

## Displacement field visualization of particle beds after slow impacts using diffusing wave spectroscopy

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For low-velocity impacts into granular materials, most of the impact energy is absorbed by the soil and not transferred into the ejected material. That raises the question of how large the volume of material is that is actually affected by the impact, that is, by subsurface material displacement or compaction. Here we use diffusing wave spectroscopy to detect the changes in local soil packing structure before, during, and after an impact has occurred. We clearly identify a (half)-spherical volume where particles are rearranged, with a radius substantially larger than the diameter of the impact crater. We also show that the size of the rearrangement zone follows similar scaling laws as the crater size.

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### I. INTRODUCTION

Low-velocity impacts into granular media have been the subject of a number of laboratory experiments [1–12]. Most of these experiments typically use cameras to record the surface during an impact to quantify effects like the amount of ejecta created or impactor and/or rebound velocities. The drawback of this approach is that it is not immediately clear how the impact affects the structure of the soil itself and how exactly the material below the surface is disturbed. Analyzing the inside of a nontransparent target medium remains a challenge.

For sticking dust beds, where craters do not collapse, postimpact analysis is possible, and x-ray tomography has been performed [13]. In Refs. [14–16], x-ray radiography is used to study the response of a very loose granular bed by directly observing the change in the target medium structure during an impact, but calibrating the response to even obtain a proper packing fraction for a dense granular material is nontrivial [17,18].

An impact also causes waves to spread into the particle bed, and grains become displaced. This displacement is largest in the area where the projectile comes into direct contact with the target and decreases away from the impact site. Up to a certain distance, this displacement is inelastic. Therefore, low-velocity impacts into granular materials have the potential to affect the material even if the impact is of such a low energy that no cratering occurs.

One consequence can be (impact) tapping-induced compaction [19,20]. Furthermore, granular packings are often of very low packing fraction and thus can be easily disturbed;

that is, avalanches can be triggered. Knowing the radius within which an impact event can create perturbations that might lead to larger-scale rearrangements is therefore important [21,22]. Even small displacements are important for global material parameters such as rigidity [23], especially under low confining pressures, for example, in low gravity [24].

While it is straightforward to measure strong displacement of material (i.e., crater excavation, ejecta), identifying microscopic changes to the local packing structure is not. The aim of the work we report here is to show that Diffusing Wave Spectroscopy (DWS) [25] is a suitable method to visualize the area and/or volume affected by a slow impact as well as to determine the extent of this volume down to a level of minute submicron displacements. For this purpose, we carry out experiments where glass spheres of two different sizes impact into a sample cell filled with fine basalt particles.

### II. DIFFUSING WAVE SPECTROSCOPY

DWS is a technique that allows the visualization of displacements in disordered media such as foams [26], colloidal suspensions [27,28], and granular materials [25,29–31]. The main advantage of this technique is its sensitivity to particle movements on very short length scales [27].

The experimental setup and evaluation of this work are based on the multispeckle method [32] as described in Ref. [25]. The soil sample is illuminated by an expanded laser beam, which results in a speckle pattern. This speckle pattern is highly sensitive to small changes in the arrangement of the individual grains making up the sample material; that is, even small changes to the particles' relative positions will create large changes in the observed speckle pattern.

In the so-called backscattering geometry, the laser light enters the sample on one side, is scattered several times, and leaves the sample again on the same side. The scattering medium is characterized by its transport mean free length  $l^*$ . On their way through the sample, the photons examine a volume on average on the order of  $l^{*3}$ . Hence, the scattering

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process limits the spatial resolution of the method to the transport mean free length. In practice, the speckle pattern is recorded with a digital camera, creating an image of  $X$  by  $Y$  pixels in size. Depending on the spatial resolution as determined by  $l^*$ , these pixels are then grouped into *Metapixels*.

Areas where displacements occur can be visualized in a correlation plot comparing corresponding metapixels from images taken at different times  $t$ . The intensity correlation function  $G_l$  is calculated for the corresponding  $l$ -th metapixel between the initial frame at  $t = 0$  and one of the following frames as

$$G_l = \frac{\langle I_{ll} \cdot I_{il} \rangle - \langle I_{ll} \rangle \langle I_{il} \rangle}{\sqrt{\langle I_{ll}^2 \rangle - \langle I_{ll} \rangle^2} \cdot \sqrt{\langle I_{il}^2 \rangle - \langle I_{il} \rangle^2}}. \quad (1)$$

Each frame is represented by its intensities (brightness)  $I_{il}$ , where  $i$  denotes the frame number. Here we denote the  $i$ -th frame as occurring  $(i - 1) \cdot \Delta t$  after the initial frame ( $i = 1$ ) with  $\Delta t$  as the inverse of the frame rate.  $\langle I \rangle$  is the average of the intensity  $I$  over all pixels inside the  $l$ -th metapixel.  $\langle I_{ll} \cdot I_{il} \rangle$  denotes the average of the elementwise multiplication of respective pixels within the two metapixels. Each frame consists of  $j$  metapixels in the  $x$ -direction and  $k$  metapixels in the  $y$ -direction. In one frame, there are  $j \times k$  metapixels and there are  $N$  frames in total.  $G_l$  is calculated for each of the  $j \times k$  metapixels in each of the  $N - 1$  frames. At  $t = 0$  s, the sample is considered undeformed. The deformation develops with time and therefore can be seen as a decrease in the correlation value. A correlation value close to 1 indicates that no or very weak displacement of scattering particles has taken place. The correlation values can then be plotted spatially resolved, building a correlation map where each correlation value is a measure of the deformation occurring in a cell of  $(l^*)^3$  size.

### III. EXPERIMENT

Figure 1 presents a sketch of the experimental setup. The soil sample is placed in a cell consisting of two glass plates glued on a three-sided, 1-cm-thick frame made of PET with the dimensions of 10 cm  $\times$  10 cm on the outside and 9 cm  $\times$  9.5 cm on the inside. This way, the cell stays open on the upper side. The front glass plate of the cell is transparent, and the back glass plate is painted white. The glass plates, having dimensions of 10 cm  $\times$  10 cm  $\times$  0.2 cm, are made of flat glass. Irregularly shaped basalt grains are used as a target soil sample (for the size distribution, see Fig. 2), and the sample cell is filled up to a height of 4.6 cm, thus giving a total sample volume of 9.0  $\times$  1.0  $\times$  4.6 cm<sup>3</sup>. The size distribution of the target material is measured with a laser diffraction-based particle size analyzer, the “Malvern Mastersizer 3000.” The given size distribution is volume-based, which means that the volume of the particles found in a certain diameter range is the stated percentage of the entire tested sample volume. After the material is filled into the sample cell, the cell is repeatedly tapped until an approximately flat surface level was observed. In this way, we achieve bulk densities of  $\rho_{t,1} = 1580$  kg m<sup>-3</sup> and  $\rho_{t,2} = 1668$  kg m<sup>-3</sup> for the experiments with impactors of diameters  $d_{p,1}$  and  $d_{p,2}$ , respectively. The packing densities of the respective samples are 0.53 and 0.56. Since

