy in granular flows (see, for example, Ref. [1]). The understanding of collision processes is therefore crucial in order to develop numerical and theoretical studies in granular flows. The bead–bead collision is now fairly well understood [2] but collisions involving more than two particles are still an open problem. Only a few experiments have been carried out to investigate such problems. The collision of a granular column on a solid plane has been explored recently in order to study the mechanisms of momentum transfer in granular media [3,4]. The collision of a bead on an assembly of beads has not retained much attention among physics community although it has many implications in geomorphological processes which involve aeolian transport of grains. Indeed, in the transport of grains over granular surfaces (as sand deserts) subjected to wind blow, the collisions between the granular bed and grains in motion play a very important role. In particular, the transport of sand by saltation—where the grains move by successive jumps along the granular surface, alternatively bouncing on the bed and being accelerated by the wind—depends crucially on the impact process between the saltating grains and the sand bed.

Our purpose is to focus on the collision of a grain on a granular bed in the context of aeolian sand transport. First of all, we would like to recall the main lines of the mechanisms of aeolian transport. According to Bagnold [5], there are two main modes[1] of transport: saltation evoked above and reptation. Under the impact of the saltating grains, some grains of the granular bed can be ejected. These ejected grains generally of low energy are creeping or rolling over short distances. Some of these reptating grains, if their launch velocity is high enough, can enter the saltation cloud after a few rebounds. In the initial period after the wind set in, the promotion of reptating grains in the saltation cloud is usually much greater than the trapping of the saltating grains by the bed so that the density of saltating grains increases drastically. As a result, the wind velocity is reduced at the bed surface and the saltating grains are less accelerated by the wind. The ejected grains are therefore less energetic and less grains are promoted to the saltation cloud. The saltation cloud finally reaches a state of equilibrium with the wind where the number of saltating is in average constant. In the ''equilibrium state'' of saltation, the promotion rate of reptating grains in the saltation cloud is exactly balanced by the probability of the saltating grains to be caught up by the bed surface. This picture of aeolian transport has been confirmed by several authors (see [6]). Some models incorporating the coupling between the bed and the saltation curtain have been proposed to describe this self-regulatory process [7,8]. In particular, it has been shown that the collision process is determinant: the energy involved in the collision is used for the reemission of the saltating grain and also for the ejection of low energy grains. In addition, numerical simulations have given evidences that the shear stress exerted by the wind on the bed is inefficient to eject grains [6]. In other words, the direct entrainment of the grains by the wind is negligible in the equilibrium state of saltation, only the impacts of the saltating grains are able to eject grains from the bed.

Our objective here is to analyze carefully the way by which the energy of the impacting grain is redistributed, respectively, to the rebound grain and the granular bed. For that purpose, we have carried out an experiment which simply consists of throwing a bead onto a packing of beads. Several experimental and numerical studies have been al-

[1]In fact, on should add a third mode of transport which is suspension and concerns only very small grains ($<100\ \mu$m).

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ready performed on this collision process. It is thus worth presenting succinctly the main outcomes known from the earlier studies. Rumpel [9] proposed in 1985 a collision model in a two-dimensional geometry. The angle of rebound is not 90° as Bagnold [5] thought but much less, roughly 50° with respect to the horizontal. His model predicts an amplification mechanism of the vertical velocity as the angle of impact decreases, a compulsory ingredient for the maintenance of the saltation process. Willets and Rice [10] have observed the collision phenomena *in situ*, by high speed film, in a wind tunnel experiment. In a typical collision, the incident grain hits the surface at small angles of 10°–16° and bounces with an angle between 20° and 40°. A few grains are ejected from the bed with a speed of one order of magnitude less than the impacting grain. The angle of ejection is found to be of about 50° with large fluctuations. Mitha *et al.* [11] studied directly the collision of a steel bead on a three-dimensional packing of steel beads. The phenomena was recorded through stroboscopic photography. Their results essentially confirm the previous studies and supports Rumpel's hypothesis about the amplification mechanism of the vertical speed at low angles. Ungar and Haff [12] proposed to summarize the outcomes of an impact event by means of a statistical function called the ''splash function.'' It is defined as the probability that a grain be ejected at a given launch velocity. Numerical studies of collisions on two-dimensional beds have been also developed using molecular dynamics algorithms (see works of Werner and Anderson [7,13]). The results—despite obtained in a two-dimensional geometry—show a good agreement with the experiments cited above.

In this context, we have developed an experiment to get a greater physical insight into this splash law. Our idea has been to consider a simple situation in order to control all the experimental parameters. We have therefore decided to confine ourselves to a two-dimensional geometry: a bead is thrown on a 2D ordered packing of single size beads. Although this experiment is two-dimensional, some of the results could be extrapolated to natural saltation since it has been seen that numerical 2D studies and 3D experiments gave rise qualitatively to very similar outcomes. The physical mechanisms for the redistribution of energy are expected to be similar in 2D and 3D. In this experimental study, we have investigated the influence of two parameters on the collision process, that is (i) the speed of the impacting grain and (ii) the height of the packing. (i) The influence of the impact speed on the collision is of great physical interest. Indeed, during the transient state of saltation, saltating grains explore different impact speeds before reaching a state of equilibrium with the wind. The dependence of the collision process on the impact speed can thus give us precious informations on the interaction between the wind and the saltation curtain. (ii) The second aspect we have dealt with is the influence of the height of the packing on the collision. It turns out that with our 2D geometry the variation of the packing height drastically changes the outcomes of the ejection process.

The paper is organized as follows. We present in the second section the experimental setup and the procedure used to analyze the pictures taken from the collision process. Then, in the third section, we report the properties of the rebound bead as a function of the impact speed and the packing height whereas Sec. IV is devoted to the analysis of the features of the ejected beads. Finally, we present conclusion and outlook in Sec. V.

