Impact

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According to Shoemaker, the "impact of solid bodies is the most fundamental process that has taken place on the terrestrial planets" [1], as they shape the surfaces of all solar system bodies. A lot of information on this process has been extracted from remote observations of impact craters on planetary surfaces. However, the nature of the geophysical impact events is that they are non-reproducible. Moreover, their scale is enormous and direct observations are not possible. Therefore, we choose an alternate and of course downscaled experimental approach in order to guarantee reproducible results: We prepare very fine sand in a *well defined* and *fully decompactified* state by letting gas bubble through it. After turning off the gas stream, we let a steel ball fall on the sand. The series of events in the experiments and corresponding discrete particle simulations is as follows: On impact of the ball, sand is blown away in all directions ("splash") and an impact crater forms. When this cavity collapses, a *granular jet* [2, 3] emerges and is driven straight into the air. A second jet goes downwards into the air bubble entrained during the process, thus pushing surface material deep into the ground. The air bubble rises slowly towards the surface, causing a granular eruption. In addition to the experiments and the discrete particle simulations we present a simple continuum theory to account for the void collapse leading to the formation of the upward and downward jets. We show that the phenomenon is robust and even works for *oblique* impacts: the upward jet is then shooting *backwards*, in the direction where the projectile came from.

It has long been known that jets can be created when a ball or a fluid droplet impacts on a fluid surface [4, 5, 6, 7, 8]. S. Thoroddsen and A. Shen found similar jets on impact of lead spheres on monodisperse spherical glass beads [2]. We did similar experiments on fine sand, but found it hard to achieve quantitatively reproducible results, presumably due to the random nature of the force-chain-networks in the granular material [9, 10, 11, 12]. Therefore, in order to prepare a well-defined initial state, we decompactify and homogenize extremely fine sand (average grain-size of about $40\mu m$; grains are non-spherical) by blowing air through it via a perforated bottom plate. The height of the sand bed above the bottom plate is typically 25-40cm. The air is slowly turned off before the experiments and the grains are left to settle in an extremely loose packing with the force-chains either broken or substantially weakened. We call this a "fluid-like" state. Impact events on this well-prepared fine sand will be gravity-dominated. We let a steel ball (radius $R_0 = 1.25$cm) fall from various heights (up to 1.5m) onto the sand and observe the dynamics of the sand with a digital high-speed camera (up to 2000 frames per second).

The series of *visible* events is as follows (see figure 1): First, the ball vanishes in the sand and a crown-like *splash* is created. Inhomogeneities develop in the crown, due to the inelastic particle-particle interaction (figure 1, frames 3-5). Then, after a while, a *jet* shoots out of the sand at the position of impact. In all our experiments the jet height exceeds the release height of the ball. (The jets of ref. [2] never reach the release height, because the sand is less fine and much less decompactified.) While the upper part of the jet is still going upwards, in the lower parts the inelastic particle-particle collisions lead to density inhomogeneities in the jet (figure 1, frames 7-8). These inhomogeneities resemble those of the surface tension driven Rayleigh-instability of a water jet, even though there is no surface tension in granular matter. Finally, after about half a second, a *granular eruption* is seen at the position of impact, resembling a volcano (figure 1, frames 8-9). The collapsing jet first leaves a *central peak* in the crater[32], but the granular eruption violently erases this peak.

How does the jet form? To find out what is going on *below the surface* of the sand, we (i) performed direct numerical simulations, (ii) redid the experiments in two dimensions, meaning that we replaced the ball by a cylinder (with axis parallel to the surface and orthogonal to the side plates) which we let fall into a bed of sand between two transparent plates, and (iii) employed the analogy to jet formation in fluids [4, 5, 6, 7, 8, 15].

(i) In the discrete particle simulations, the sand particles are modeled as spheres which interact via inelastic "soft-sphere" collision rules. The interaction of the particles with the surrounding air is included via empirical drag force relations [16]. Since the maximum number of particles that can be simulated is presently of the order of one million, we can perform only quasi-two-dimensional simulations, where the thickness of the sand bed between the parallel plates is eight grains[33]. Altogether, the calculation includes N= 1.3 million homogeneous beads of density $1000 kg/m^3$ and diameter $500\mu m$ (i.e., approximately a factor 10 larger than in experiment) in a container of 24cm × 0.4cm ground area and a sand bed height of about 17cm. The beads are pre-fluidized with air, just as in the experiments, and then a 1.5cm diameter