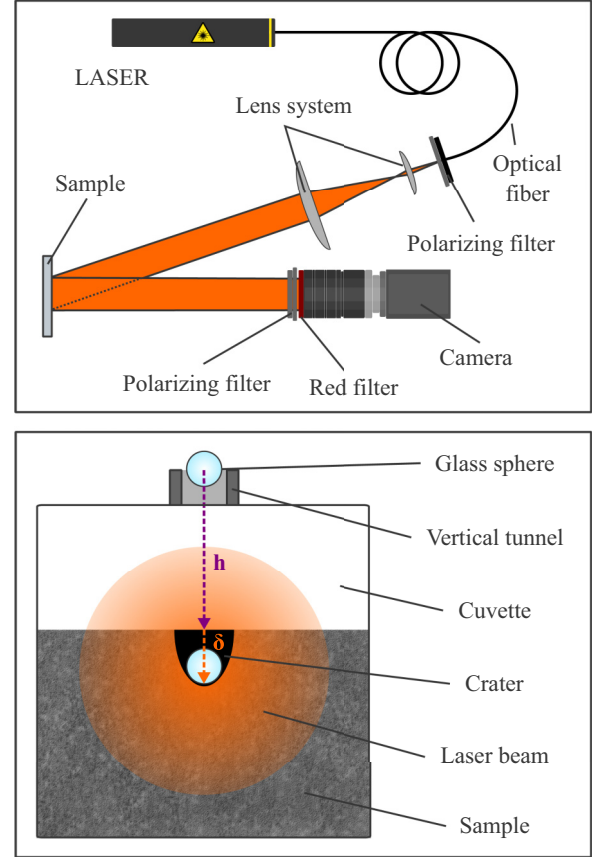


FIG. 1. Sketch of the experimental setup. Top: View from above. Bottom: Front view of the cuvette.

the sample is not monodisperse, the mean particle diameter of  $d = 58 \pm 33 \mu\text{m}$  is used for all calculations. Soda-lime glass spheres with  $\rho_p = 2460$  kg m<sup>-3</sup> of  $d_{p,1} = 900 \pm 100 \mu\text{m}$  and  $d_{p,2} = 460 \pm 70 \mu\text{m}$  diameter are used as projectiles. At the upper edge of the front glass plate of the cell, at a distance of approximately 6 cm above the sample surface, a 10 mm  $\times$  10 mm  $\times$  1 mm-sized rectangular tube is attached, which serves as a vertical guide from which the glass spheres are dropped onto the sample.

A 2-mW 632.8-nm He-Ne-Laser (Melles Griot) is expanded by a set of two lenses (focal lengths 10.8 mm and 300 mm).

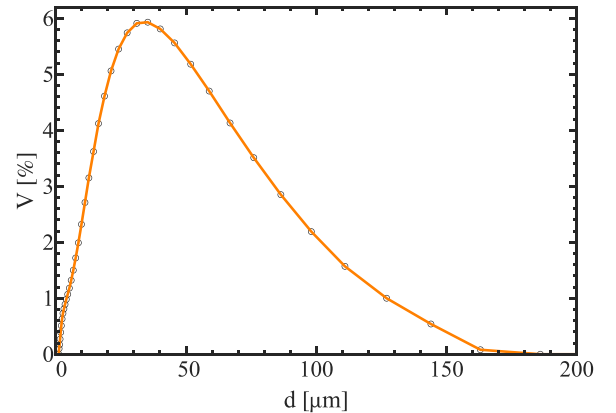


FIG. 2. Volume size distribution of the used sample.

The expanded laser beam is directed onto the cell so that in horizontal direction ( $x$ ), the center of the beam lies centrally between the frame sides, and in the vertical direction ( $y$ ), the sample surface is in the center of the speckle pattern. The camera is focused not on the sample, but on the speckle pattern in the front plane of the front glass plate. The intensity of the laser and the light sensitivity of the camera sensor determine the frame rate at which a sufficiently intense signal from the speckle pattern can be recorded. Here, for all experiments, the frame rate is  $10 \text{ s}^{-1}$ , which limits the time resolution of the examined process to 100 ms.

The experiment is performed as follows. The glass sphere is held above the vertical guide and then released, allowing it to fall onto the dust bed. The sphere is dropped as closely as possible to the back plane of the glass plate facing the camera, but with a sufficient distance so that the crater does not touch the wall. For repeating experiments, the bed is not always reset, but the next point of impact is chosen to be away from the previous impact point. We check that there is no systematic trend depending on the experiment progression. In addition to the DWS measurement, an image is taken from directly above the sample to record the actual impact position and the diameter of the crater created.

#### DWS analysis

Figure 3(a) shows an example of a processed frame, as it is used in the DWS analysis. Specifically, Fig. 3(a) presents an image of a speckle pattern obtained in backscatter geometry. The image is cropped to the region of interest, and for this purpose, the figure is also contrast-enhanced for better visibility. The bright patches, visible in the image, are clusters of speckles. When focusing in on a cluster of speckles, for example, into the area covered by the red rectangle, one can see single speckles, as shown in the yellow rectangle in Fig. 3(c). Each single speckle has an average size of about 2 pixels. Figure 3(b) shows Fig. 3(a) divided in metapixels of  $20 \text{ Px} \times 20 \text{ Px}$  size. Each metapixel corresponds to an absolute area of  $200 \pm 4 \mu\text{m} \times 200 \pm 4 \mu\text{m}$ . It should also be noted that Fig. 3(b) depicts the average gray value within each metapixel and not the gray value of each individual pixel.

Of practical consideration is the actual choice of the size  $dx$  of the metapixels. Concerning the spatial resolution, the optimal metapixel size contains image information from an area of size  $l^{*2}$  on the sample [33]. If the metapixel size is set too small, metapixels might not contain enough speckles for averaging. If the metapixel size selected is too big, they are averaging over too large an area of the image. Considering the magnification of the optics  $\gamma = 0.5$  and pixel size of the camera sensor  $l_p = 4.8 \mu\text{m}$ , the best choice for the metapixel size is [33]:

$$dx = \gamma \cdot \frac{l^*}{l_p}. \quad (2)$$

For basaltic dust surrounded by air  $l^*$  as a function of the scattering particles, diameter  $d$  can be estimated as [29]:

$$l^* \approx 3.4d. \quad (3)$$

Note that in our case, this is just an approximation, as our sample is nontransparent, but absorption does not enter the