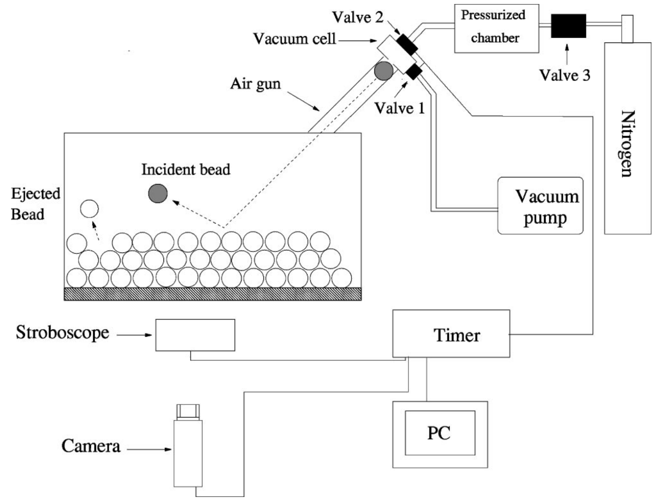

FIG. 1. Experimental setup.

II. EXPERIMENTAL SETUP AND IMAGE ANALYSIS

A. Experimental setup

We have used for the experiments spherical plastic beads. The diameter of these beads is 5.85 ± 0.04 mm and their mass is 0.195 g (the density is 1.86 g/cm^3). The experimental setup is sketched in Fig. 1. Grains are confined in a cell made of two vertical glass plates separated by a distance of 6.1 mm. The pile of grains lies on a bottom made of PVC. An air gun has been designed to throw grains on the pile. The air gun is composed of several parts: (i) a 15 cm long pipe used to guide the bead between the plates (lateral holes have been bored in order to avoid residual blow effects in the cell which could perturb the collision), (ii) a vacuum cell used to sustain the bead at the beginning of the pipe before the shot, (iii) a vacuum pump linked up to the vacuum cell via a valve (valve 1 in Fig. 1), and (iv) a pressurized chamber connected to the vacuum cell via a second valve (valve 2 in Fig. 1). The pressurized chamber is fed by a bottle of nitrogen under pressure. Finally, an electronic device coordinates the following successive operations: valve 1 is opened, vacuum is drawn in the vacuum cell in order to sustain the bead, valve 1 is shut, valve 2 is opened, the pressurized air enters the vacuum cell and propels the bead in the pipe.

The visualization of the collision is insured by a CCD video camera (which is used as a photo camera) coupled to a stroboscope which illuminates the scene of collision. A single picture is taken for each collision with a long exposure time of $\tau=0.2$ s. This time is found to be sufficient to catch the track of the impacting bead and the trajectories of the ejected beads.

B. Experimental conditions

The experiments have been performed with a hexagonal packing. The incident angle has been kept fixed to a value of 53° while (i) the impact speed and (ii) the packing height have been varied. (i) Following [11], the order of magnitude of the impact speed has been chosen according to the value

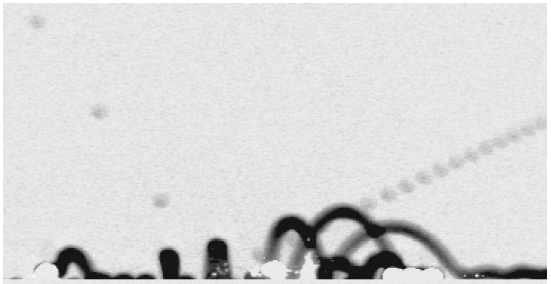

FIG. 2. Typical picture of a collision: the incident grain is coming from the left-hand side of the picture.

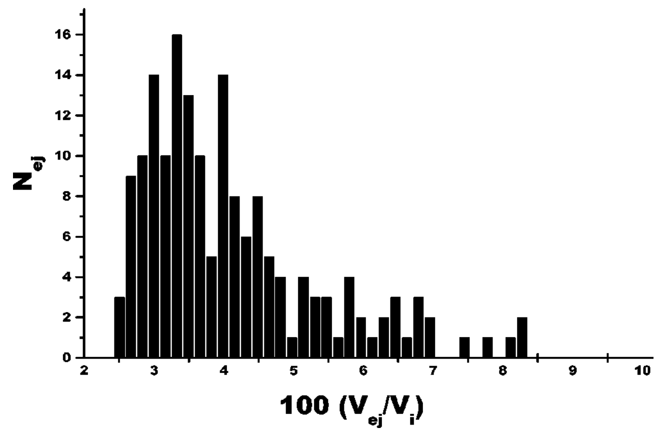

FIG. 3. An example of distribution: distribution of the modulus of the ejection speed V_{ej} of the ejectas. The ejection speed has been renormalized by the the impact speed V_i . N_{ej} stands for the number of ejected grains.

of the Froude number measured in typical natural conditions of saltation (the Froude number is defined as $\mathrm{Fr}=V_i^2/gd$ where V_i is the impact speed and d is the grain diameter). The typical size of sand grains in desert is of order of 200 μm and the saltating grains can reach speeds of about 5 m/s during sand storms. As a result, the Froude number is estimated to be of order of 10 000. Taking into account the grain size used in our experiment (about 6 mm), one gets impact speeds of order of 10 m/s if one desires to reach a Froude number close to that measured in the field. We have thus chosen impact speeds ranging from 6 to 22 m/s. The impact speed is changed by modifying the air pressure in the pressurized chamber. However, for a given air pressure, the resultant speed of the incident bead fluctuates a lot. This is mainly due to the fact that the axis of the air gun does not lie exactly in the plane formed by the glass plates of the cell. The bead, as it enters the cell, undergoes therefore lateral collisions and friction with the glass plates before acquiring a steady velocity. In other words, the incident bead looses some energy in the beginning of its motion between the plates in a way that is not predictable. As a consequence, the exact impact velocity is measured a *posteriori* on the pictures of the collision. (ii) The packing height has been varied from a few layers (i.e., 6) up to 36 layers.

A few important additional remarks follow. First, we should point out that before each collision the surface of the packing is made perfectly horizontal. This precaution is important since some studies have shown that disorder or defect at the surface could modify the splash function [13]. We stress also the fact that the geometrical order in the packing does not prevent the presence of a disorder in the contacts between the beads in the packing: this is unavoidable since a real sample of beads is always slightly polydisperse. Finally, it is important to point out the limitations of our experiment. We are not able to control the spin of the incident bead and the position of the impact point. Due to the lateral friction with the plates, the incident bead is rotating but the rotational energy is expected to be negligible in comparison with the translational energy. Concerning the the impact point, there is always an uncertainty about its exact location. This is due to the inherent dispersion of the incidence angle.

C. Image analysis

A typical collision between a bead and the granular packing is shown in Fig. 2. The stroboscope is working at a frequency of 500 Hz. For the range of impact speeds investigated, this frequency is in fact adequate to get distinct spots for the rebound bead and a continuous track for the ejected grains. The procedure of image analysis is as follows. For the incident bead, we extract two successive positions before the collision and two after the rebound. For the ejected grains, we extract six points of the trajectory and fit it by a parabola. The speeds of the ejected grains are so low that air friction is negligible. Furthermore, friction with the lateral glass plates is also found to be practically inexistent for the ejected grains. The presence of friction is detected when the trajectories deviate from parabolic shapes. For the great majority of the ejected grains, no deviation is observed. However, in the rare cases where friction is present, we fit only the beginning of the trajectory. From these data, we can easily obtain the parameters of the parabolas and deduce the launch velocities and locations of ejection of the grains. The grains whose hop height is very small (i.e., below 1.5 bead diameter) have not been taken into account in the statistics. These grains usually fall back to their initial position (see Fig. 2) and have not retained our attention.

For given values of the impact angle and of the packing height, about 200 collisions are performed with impact speeds ranging from 6 to 22 m/s. As seen before, the impact speed is determined *a posteriori* because there is no univocal relation between the pressure used and the speed of the incident bead. The collisions, after image analysis, are then sorted out according to the impact speed in different bins of 2 m/s width. The width of the bins have been chosen such that the number of collisions in each bin be sufficient to perform correct statistics. For 200 collisions, we get an average of 20 pictures per bin (which corresponds to about 100 ejected grains). From all collisions belonging to a specific bin, we can extract the distribution of the different quantities characterizing the ejected grains. For a given quantity we calculate the average value and estimate the dispersion from the variance of the distribution. Figure 3 shows a typical example of such distributions.

III. PROPERTIES OF THE REBOUND BEAD

As it has been observed by Mitha *et al.* [11], one can distinguish, in a typical collision, between the rebound particle and the ejected grains. The rebound bead is characterized by high speed in comparison with the ejected grains.

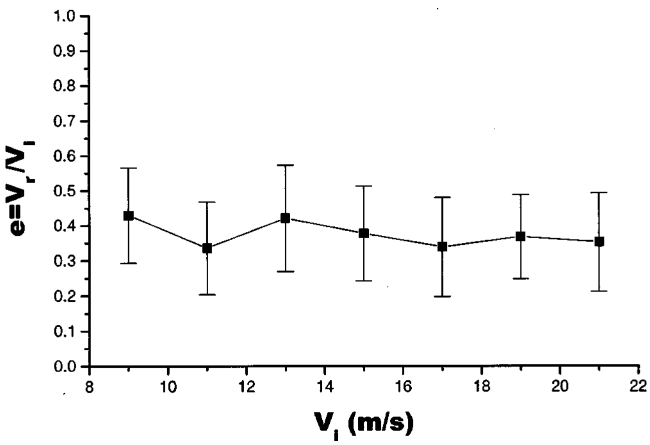

FIG. 4. Dependence of the restitution coefficient e on the impact speed V_i.

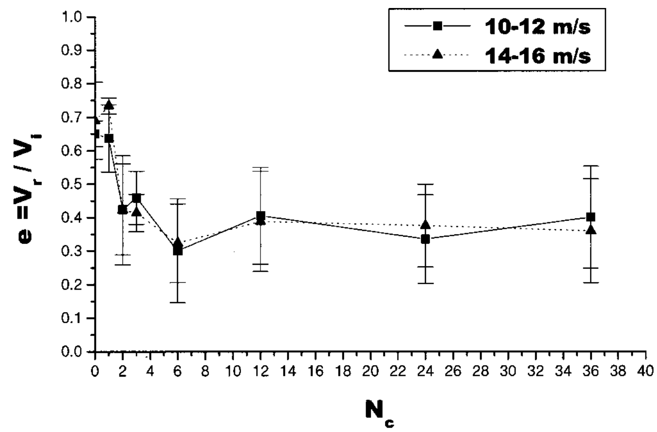

FIG. 5. Dependence of the restitution coefficient e on the packing height N_c for two different impact speeds.

The speed of the rebound bead, as to be shown below, is usually about one-third of the incident speed. We present here the main features of the rebound bead as we vary the impact speed and the packing height while the features of the ejected grains are exposed in next section.

A. Influence of the impact speed

We have performed here a set of experiments for a packing of 24 layers varying the impact speed from 6 to 22 m/s. The properties of the rebound bead are analyzed through the restitution coefficient of the packing and the angle of rebound. The results are summarized below.

Restitution coefficient: The coefficient of restitution defined as the ratio between the rebound and impact speed is found to be slightly decreasing as the impact speed gets higher (see Fig. 4). To calculate the average value of the restitution coefficient, we have not taken into consideration the collisions where the incident bead is trapped in the packing. The coefficient of restitution is 0.43 for impact speeds of 10–12 m/s and 0.35 for impact speeds of 20–22 m/s. One can note that the restitution coefficient is much smaller than that for a binary collision. As to be seen further, the direct collision of a bead upon PVC gives a restitution coefficient of order of 0.7. The collision process investigated here cannot clearly be considered as a binary collision. The energy of the incident bead can be dissipated either by the inelastic interactions between the beads of the packing or by the internal reorganization of the granular packing (essentially through a modification of the network of bead contacts). These two mechanisms are likely to occur. One should note however that even slightly inelastic interactions between the beads can lead to such high dissipation as it has been shown for the collision of a column of beads with a wall [14].

A few remarks should be added. First, the same evolution of the restitution coefficient with the impacting speed has been also observed by Willets and Rice [10] as well as by Anderson [6]. Second, it is worth noting that the amount of energy kept by the bouncing grain is about 20% of the impact energy whereas (as to be seen later) the total energy of the ejected grains represents less than 1% of the impact energy.