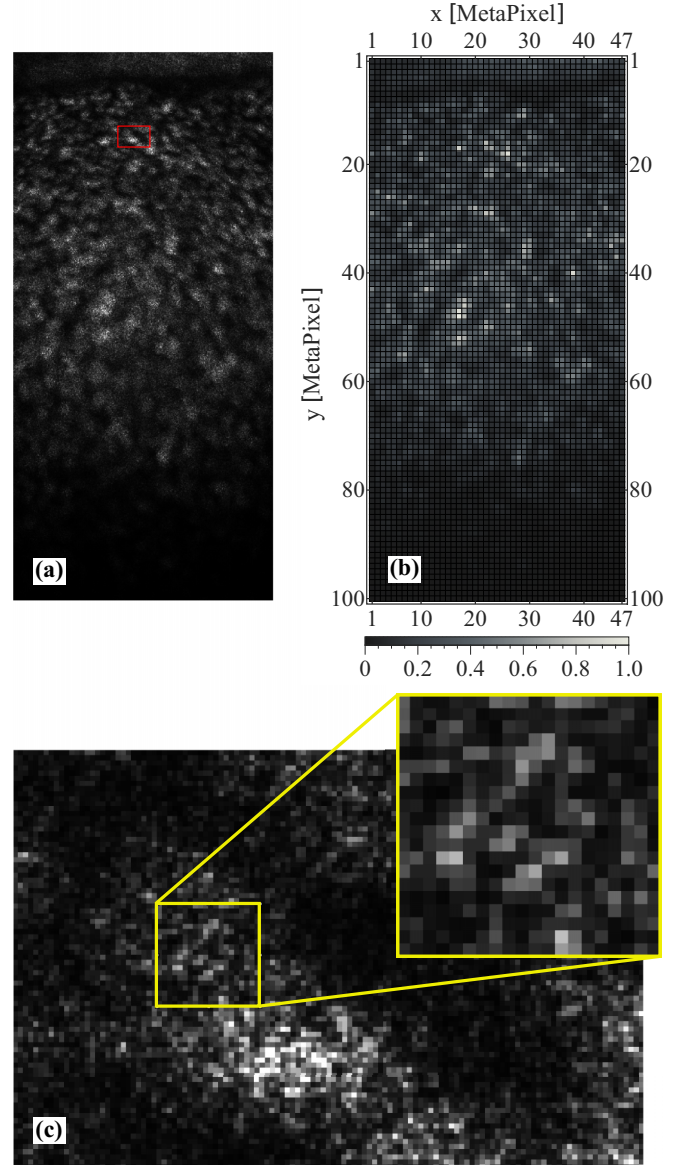


FIG. 3. (a) Backscatter image, contrast enhanced for better visibility. Note that the visible bright patches are clusters of speckles. The red rectangle encircles an area shown in (c). (b) The image from (a) divided in metapixels of  $20 \text{ Px}$  size. In (b), the intensity now symbolizes the mean intensity inside a metapixel. The mean intensity values are scaled so that the maximum mean intensity has a value of 1. This scaling is not part of the Diffusing Wave Spectroscopy analysis and is done for better visibility purposes only. (c) A magnified portion of the area marked by the red rectangle in (a). The further enlarged yellow marked area corresponds to the metapixel size ( $20 \text{ Px}$ ). The average size of a speckle is  $2 \text{ Px}$ .

calculation of  $l^*$ . We checked that our results are not sensitive to small variations in metapixel size.

Besides the scattered intensity, the measured intensity also includes stray light and dark noise from the camera. In our work, the influence of stray light is reduced by a narrow band filter matching the wavelength of the laser. The camera noise is reduced by dark-frame correction, and artifacts are removed by flat-field correction.

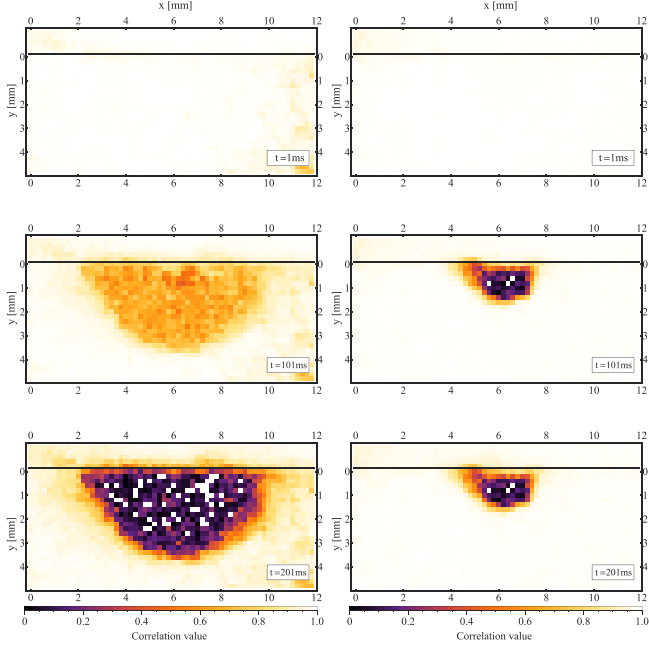


FIG. 4. Uncorrected correlation plots comparing the initial state of the packing to the time immediately before impact (top row), during impact (middle row), and after impact (bottom row) for the large (left column) and small impactor (right column). The black line at  $y = 0$  indicates the surface. The colors indicate the mean time correlation of each metapixel. The larger impactor creates a larger area of effect. White pixels inside the affected area indicate that the particle displacement was larger than can be quantified.

We observe that the impact process and resulting deformation of the granular bed are fast compared with the time resolution of our DWS camera. In the recorded video, the impact takes place during 2 to 3 frames, that is, within 200 ms to 300 ms. So for the analysis, we consider three images that we correlate with an image before. Since the first preimpact image has no signal from the impact, we use its correlation as a reference for the postimpact correlation, as detailed later. Uncorrected correlation plots for these three frames and for experiments with both impactor sizes are shown in Fig. 4. In the first image, where no impact can be seen, the correlation stays close to 1 (Fig. 4, top left). In the second frame, the correlation in the affected area drops slightly (Fig. 4, middle left). This means that this frame lies within the propagation time of the impactor in the target medium. In the third frame, after the impact is complete, we observe an area where the correlation is close to 0—the area affected by the impact. Inside this area, we also observe that some metapixels have a correlation value of 1 (Fig. 4, bottom left). In this case, the particles in the area corresponding to the respective metapixel have been displaced more than can be quantified by our DWS setup.

We observe a sharp drop from the highly affected area to the nonaffected area. The affected area is semielliptical (and approximately semicircular) in shape, where semicircular means that half of the width is almost equal to its depth. To quantify the width and depth of the affected area, we reduce the correlation data. We first take the inverted difference of the postimpact and preimpact correlation maps. We then apply

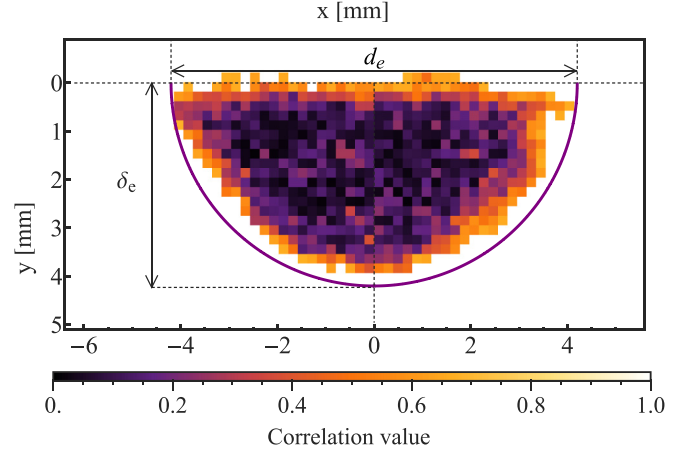


FIG. 5. Front view of the area affected by the impacting sphere obtained from a Diffusing Wave Spectroscopy measurement shown in Fig. 4, left panel. The colors indicate the correlation inside the metapixels. The plotted values are corrected for uneven illumination, and a threshold was applied to isolate the area disturbed by the impact. Purple: semiellipse with semiminor axis  $\delta_e$  and semimajor axis  $d_e/2$ . The surface is indicated by the dashed black line at  $y = 0$ .