Angle of rebound: The angle of rebound is in average constant for all impact speeds and it is about 25°. However, one should note that there are large fluctuations of order of 20°. This large dispersion may be partially explained by the fact that the location of impact of the incident bead (with the target beads of the packing) is different at each shot. As said above, due to the inherent dispersion in impact angles which has been found to be of about 4°, it follows that the impact zone has a spatial extension of about five grains. We thus expect that all the possible positions of impact be explored (collision on the top of the target bead, collision between two target beads, etc.) This may explain the large fluctuations observed in the rebound angle.

Finally, it is worth noting that in some rare cases the incident bead is caught up by the granular packing. This happens when the incident bead impacts between two beads. Although the statistics of trapping is relatively poor, one can estimate the probability of capture to be of the order of a few percent. A more specific study is necessary if one desires to explore in details this process of capture, but it is beyond the scope of this paper.

B. Influence of the packing height

We have investigated the influence of the packing height on the properties of the rebound bead. We have varied the packing height from 0 up to 36 bead layers. The results presented below correspond to collisions performed at intermediate impact speeds (10–12 and 14–16 m/s). However, it is important to note that the observed features remain the same at higher or lower impact speed.

Restitution coefficient: In Fig. 5, we have plotted the restitution coefficient as a function of the packing height. One clearly sees that for packing heights ranging from 6 to 36 layers, the restitution coefficient is almost constant. We have also performed some experiments for packing heights smaller than 6 layers (3, 2, 1, and 0 layers) and we have found that the restitution coefficient increases from 0.3 (for 6 layers) to 0.65 (for a collision on the PVC bottom). From these results, one can conclude that the incident bead does not feel the presence of the bottom of the pile when the height of the packing is of 6 layers or more. It suggests that the incident bead interacts—through the contact network of the grains —only with the superficial layers of the packing. The critical number of layers involved in the rebound of the incident bead with the packing has not been determined accurately. One can only argue that it lies between 3 and 6 layers since we have not performed experiments for packing heights in between.

Angle of rebound: The angle of rebound is found to be almost constant (about 26°) for packing heights ranging from 6 up to 36 layers. This result confirms the fact that only a few layers (smaller than 6) are involved in the process of rebound. As the packing height is decreased below 6 layers, the angle of rebound increases. The angle of rebound goes up to 36° for a packing of 2 layers and reaches 49° for a rebound on the PVC bottom.

C. Conclusion

We have characterized the properties of the rebound bead according to the impact speed and the packing height. We have put forward several interesting features. The restitution coefficient is around 0.4 (it is roughly twice lower than that obtained in a bead to bead collision) and decreases weakly with the impact speed. The study of the influence of the packing height has revealed that the incident bead during the collision only feels the first layers of the packing (a maximum of 6 layers). The layers below have no significant influence on the rebound of the incident bead. These results can be interpreted by the fact that the interaction between the incident bead and the target bead(s) lasts a time smaller than that necessary for the shock wave to propagate down to 6 layers and to be reflected to the surface. Finally, we have noticed an important dispersion in the data probably because we do not control the location of the impact between the impacting bead and the target bead(s).

IV. PROPERTIES OF THE EJECTED GRAINS

We present here a detailed analysis of the properties of the ejected grains as a function of the impact speed and the packing height. We will see that the properties of the ejected grains are quite different from those of the rebound bead. Before going into details, we shall present first the general features of the ejected grains. The ejected grains are much less energetic than the rebound grain. Their launch velocity rarely overcomes 10% of the impact speed. The other salient feature of the ejected grains is that they can launch in both directions. Most of them are moving forward (with respect to the incident direction) but a non-negligible part is moving backward. It is worth noting that beads ejected from a point located in front of the impact position are jumping forward whereas those ejected from a point at the back are moving backward.

A. Influence of the impact speed

The results presented below have been extracted from a set of experiments performed with a packing of 24 layers varying the impact speed between 6 and 22 m/s.

Number of ejected grains: We have first investigated the number of ejected grains per impact as a functionof the impact speed (see Fig. 6). We have found that for impact speeds below 6 m/s, there are no ejected grains. There exists therefore a threshold velocity below which ejection is impossible. Above the threshold impact speed, some grains from the bed are ejected. One clearly sees in Fig. 6 that the number of ejected grains increases roughly linearly with the impact speed. This result confirms the numerical findings from [7]. Moreover this behavior has also been found in three-dimensional (3D) collision experiments [11].

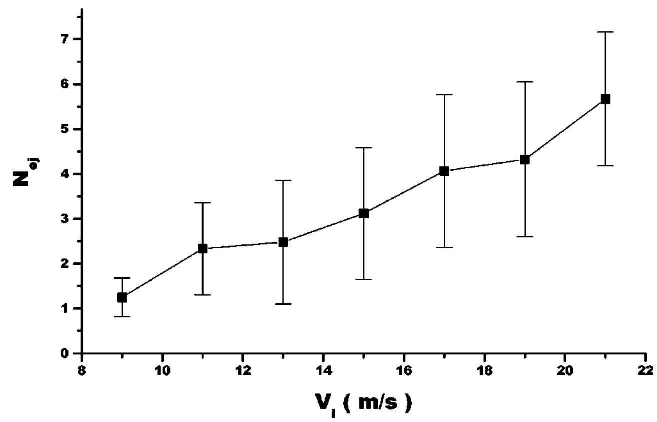

FIG. 6. Dependence of the number of ejected grains N_{ej} on the impact speed V_i.

Velocity and energy of the ejected grains: To analyze more carefully the properties of the ejected grains, we have plotted their energy distribution for three different impact speeds (see Fig. 7). Statistics have been established over all the ejected grains resulting from the collisions corresponding to a given impact speed. The energy distribution represents in a strict meaning the splash function of the collision process. The energy has been measured in terms of the maximum height reached by the ejected grains. This energy does not represent the total kinetic energy of the ejected grains but reflects only the vertical speed of ejection. In the context of saltation, the vertical speed of ejection is of crucial importance since it determines the amount of energy stocked by the grain during his jump. Indeed, as wind stress increases with height, the higher the grain is, the larger is the energy transmitted by the wind to the grain.