a threshold and set larger values to 1. As a threshold, we use the minimum value of the preimpact correlation, which approximately filters out all noise. Figure 5 shows an image of the obtained array for the measurement shown in the left panel of Fig. 4. To obtain the width  $d_e$  of the disturbance zone, we take the maximum number of metapixels per row having a value smaller than 1.  $d_e$  is then converted to millimeters. To obtain the depth  $\delta_e$  of the disturbance area, we take the maximum number of metapixels per column with a value smaller than 1. To make this clear, Fig. 5 shows an ellipse having the depth  $\delta_e$  as the semiminor axis and the half width  $d_e/2$  as the semimajor axis, with the impact point as the origin of the ellipse encompassing the affected area.

#### IV. IMPACTS

When a sphere with diameter  $d_p$  and density  $\rho_p$  is dropped from height  $h$  onto a target body (in this work, a dust bed) of density  $\rho_t$ , it can produce a crater depending on impact velocity as determined by drop height. Depending on the impactors' and the targets' characteristics, such as the diameter, density, and shape of the projectile or the gravity or density of the target, there are several outcomes in the morphology of the formed crater, ranging from simple bowl-shaped craters to more complex crater forms. In a shallow impact, the impactor only partly intrudes into the target, so that the depth of the crater is smaller or comparable with the radius of the impactor. The impactor can also submerge deeper into the target and sometimes even be buried deep inside the target, forming a transient crater and causing the collapse of the material in the vicinity of the impact point.

In the search for the solution to the crater formation problem and for analyzing data from impact events or impact experiments, a  $\Pi$ -groups approach is often used [34]. Based on a dimensional analysis, four dimensionless groups are defined. The first is the cratering efficiency, which is the ratio of

the crater target mass and the impactor mass, or in terms of the crater diameter  $d_c$ ,

$$\Pi_D = d_c \left( \frac{\rho_t}{m_p} \right)^{\frac{1}{3}}, \quad (4)$$

with  $m_p$  as the mass of the projectile. The second group  $\Pi_2$  is the gravity-scaled size parameter, calculated by dividing the product of the surface gravity  $g$  and the impactor radius by the squared velocity  $v_{imp}$  of the impactor:

$$\Pi_2 = \frac{gd_p}{2v_{imp}^2}. \quad (5)$$

$\Pi_3$  is the dimensionless strength parameter, obtained as the ratio between the target material strength  $Y$  and the product of the target bulk density and squared impactor velocity:

$$\Pi_3 = \frac{Y}{\rho_t v_{imp}^2}. \quad (6)$$

The last group,  $\Pi_4$ , is the ratio of the target bulk density to the impactor density:

$$\Pi_4 = \frac{\rho_t}{\rho_p}. \quad (7)$$

The impact process can be dominated by one of two regimes, the “strength” or the “gravity” regime, or can be a combination of both. On one side, the crater is produced in the strength regime if the target material strength is large compared with the factor  $g\rho_t d_p$ . If, on the other side,  $Y$  is much smaller than  $g\rho_t d_p$ , the impact happens in the gravity regime.

In the context of hypervelocity impacts, a scaling law has been found to describe the crater size dependence on impact energy  $E$  [34,35]. In the gravity regime, the crater width is proportional to  $E^{1/4}$ . In the strength regime, however,  $d_c$  is proportional to  $E^{1/3}$ . For slower impacts, it was shown [1] that  $d_c \sim E^{1/4}$  applies. So, while there is a good understanding of crater sizes, we are not aware of any such theory for the extent of the affected volume, that is, subsurface material that is not excavated but displaced or compacted in low-velocity impacts.

### A. Impactor size

For the first set of experiments, the drop height was kept constant and, assuming free fall, this resulted in an impact velocity of  $v_{impact} = 1.15 \pm 0.04 \frac{m}{s}$ .

In Fig. 6 (left panel), a crater generated by a glass sphere of  $900 \pm 100 \mu m$  diameter can be seen. The impactor is buried completely. Figure 6 (right panel) shows the sample surface hit by smaller glass spheres. Compared with the larger impactors, the smaller spheres only partially penetrate the sample and therefore can be seen on the surface.

The crater diameter was measured in two directions perpendicular to each other (longest extent) in the  $x$ - and  $z$ -direction along the sample surface (as indicated in Fig. 6). The  $y$ -direction is the vertical and orthogonal to the surface of the sample. If the impacting sphere is buried completely, the crater diameter is measured as the visible final crater size, which might include some crater collapse. If the sphere only

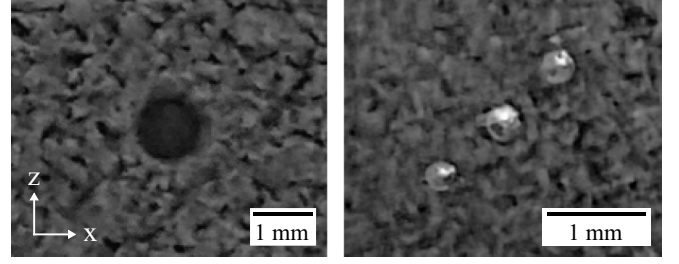


FIG. 6. Picture of a dust bed surface after impact. (Left) Crater from impactor with  $d_{p,1} = 900 \pm 100 \mu m$ . The impactor is buried, leaving a circular crater. (Right) Almost all impactors with  $d_{p,2} = 460 \pm 70 \mu m$  end up at the surface.

partially enters the sample and can be seen on the surface, we take the visible size of the impactor itself, if no crater outline is visible, or the visible crater outline of the crater surrounding the impactor, if the crater outline can be seen. In the latter case, the crater size can be smaller than the diameter of the projectile as the sphere can also be partly covered by target material after impact. We note that it was not an option to remove the sphere before measuring the crater size, as this would destroy the crater being measured.

The crater diameters  $d_{c,x}$  and  $d_{c,z}$  are presented in Fig. 7 for both impactor sizes. The dashed line indicates  $d_{c,x} = d_{c,z}$ , that is, circular craters. From this data, we can determine the mean crater diameter for the larger impactors to be  $1.06 \pm 0.02 mm$  and  $0.380 \pm 0.003 mm$  for the smaller spheres. Interestingly, we systematically find the observable crater diameter  $d_c > d_p$  for the larger impactors and  $d_c < d_p$  for the smaller impactors.