One can note that the majority of the ejected grains reach a height corresponding to 2–3 grain diameters whatever the

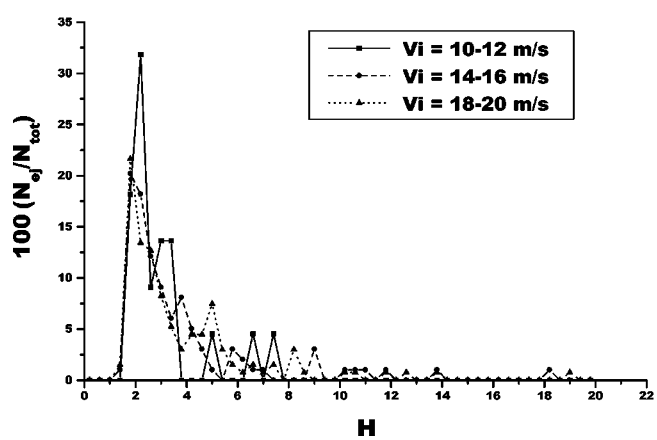

FIG. 7. Energy distribution of the ejected grains for different impact speeds. The energy is measured in terms of the maximal height H reached by the ejected grains. The number of grains N_{ej} has been normalized by the total number of ejected grains N_{tot} over all collisions performed at a given impact speed and H is measured in units of grain diameter.

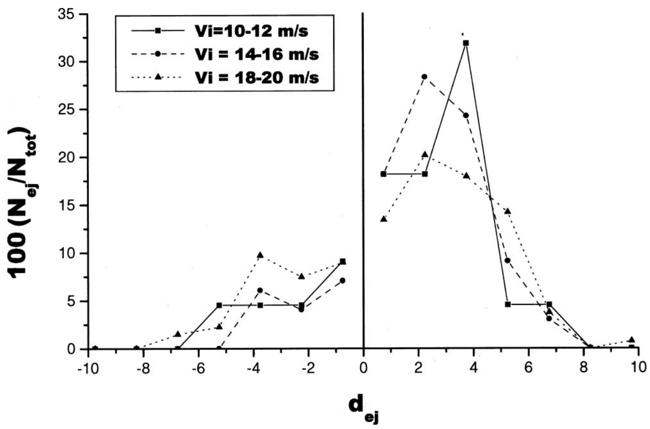

FIG. 8. Distribution of the ejection distance d_{ej} measured in units of grain diameter. The number of ejected grains N_{ej} has been normalized by the total number of ejectas N_{tot} over all collisions performed at a given impact speed.

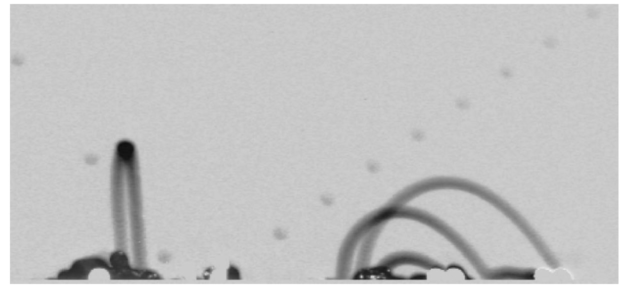

FIG. 9. An example of a collision showing ejectas taking off at a distance of about 10 grain diameters from the impact point.

impact speed. More than one-third of the total number of ejectas reach such a height for impact speeds of 10–12 m/s. Nevertheless the proportion of these ejectas of low energy decreases as the impact speed is increased. The proportion falls to one-fifth for impact speeds above 14–16 m/s. One can also note that as the impact speed increases, the probability to get high energy grains is increased. For impact speeds of 10–12 m/s, no ejected grains reach a height greater than 8 grain diameters whereas for impact speeds of 18–20 m/s, more than 10% of the ejectas go up to such a height or higher. We have also calculated from these distributions the evolution of the mean value of the vertical speed of the ejectas as a function of the impact speed and we have found a slight increase (from 0.55 to 0.65 m/s). The existence of the high energy ejectas at high impact speeds are responsible for this slight increase. However, as seen just above, the most likely value of the vertical velocity of ejection is independent of the impact speed.

We have also investigated the horizontal speed of ejection and have found no significant evolution with the impact speed. Its mean value fluctuates between 0.2 and 0.3 m/s which is less than one-half of the vertical speed of ejection.

Finally, we have calculated the total energy transmitted to the ejected grains by the impacting grain. We have noted that the total energy of the ejectas is increasing with impact speed. This is mainly caused by the increase of the number of ejected grains since the individual mean energy of the ejectas is increasing weakly with impact speed. The total energy of the ejected grains represents about 0.2% of the energy of the impacting grain for impact speeds of 10–12 m/s and about 0.8% for impact speeds of 20–22 m/s.

Angle of ejection: Concerning the mean value of the angle of ejection, we do not find any significant evolution with the impact speed. The mean ejected angle is about 67° with a dispersion of 8° for forward ejectas and 100° with a dispersion of 4° for backward ejectas.

Location of ejection: We define the distance of ejection as the distance between the impact point and the location of take-off of the ejected grain. We have first extracted from our data the distribution of the ejection distance for three different impact speeds (see Fig. 8). One should point out that for impact speeds of 10–12 m/s the statistics is rather poor since the number of ejected grains per impact is low (the statistics has been done over a total of 22 ejected grains). Second, concerning the grains ejected close to the impact point, it is difficult (due to the imprecision of the measurements) to determine whether they are ejected backward or forward and it may happen that forward ejectas are counted as backward ejectas (and vice versa). Therefore the points of the curve in Fig. 8, close to the impact position, should be analyzed with caution. Let us first analyze the forward ejectas. One can note that the width of the zone concerned by ejection is of the order of 8 grains and does not seem to vary significantly with impact speed. The ejection distance of the majority of the grains is about 3–4 grains whatever the impact speed. Concerning the backward ejectas, there is no clear peaks. The region concerned by the ejection is comprised between 1 and 4 grain diameters from the impact point. We have also calculated the mean value of the ejection distance as a function of the impact speed and have found no significant evolution for forward and backward ejected grains.

As seen above, the ejected grains come essentially from a local region surrounding the impact point of the collision. However, in some cases, grains can be ejected from a location which is far from the impact point. This may suggest that there exist two different modes of ejection. The part of the energy of the impacting bead which is transferred to the granular bed can either be dissipated in a localized region in the neighborhood of the impact point or propagate over long distances along the lines of contact between grains. In the first case, only local grains are dislodged and a crater is formed around the impact point. In the second case, the shock wave seems to propagate over long distances and reemerges rather far from the impact point producing ejection of few grains (see Fig. 9 for an illustration of this phenomenon).

Correlations between the distance of ejection and the speed of ejection: For a more accurate analysis of the energy transfer between the impacting grain and the granular bed, it can be instructive to study correlations between the energy of the ejected grains and the location of ejection. We have examined the dependence of the vertical speed of the ejected grains as a function of their location of ejection. In Fig. 10 is plotted the vertical speed of ejection against the location of ejection at a given impact speed of 18–20 m/s as observed from 30 collisions. No correlation is found between the two quantities. In other words, at a given distance from the impact position, one can find ejected grains with all the possible values of energy with equal probabilities. Finally, concerning

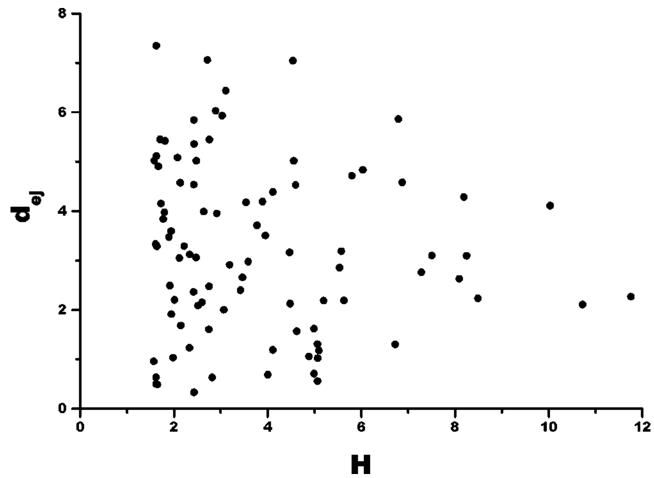

FIG. 10. Ejection distance d_{ej} against the maximal height reached H by the ejectas at a given impact speed of 18–20 m/s as observed from 30 collisions. d_{ej} and H are measured in units of grain diameter.

the horizontal speed of ejection, no variation with the location of ejection is noticed.

Correlations between the distance of ejection and the angle of ejection: Although there is no correlation between the distance of ejection and the speed of ejection, the angle of ejection is found to decrease as the ejection distance gets larger. The angle of ejection is 75° for an ejection distance of one grain size and 57° for an ejection distance of 7 grain sizes. For the backward ejectas, the angle of ejection is about 100° whatever the ejection distance.

B. Influence of the packing height

The packing height turns out to be a very important parameter for the properties of the ejected grains. During the collision process, a part of the energy of the incident grain is transferred in the granular bed and scattered partly among ejected grains. The number of layers of the granular packing which is involved in this transfer is not known. Our purpose is to get an evaluation of the depth over which the shock wave generated by the collision penetrates into the packing. It has been already observed by numerical simulations that the shock wave could reflect on the bottom of the pile and give rise to additional ejected grains [7]. We have investigated here the collision process for four different packing heights (6, 12, 24, and 36 layers).

Number of ejected grains: We have noted that the packing height alters the mean number of ejected grains per collision. Indeed, we find that the number of ejectas decreases as the packing height increases, as it can be seen in Fig. 11. In this figure is plotted the mean number of ejected grains per collision as a function of the impact speed for three packing heights. The effect of the packing height is spectacular at high impact speed (i.e., 18–20 m/s). One gets 10 ejectas for a packing of 6 layers and 4 ejectas for a packing of 36 layers whereas at low impact speed the packing height has a very tiny effect on the number of ejectas. This result can be explained as follows. The presence of the bottom of the pile enhances the number of ejectas only if the impact energy is high enough so that the shock wave generated by the collision is able to propagate down to the bottom of the pile and

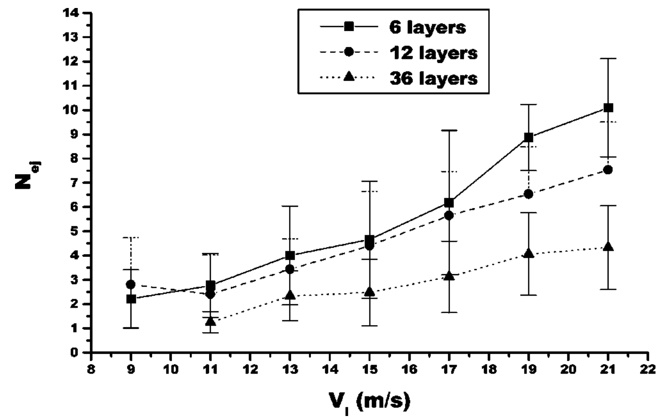

FIG. 11. Evolution of the number of ejected grains N_{ej} with the impact speed V_i for different packing heights.

to go back up to the superficial layer after reflection on the bottom. At low impact speed (i.e., 10–12 m/s), the amplitude of the shock wave after reflection on the bottom is not strong enough to produce additional ejectas even for small packing heights. On the contrary, at high impact speed (i.e., 18–20 m/s), the reflected shock wave is able to create additional ejectas for packing heights up to 24 layers. These features are clearly illustrated in Fig. 12 which displays the number of ejectas as a function of the height of the packing for different impact speeds. One can conclude here that the presence of the bottom enhances the number of ejectas when the packing height is smaller than a critical height which depends on the impact speed. This critical height is less than 6 layers at low impact speeds, about 12 layers at intermediate speeds, and of 24 layers at high speeds.