DWS now further gives the diameter of the affected area. While the impacting spheres have a diameter ratio of 2, the

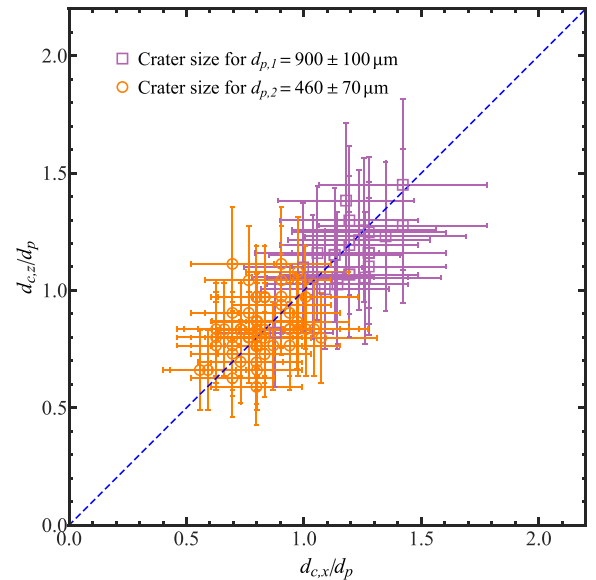


FIG. 7. Crater sizes scaled by the diameter  $d_{p,2} = 460 \pm 70 \mu m$  (orange circles) and  $d_{p,1} = 900 \pm 100 \mu m$  (purple squares) of the impactors. Crater diameters are measured separately in  $x$ - and  $z$ -directions (both are orthogonal to the direction of the impact). The dashed blue line represents circular craters ( $d_{c,x} = d_{c,z}$ ).

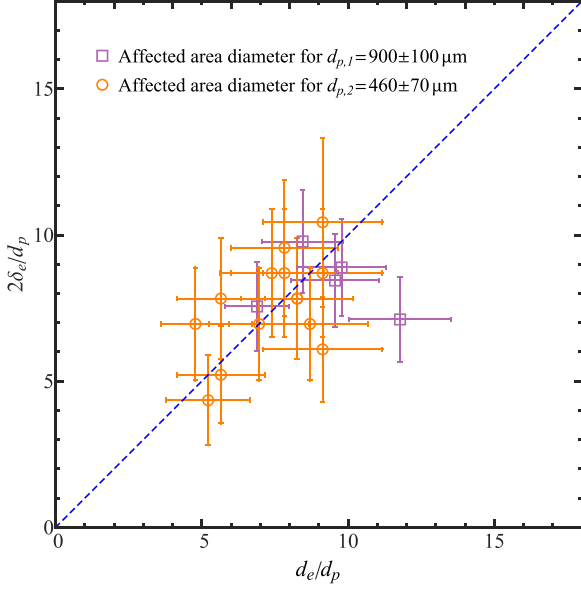


FIG. 8. The doubled depth  $2\delta_e$  of the affected area against the corresponding horizontal diameter of the affected area  $d_e$ , both obtained from the Diffusing Wave Spectroscopy measurement and scaled by the diameter  $d_p$  of the impacting sphere. Purple squares: data for impactor with  $d_{p,1} = 900 \pm 100 \mu\text{m}$ . Orange circles: data for impactor with  $d_{p,2} = 460 \pm 70 \mu\text{m}$ . The dashed blue line represents areas having a semicircle shape ( $d_e = 2\delta_e$ ).

radius of the area affected by the large sphere is approximately twice as large as the radius of the area affected by the small sphere. In detail, we can measure the depth  $\delta_e$  and width  $d_e$  of the affected area as previously defined.

Figure 8 summarizes the measured widths  $d_e$  and depths  $\delta_e$  of the affected area for both glass sphere sizes. Here we find a mean measured depth of the affected area of  $3.8 \pm 0.2 \text{ mm}$  and  $1.7 \pm 0.1 \text{ mm}$ , for the large and small impactors, respectively.

The impacting sphere influences target particles inside a volume, which has approximately the shape of a semisphere surrounding the impact point. We only observe a cross-section of this semisphere with the observation plane in the experiment. Since the impactor does not hit directly above the observation plane, the extent of the measured cross-section does not reflect the diameter of the affected volume. Instead, what we obtain is a lower boundary. Assuming the affected volume is semispherical, together with the known location of the impact, we can correct the observed diameter to obtain the maximum extension of the affected volume. This was done for the data presented in Figs. 10 and 11. Impacts too far away from the window were excluded from this analysis. This reduces the number of data points compared with the data on crater size. For the data presented in Fig. 8, the distance from the impact to the wall was  $1.8 \pm 1.4 \text{ mm}$  and  $0.8 \pm 0.4 \text{ mm}$ , for the larger and smaller spheres, respectively. From this scatter and error propagation, assuming a mean impactor size and the mean of the measured depth of the affected area, we can refine our results for the actual mean radius of the affected volume to  $4.2 \pm 0.6 \text{ mm}$  for the larger spheres and  $1.9 \pm 0.2 \text{ mm}$  for the smaller ones.

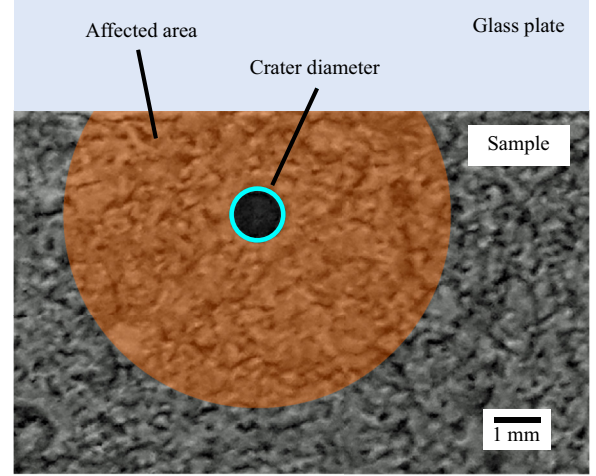


FIG. 9. Top-view picture of a dust bed surface after the impact of a glass sphere ( $d_{p,1} = 900 \pm 100 \mu\text{m}$ ) with superimposed crater diameter (cyan) and affected area as determined by Diffusing Wave Spectroscopy (orange). The light blue area indicates the front glass plate, through which the Diffusing Wave Spectroscopy measurement is made.

Finally, we can compare the extent of the affected volume with the crater diameter. Figure 9 shows a picture of the impact crater created by a glass sphere of  $900 \pm 100 \mu\text{m}$  diameter. The crater diameter is indicated by a cyan circle. The orange area, drawn to scale, represents the extent of the affected volume as determined by the DWS measurement. For our experiments with the larger impactor, we find that the maximal diameter of the affected area is approximately 7 to 9 times larger than the crater diameter and approximately 7 to 12 times the diameter of the impactor. For the smaller impactor, we get an affected area diameter approximately 9 to 11 times

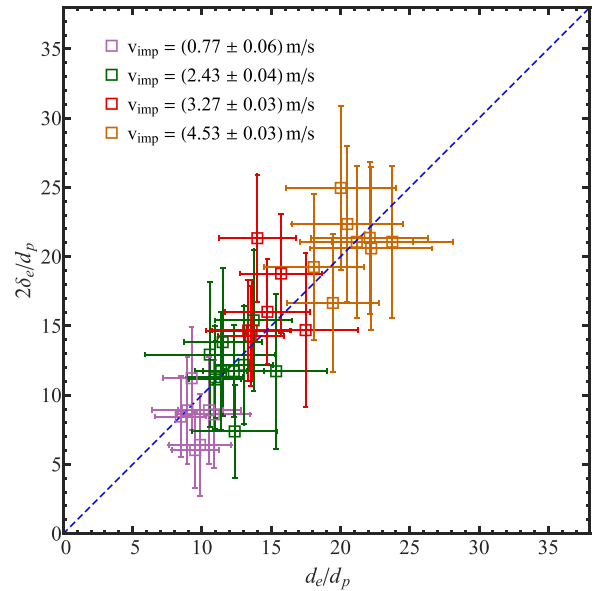


FIG. 10. The doubled depth  $2\delta_e$  of the affected area against the corresponding horizontal diameter of the affected area  $d_e$ , both scaled by the diameter  $d_{p,1} = 900 \pm 100 \mu\text{m}$  of the projectile, for different impact velocities. The dashed blue line represents areas with  $d_e = 2\delta_e$ .