Velocity and energy of the ejected grains: To have a more accurate description of the additional ejectas due to the presence of the bottom, we have plotted the energy distribution of the ejectas for different packing heights at a given impact speed of 18–20 m/s (see Fig. 13). We recall that the energy of ejection is measured in terms of the maximal height reached by the ejected grain.

One can note that the additional ejected grains essentially reinforce the peak located at an energy corresponding to a height of 2–3 grain diameters. They are therefore of low energy. The tail of the distribution at high energy is also affected by the height of the pile: the probability to get high

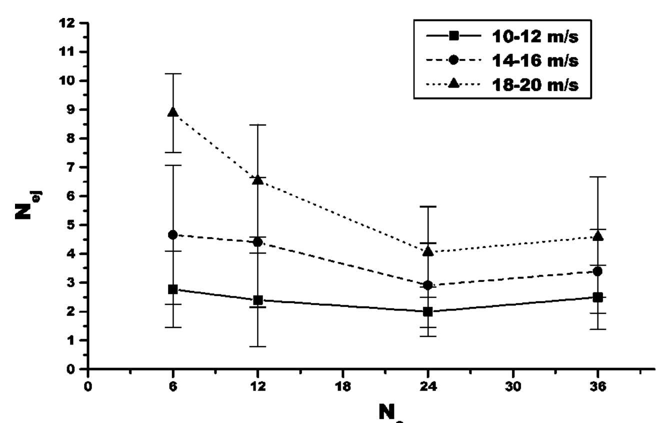

FIG. 12. Dependence of the number of ejectas N_{ej} on the packing height N_c for different impact speeds V_i.

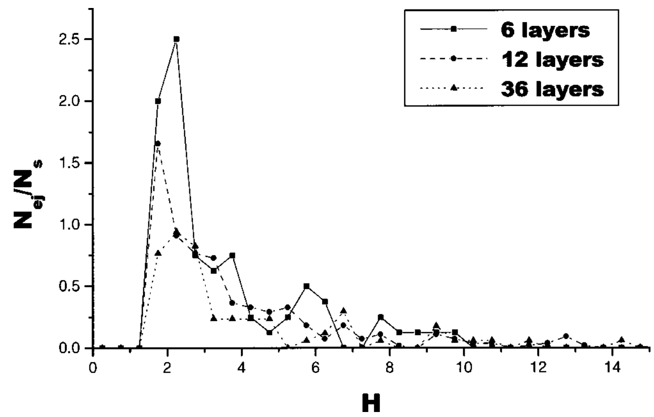

FIG. 13. Energy distribution of the ejected grains different packing heights N_c at impact speeds of 18–20 m/s. The energy is again measured in terms of the maximal height H reached by the ejected grains. The number of ejected grains N_{ej} has been normalized by the total number of collisions N_s performed at a given packing height and H is measured in units of grain diameter.

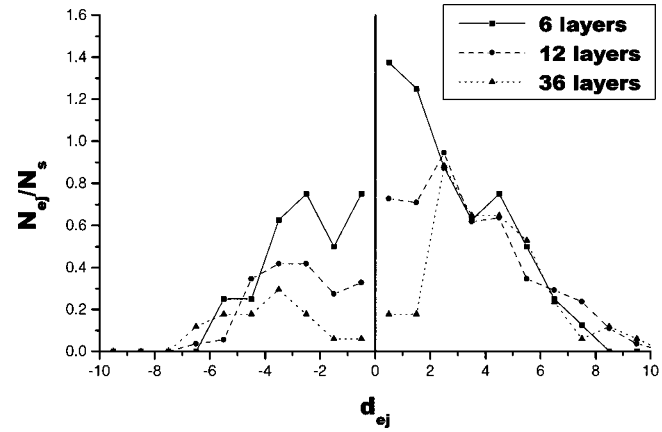

FIG. 15. Distribution of the ejection distance d_{ej} for different packing heights at impact speeds of 18–20 m/s. The number of ejected grains N_{ej} has been normalized by the total number of collisions N_s performed at a given packing height.

energy ejectas is increased for packings of low heights. As a result, the effect of the bottom is to create additional ejectas. One should finally add that the mean value of the vertical ejection speed seems to be independent of the packing height.

We have also analyzed the mean horizontal speed of ejection as a function of the packing height. As the packing height increases from 6 layers to 36 layers, the average horizontal speed of an ejecta is doubled for forward ejectas from 0.10–0.15 m/s to around 0.3 m/s and does vary significantly for the backward ejectas (the value fluctuates around 0.10–0.12 m/s).

Angle of ejection: The mean ejection angle of the forward ejectas is decreasing as packing height is increased and is almost constant for the backward ejectas (see Fig. 14). The mean ejection angle of the forward ejectas is about of 65° for 36 layers and of 80° for 6 layers whereas the backward ejectas take off at angle of 100° whatever the packing height. The conclusion is twofold. First, the forward ejectas for small packing heights take off with a steeper angle. Second, the ejection angle of the backward ejectas does not seem to be affected by the height of the pile.

Location of ejection: In Fig. 15, we have plotted the distribution of ejection distance for different packing heights at impact speeds of 18–20 m/s. One sees that for small packing heights the peak of the distribution (for the forward ejectas as well as for the backward ones) is closer from the impact point. In other words, the ejection near the impact point is enhanced at low packing height. As a result, the mean value of the ejection distance increases with the packing height. This rise is more marked for backward ejectas. The above feature can be explained partially by geometrical properties. We have seen that some of the ejectas observed for small packing heights are generated by the reflection of the shock wave on the bottom of the pile. The smaller is the packing height, the higher is the probability that the shock wave after reflection reemerges close to the impact point. A small packing height would prevent the shock wave to explore all the different possible paths in the pile. We thus expect the distance of ejection to be smaller as the height of the pile decreases.