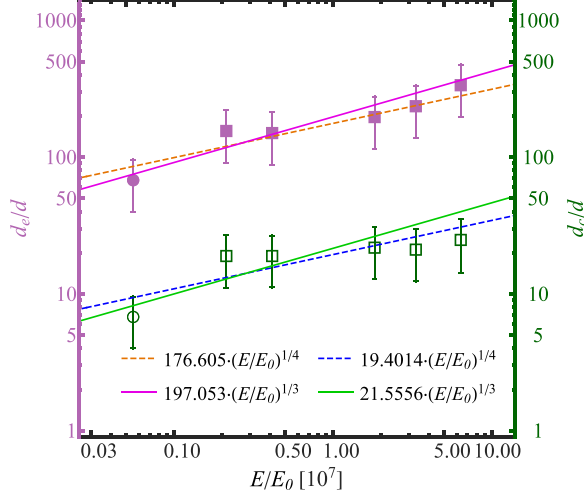


FIG. 11. Affected area size and crater size over impact energy. Filled symbols: Diameter  $d_e$  of the affected area scaled by the mean bed particle diameter  $d$ . Open symbols: Crater diameter  $d_c$  scaled by the mean bed particle diameter  $d$ . Both  $d_e/d$  and  $d_c/d$  are plotted as a function of the impact energy  $E$  scaled by  $E_0 = \frac{1}{6}\pi\rho_bgd^4$ , with  $\rho_b$  as the density of basalt. This scaling is analogous to Ref. [1]. Dashed orange and blue lines: Weighted fit to the  $E^{1/4}$  scaling model from Ref. [1]. Solid magenta and green lines: Weighted fit to the  $E^{1/3}$  scaling model. Squares: Impactor with  $d_{p,1} = 900 \pm 100 \mu\text{m}$ . Circles: Impactor with  $d_{p,2} = 460 \pm 70 \mu\text{m}$ .

as large as the mean crater diameter and approximately 6 to 10 times as large as the impactor.

### B. Impact energy

We repeated the experiments with the  $900 \pm 100 \mu\text{m}$  impactors, but now at different impact velocities. We performed these measurements several months after the measurements described in Sec. IV A. As no original sample was available, we used a slightly different basalt target. This target had a bulk density of  $1650 \text{ kg} \cdot \text{m}^{-3}$  and a packing fraction of 0.55. The size distribution of this target is slightly narrower, which results in a mean particle size of  $d = 56 \pm 23 \mu\text{m}$ . The results are shown in Fig. 10, where we see that higher impact velocities lead to a higher depth of the affected volumes. We can again compare the extent of the affected volume with the crater size, as well as the previously reported scaling laws for the latter. This is done in Fig. 11, where we also include the data from the smaller impactor scaled by its respective energy. With cohesion of the target on the order of  $Y = 1 \text{ kPa}$ , the craters we studied here should be formed in the strength regime, as the strength parameter  $\Pi_3$  is two orders of magnitude larger than  $\Pi_2$ , the gravity parameter. In the strength regime, the crater diameter scales as the third root of the projectile energy [34]. We found that  $d_e$  is proportional to  $d_c$ , and thus should follow the same energy scaling as the crater diameter  $d_c$ . Figure 11 shows the data that are consistent with this trend. The gravity regime energy scaling with  $d_c \propto E^{1/4}$  also fits well to our results, though. Since we conducted the experiment only over one order of magnitude in the velocity, we can not clearly discern between both energy scalings.

Figure 12 shows the cratering efficiency  $\Pi_D$  over the strength parameter  $\Pi_3$  for both impactor sizes and different

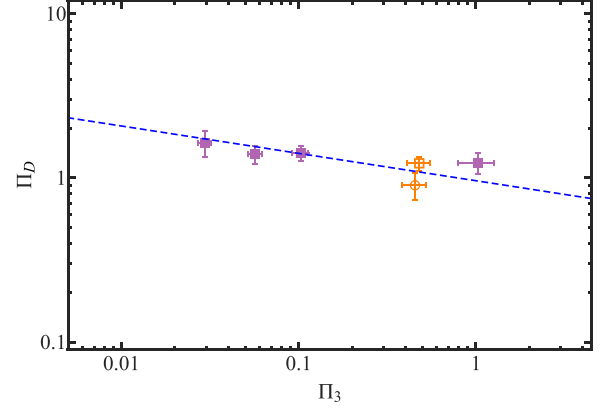


FIG. 12. Cratering efficiency  $\Pi_D$  in terms of diameter over the strength parameter  $\Pi_3$ . Open orange symbols: measurements for  $v_{\text{impact}} = 1.15 \text{ m/s}$  and the target described in Sec. III. Filled violet symbols: measurements with impact velocities from Fig. 10 and the target described in Sec. IV B. Circles: Impactor with mean diameter  $d_{p,2} = 460 \pm 70 \mu\text{m}$ ; Squares: Impactor with mean diameter  $d_{p,1} = 900 \pm 100 \mu\text{m}$ . The dashed blue line is the weighted fit ( $\Pi_D = C\Pi_3^{-\mu/2} \cdot \Pi_4^{(1-3\nu)/3}$ , with  $\nu = 0.4$ ,  $C = 0.93 \pm 0.02$  and  $\mu = 0.33 \pm 0.02$ ) to the strength regime model from Ref. [36] to the data presented in Sec. IV B.

velocities. The dashed blue line is the fit with  $\Pi_D = C\Pi_3^{-\mu/2} \cdot \Pi_4^{(1-3\nu)/3}$  [36].  $\mu$  and  $\nu$  are the exponents of the parameter coupling the energy and momentum of the projectile [37]. Both exponents find their use in scaling laws of impact cratering.  $\mu$  ranges from  $1/3$  for the momentum scaling to  $2/3$  for the energy scaling, depending on what is responsible for the crater growth, and  $\nu = 0.4$  is suitable for most materials [36]. As fit parameters, we get  $C = 0.93 \pm 0.02$  and  $\mu = 0.33 \pm 0.02$ . Porous targets show values of  $\mu$  closer to the momentum limit [38]. The value of  $\mu$  we find here is around the momentum-scaling limit, which fits well with the image of a porous target.