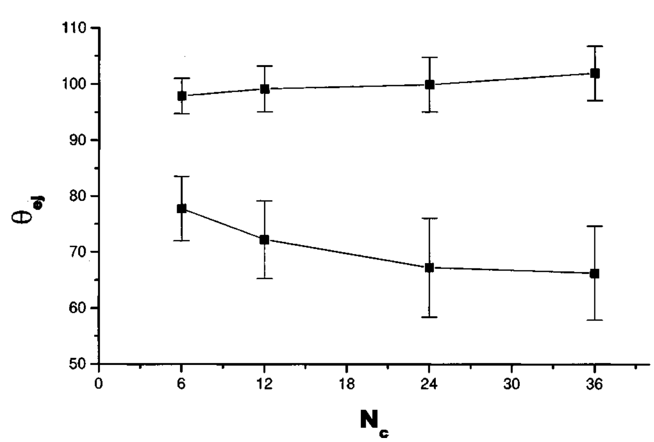

FIG. 14. Evolution of the ejection angle θ_{ej} with the packing height N_c at impact speeds of 18–20 m/s.

Finally, it is worth noting that the proportion of backward ejectas strikingly increases as the packing height decreases. They represent 25% of the total number of ejectas for a packing of 36 layers and 42% for a packing of 6 layers. For small packing heights, the grains seem to be ejected much more symmetrically with respect to the location of the collision impact.

C. Discussion

The above experiments have put forward some important features. They have shown that the impact speed is a crucial parameter in the ejection process. (i) They have revealed the existence of a threshold impact velocity below which the ejection of grains is forbidden. For impact speeds below 4–6 m/s, the impact bead bounces over the granular pile without producing ejectas. (ii) Above the threshold impact velocity, some grains of the upper layer of the packing are ejected. The ejected grains preferentially move forward but a non-negligible part lift off backward. (iii) Most of the ejected grains are weakly energetic in comparison to the rebound grain. Only a few of them are highly energetic and their proportion increases with the impact speed. (iv) An increase of the impact speed rises the number of ejectas but the most likely value of the vertical ejection velocity is surprisingly independent of the impact speed. (v) The spatial extension of the ejection zone is of order of 8–10 grains on both sides of the impact point. The most likely value of the ejection distance is of about 3–4 grains and does vary significantly with the impact speeds investigated so far.

Experiments have also shown that the packing height has an important effect on the ejection process. (vi) As the packing height is decreased, the number of ejected grains is enhanced if the impact speed is high enough. This enhancement is interpreted as to be due to the reflection of the shock wave on the bottom of the pile. (vii) Moreover, a variation of the packing height alter the features of the ejected grains. In particular, the smaller is the packing height, the smaller is the ejection distance and the steeper is the angle of ejection.

Some of these above features can be explained by geometrical arguments considering the propagation of the shock wave created by the impact throughout the packing of beads. However, if one desires to have a clear picture of the mechanisms of the shock wave propagation in the packing, it is strongly needed to develop a numerical or analytical model. This is one of our future preoccupation.

Finally, we shall say a few words about the implications of our results for the aeolian transport of sand. First, one shall say that our experiment is not relevant to all situations of sand transport. In particular, for strong winds, the whole bed surface appears to be creeping so that the saltating grains collide with a moving layer and not with a static bed. Therefore, our experiment is expected to be pertinent solely for saltation under moderate wind conditions. In this case, the density of creeping grains is sufficiently low so that the saltating grains essentially collide with immobile grains of the sand bed. Second, we have dealt with a single collision process and it is clear that in real situations there are many collisions and possible resulting collective effects. Despite these restrictions, one can draw from our experimental results some interesting information about sand transport. In the context of saltation transport, the existence of high energy ejectas is very important even if their proportion is small. Indeed, these grains have the possibility to reach the saltation cloud. In the equilibrium state of saltation, the coupling between the population of reptating grains and that in saltation is in fact compulsory to compensate the proportion of saltating grains being caught up by the surface. If there is a local increase of the saltating grains due to fluctuations, the wind speed will drop. The speed of the saltating grains therefore decreases and the probability to get high energy ejectas is then lowered as it has been shown above. As a result, the number of ejectas capable of entering the saltation cloud decreases and the density of saltating grains drops back to its equilibrium value. This feedback mechanism that controls the amount of sand in transit is very important in the aeolian sand transport.

V. CONCLUSION AND OUTLOOK

We have presented in this work the results of an experiment about the collision of a bead onto a packing of beads. We confined ourselves to the simplest geometry where the packing is two dimensional. The beads used are of plastic and have been arranged in a hexagonal packing. Although our experiment is rather far from the real situation of aeolian sand transport, we have confirmed the main features of the impact model of saltation. We have shown that the energy of the impact bead is redistributed, respectively, to the rebound bead and to the ejected grains. We have investigated the influence of two parameters, the impact speed and the packing height. The main results are the following. (i) The process of rebound of the incident bead is rather independent of impact speed and only a few layers of the packing (below 6) are involved in that process. (ii) The features of the ejected grains depend on the impact speed and the process of ejection involves a great number of bead layers in the packing. In particular, the number of ejected grains increases with the impact speed and decreases with the packing height.

Our experiment is a first step to gain insight in the mechanism about how a shock wave can propagate throughout a granular packing. In the view of our results, we are aware that there is a strong need of a theoretical model to interpret the outcome of our experiments on sound basis. There are also some other pertinent parameters to be varied. For example, we expect that the presence of a slight disorder in the packing can greatly alter the outcome of the collision. In the context of the aeolian transport, it would also be interesting to study the influence of the incidence angle. In particular, as the angle of impact decreases, we expect the number of ejectas to increase importantly and the collision to involve only the superficial layers of the granular packing.

Finally, although the 2D geometry is somewhat artificial, we are convinced that our experiment is a very good instrument to test theoretical attempts to model the splash law. Parallel to this, it also constitutes an indirect way to obtain information about the sound propagation in a granular media through the properties of the ejectas. Of course, the natural next step will be to investigate the collision process on a 3D packing. In a 3D geometry, the packing of grains is naturally disordered and, consequently, the length of the chains of contacts [15] in the packing along which the shock wave can propagate is shorter. This may alter the outcome of the collision process.

ACKNOWLEDGMENTS

We thank Stephane Bourles and Hervé Orain for the design of the setup. We are also indebted to Patrick Chasles for the electronic part of the setup and the automation of the experimental procedure.

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