### V. DISCUSSION

We observed circular craters, whose sizes are systematically smaller than predicted by Ref. [39]. The equation for crater size was deduced from dropping cm-sized spheres into targets of sub- to mm-sized grains. Our target grains are nonspherical and have a maximal diameter of about  $0.16 \text{ mm}$ , with most particles being much smaller than that. Moreover, our projectiles are also smaller, which suggests that mechanisms like cohesion might be at play, which could explain the discrepancy in the obtained crater sizes. In the case of smaller spheres, the impact is shallow. The same applies to the velocity-dependent measurements. We performed these with a target with a narrower size distribution but a bulk density and packing fraction similar to that of the measurement with a smaller impactor size. Uehara and colleagues [40] have shown that the average penetration force increases when the size of the intruder approaches the size of the target particles for  $d_p < 10d$ . The fact that the projectiles stay at the surface may be explained by the ratio  $q$  of the projectile diameter and the target particle diameter, which in our case is low, especially for the smaller spheres. For the projectiles we used in the experiments, these ratios are  $q_1 = 16 \pm 9$  and  $q_2 = 8 \pm 5$ .

Even though the shallow and the deep impact might involve different cratering mechanisms, the deformation areas of both, traced by DWS, are comparably large and show a nearly semi-circular shape, at least for the low-velocity range and small projectiles studied in this work. The fact that these disturbance zones extend extremely far beyond the crater and are not centered below, but rather symmetric around the impact, is striking. We note that this is not a spatial resolution issue. DWS detects changes on the size of  $l^*$  or on the order of  $100\text{ }\mu\text{m}$ , while the affected zone extends to several mm. This spherical extent is in contrast to the idea that material should foremost be compressed below as, for example, visualized by x-ray measurements [13]. We obviously trace a different energy dissipation channel by DWS due to its high sensitivity. The semispherical shape of the disturbance zone visualized by DWS is, however, consistent with the collisional model for the three-dimensional impact proposed by [41], who showed that the momentum transfer through collisions of target particles perpendicular to the surface of the impactor results in the drag force and found a dependence of the drag force on the shape of the projectile. In our case, the projectiles are spherical. The almost circular extent can most naturally be explained by a spherical wave emerging from the impact point.

Shear or pressure waves are common phenomena after high-energy impacts and are omnipresent in seismology. We likely trace the small version of these here or, in other words, essentially, we might trace sound waves and, for the zone with irreversible particle motion, this might be considered as small-scale microearthquakes. In three dimensions, the amplitude  $A$  of a wave depends on the distance to the excitation  $R$  as  $A = B/R$ . Here,  $B$  quantifies the excitation intensity of the wave. These waves should essentially move with sound speed. Unfortunately, even at only tens of m/s for a granular medium, they currently cannot be resolved in time at our low frame rate. In any case, these waves are essentially elastic but with some damping, especially due to the irreversible motion of some grains. Even without damping though, the  $1/R$  dependence leads to a decrease in amplitude with distance to the impact point. We can define a limiting amplitude  $A_l$ , below which all motions are elastic and all particle motion is reversible. This is where DWS no longer detects equilibrium changes in the material. For a spherical wave, this value is reached at the same distance in all directions, hence the spherical nature of the affected zone. With this in mind, a second look at the affected zone might show that the very top of the affected zone is slightly more extended, which might be due to the fact that on surfaces, two-dimensional Rayleigh waves also exist, but details are beyond the scope of this paper.

In any case, the distance  $R_l$  where the limiting amplitude is reached depends on the excitation  $B$  or  $R_l = B/A_l$ . Therefore,

if the excitation  $B$  is larger, the affected zone becomes larger. A more energetic impact will certainly increase  $B$  to a certain limit. So the fact that the affected zone becomes larger with impact energy is plausible. Whether it also has to be  $E^{1/3}$  might depend on the coupling and probably elasticity limits, but cannot be answered in detail from the limited dataset we have. However, this interpretation suggests that even low-energy impacts always launch acoustic waves or shear waves, which mobilize grains well beyond the crater size.

## VI. CONCLUSION

We conducted a series of slow-impact experiments by dropping glass spheres into basaltic powder. We found that the resulting craters are circular but systematically smaller than predicted by Ref. [39]. We can speculate that this is an effect of adhesion between the fine powder particles. We then showed that by using DWS, we can quantify the extent of the volume of bulk soil material affected by these impacts. A drawback of the experimental method is that we could only measure in a shallow region close to the sample cell wall. While we do not see a systematic variation for impacts in different distances to the observation wall, it still might affect the impact process [42,43]. We detected the volume affected by a slow impact to be a half sphere, centered at the site of impact, and having a clear boundary. We found that the size of the affected volume depends on both the size of the impactor and the impact velocity. Comparing the extent of the affected volume with the crater size, we found them to be essentially proportional. The most likely explanation is small amplitude shear or acoustic waves launched by the impact, which are still mobilizing particles in a region way beyond the crater size.

In conclusion, we successfully demonstrated that DWS can be a valuable tool in characterizing the effects of slow granular impacts. In particular, we used DWS to show that the volume affected by an impact scales with the crater size and is much larger than the crater size would naively suggest.

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## DATA AVAILABILITY

Data will be made available upon reasonable request.

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- [1] A. M. Walsh, K. E. Holloway, P. Habdas, and J. R. de Bruyn, Morphology and scaling of impact craters in granular media, *Phys. Rev. Lett.* **91**, 104301 (2003).
  - [2] S. J. de Vet and J. R. de Bruyn, Shape of impact craters in granular media, *Phys. Rev. E* **76**, 041306 (2007).
  - [3] X.-J. Zheng, Z.-T. Wang, and Z.-G. Qiu, Impact craters in loose granular media, *Eur. Phys. J. E* **13**, 321 (2004).
  - [4] K. Hayashi and I. Sumita, Low-velocity impact cratering experiments in granular slopes, *Icarus* **291**, 160 (2017).
  - [5] M. Neiderbach, B. Suo, E. Wright, A. Quillen, M. Lee, P. Miklavcic, H. Askari, and P. Sánchez, Surface particle motions excited by a low velocity normal impact into a granular medium, *Icarus* **390**, 115301 (2023).

- [6] M. Kiuchi, A. M. Nakamura, and K. Wada, Experimental study on gravitational and atmospheric effects on crater size formed by low-velocity impacts into granular media, *J. Geophys. Res.* **124**, 1379 (2019).
- [7] J. Brisset, J. Colwell, A. Dove, S. Abukhalil, C. Cox, and N. Mohammed, Regolith behavior under asteroid-level gravity conditions: Low-velocity impact experiments, *Prog. Earth Planet. Sci.* **5**, 73 (2018).
- [8] J. Brisset, C. Cox, S. Anderson, J. Hatchitt, A. Madison, M. Mendonca, A. Partida, and D. Remie, Regolith behavior under asteroid-level gravity conditions: Low-velocity impacts into mm- and cm-sized grain targets, *Astron. Astrophys.* **642**, A198 (2020).
- [9] J. E. Colwell and M. Taylor, Low-velocity microgravity impact experiments into simulated regolith, *Icarus* **138**, 241 (1999).
- [10] J. E. Colwell, Low velocity impacts into dust: Results from the COLLIDE-2 microgravity experiment, *Icarus* **164**, 188 (2003).
- [11] T. Bogdan, J. E. Kollmer, J. Teiser, M. Kruss, and G. Wurm, Laboratory impact splash experiments to simulate asteroid surfaces, *Icarus* **341**, 113646 (2020).
- [12] H. Katsuragi and D. J. Durian, Unified force law for granular impact cratering, *Nat. Phys.* **3**, 420 (2007).
- [13] C. Güttler, M. Krause, R. J. Geretshauser, R. Speith, and J. Blum, The physics of protoplanetary dust agglomerates. IV. Toward a dynamical collision model, *Astrophys. J.* **701**, 130 (2009).
- [14] J. R. Royer, E. I. Corwin, B. Conyers, A. Fiori, M. L. Rivers, P. J. Eng, and H. M. Jaeger, Birth and growth of a granular jet, *Phys. Rev. E* **78**, 011305 (2008).
- [15] J. R. Royer, B. Conyers, E. I. Corwin, P. J. Eng, and H. M. Jaeger, The role of interstitial gas in determining the impact response of granular beds, *Europhys. Lett.* **93**, 28008 (2011).
- [16] T. Homan, R. Mudde, D. Lohse, and D. van der Meer, High-speed x-ray imaging of a ball impacting on loose sand, *J. Fluid Mech.* **777**, 690 (2015).
- [17] M. Baur, J. Claussen, S. Gerth, J. Kollmer, T. Shreve, N. Uhlmann, and T. Pöschel, How to measure the volume fraction of granular assemblies using x-ray radiography, *Powder Technol.* **356**, 439 (2019).
- [18] J. E. Kollmer, T. Shreve, J. Claussen, S. Gerth, M. Salamon, N. Uhlmann, M. Schröter, and T. Pöschel, Migrating shear bands in shaken granular matter, *Phys. Rev. Lett.* **125**, 048001 (2020).
- [19] D. Arsenović, S. B. Vrhovac, Z. M. Jakšić, L. Budinski-Petković, and A. Belić, Simulation study of granular compaction dynamics under vertical tapping, *Phys. Rev. E* **74**, 061302 (2006).
- [20] A. D. Rosato, O. Dybenko, D. J. Horntrap, V. Ratnaswamy, and L. Kondic, Microstructure evolution in density relaxation by tapping, *Phys. Rev. E* **81**, 061301 (2010).
- [21] H. M. Jaeger, C.-H. Liu, and S. R. Nagel, Relaxation at the angle of repose, *Phys. Rev. Lett.* **62**, 40 (1989).
- [22] F. Zimmer, J. E. Kollmer, and T. Pöschel, Polydirectional stability of granular matter, *Phys. Rev. Lett.* **111**, 168003 (2013).
- [23] K. Liu, J. E. Kollmer, K. E. Daniels, J. M. Schwarz, and S. Henkes, Spongelike rigid structures in frictional granular packings, *Phys. Rev. Lett.* **126**, 088002 (2021).
- [24] J. Featherstone, R. Bullard, T. Emm, A. Jackson, R. Reid, S. Shefferman, A. Dove, J. Colwell, J. E. Kollmer, and K. E. Daniels, Stick-slip dynamics in penetration experiments on simulated regolith, *Planet. Sci.* **2**, 243 (2021).
- [25] A. Amon, A. Mikhailovskaya, and J. Crassous, Spatially resolved measurements of micro-deformations in granular materials using diffusing wave spectroscopy, *Rev. Sci. Instrum.* **88**, 051804 (2017).
- [26] D. J. Durian, D. A. Weitz, and D. J. Pine, Multiple light-scattering probes of foam structure and dynamics, *Science* **252**, 686 (1991).
- [27] D. A. Weitz and D. J. Pine, Diffusing-wave spectroscopy, in *Dynamic Light Scattering: The Method and Some Applications*, edited by W. Brown, Monographs on the Physics and Chemistry of Materials Vol. 49 (Clarendon Press, Oxford, 1993), pp. 652–720.
- [28] R. Höhler, S. Cohen-Addad, and H. Hoballah, Periodic nonlinear bubble motion in aqueous foam under oscillating shear strain, *Phys. Rev. Lett.* **79**, 1154 (1997).
- [29] J. Crassous, Diffusive wave spectroscopy of a random close packing of spheres, *Eur. Phys. J. E* **23**, 145 (2007).
- [30] M. Erpelding, A. Amon, and J. Crassous, Mechanical response of granular media: New insights from diffusing-wave spectroscopy, *Europhys. Lett.* **91**, 18002 (2010).
- [31] T. Bila, J. Kollmer, J. Teiser, and G. Wurm, Thermal creep on Mars: Visualizing a soil layer under tension, *Planet. Sci.* **4**, 16 (2023).
- [32] V. Viasnoff, F. Lequeux, and D. J. Pine, Multispeckle diffusing-wave spectroscopy: A tool to study slow relaxation and time-dependent dynamics, *Rev. Sci. Instrum.* **73**, 2336 (2002).
- [33] M. Erpelding, A. Amon, and J. Crassous, Diffusive wave spectroscopy applied to the spatially resolved deformation of a solid, *Phys. Rev. E* **78**, 046104 (2008).
- [34] K. A. Holsapple, The scaling of impact processes in planetary sciences, *Annu. Rev. Earth Planet. Sci.* **21**, 333 (1993).
- [35] H. Melosh, *Impact Cratering: A Geologic Process*, Oxford Monographs on Geology and Geophysics (Oxford University Press, Oxford, 1989).
- [36] K. R. Housen and K. A. Holsapple, Ejecta from impact craters, *Icarus* **211**, 856 (2011).
- [37] K. A. Holsapple and R. M. Schmidt, Point source solutions and coupling parameters in cratering mechanics, *J. Geophys. Res.* **92**, 6350 (1987).
- [38] K. R. Housen and K. A. Holsapple, Impact cratering on porous asteroids, *Icarus* **163**, 102 (2003).
- [39] J. S. Uehara, M. A. Ambroso, R. P. Ojha, and D. J. Durian, Low-speed impact craters in loose granular media, *Phys. Rev. Lett.* **90**, 194301 (2003).
- [40] V. Paume, P. Aussillous, and O. Pouliquen, Finite size effects during the penetration of objects in a granular medium, *Soft Matter* **20**, 245 (2023).
- [41] C. S. Bester and R. P. Behringer, Collisional model of energy dissipation in three-dimensional granular impact, *Phys. Rev. E* **95**, 032906 (2017).
- [42] A. Seguin, Y. Bertho, and P. Gondret, Influence of confinement on granular penetration by impact, *Phys. Rev. E* **78**, 010301(R) (2008).
- [43] V. L. Díaz-Melián, A. Serrano-Muñoz, M. Espinosa, L. Alonso-Llanes, G. Viera-López, and E. Altshuler, Rolling away from the wall into granular matter, *Phys. Rev. Lett.* **125**, 078002 (2020).