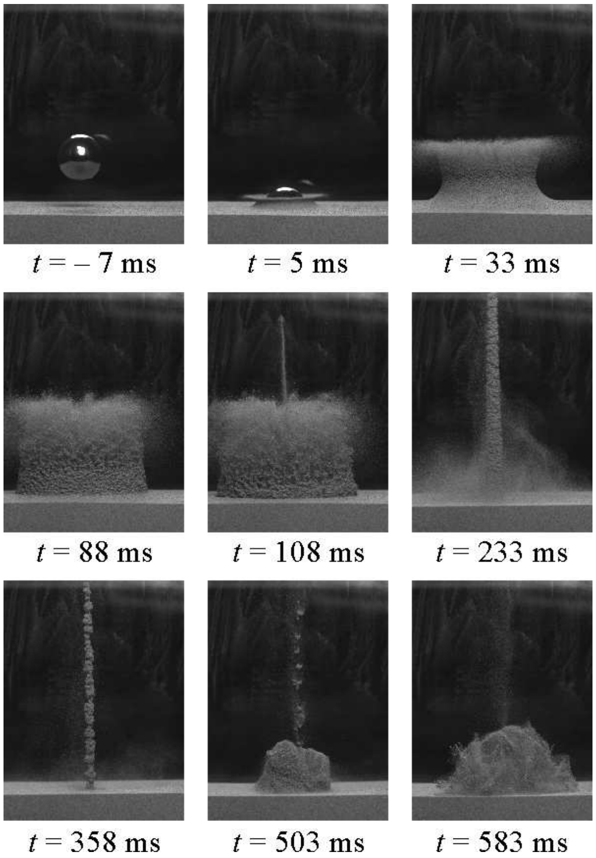


FIG. 1: Jet formation after the impact ($v_0 = 2.43 m/s$) of a steel ball of $R_0 = 1.25 cm$ on loose very fine sand. The jet in this experiment exceeds the release height of the ball. Frames 2-4: splash; frames 5-6: a jet emerges; frame 7: clustering within the jet; frames 8-9: granular eruption at the surface.

ball of density $3500 kg/m^3$ is dropped onto the beads with an impact velocity of 2 m/s. The series of events can be seen in figure 2, revealing the jet formation process invisible in figure 1: The impacting ball creates a void which is then pressed together through the "hydrostatic" pressure from the side. [34] At small depth the ball passes early, meaning an early start of the void collapse, which however is weak due to the small "hydrostatic" pressure. Conversely, at larger depth the collapse of the void begins later, but is stronger due to the larger "hydrostatic" pressure. Somewhere in the middle the collapse is finished first, and the void walls hit each other. It is this singularity which leads to the formation of *two* jets: One upwards and one downwards into an air bubble which was entrained in the sand by the void collapse. The falling jet often leaves a central peak in the crater (which in our 3D experiments with the fine, decompactified sand is subsequently erased again by the granular eruption). Note that the jet in the discrete particle simulations is much less pronounced than in experiment. First, because the beads in the simulations are much larger than the sand grains in the experiment, i.e. the sand bed is less fluid-like and allows for less fine structure. Second, the singularity due to the focussing along the axis of symmetry is weaker in 2D and quasi-2D experiments or simulations than in 3D, and the jet takes the form of a sheet.

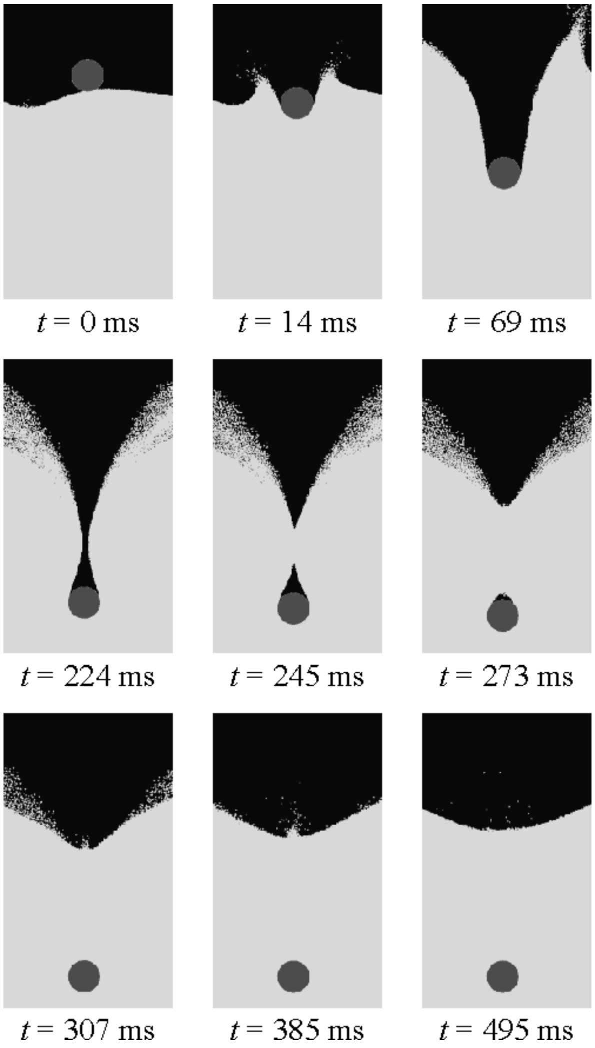


FIG. 2: Cut through the quasi-2D discrete particle simulation. Frames 1-3: the impact of the disk on the particles; Frames 4-6: the collapse of the void; Frames 7-8: the upward jet (which is less pronounced than in the 3D experiments).

(ii) We performed such 2D jet formation experiments, by letting a cylinder fall into decompactified sand between two transparent plates, and observing the jet formation process from the side (see supplementary material and ref. [3]). These experiments confirm the above sketched series of events. Again, the jet is less pronounced than in the 3D experiments. The entrained air bubble slowly rises in these experiments, finally leading to a granular eruption at the surface, just as observed in 3D.

(iii) The same series of events is also found after an analogous impact of a steel ball or a falling disk on water [4, 5, 6, 7, 8, 15, 18]. We will employ this analogy below in order to set up a theoretical model.

Before we do so, we discuss the role of the ambient

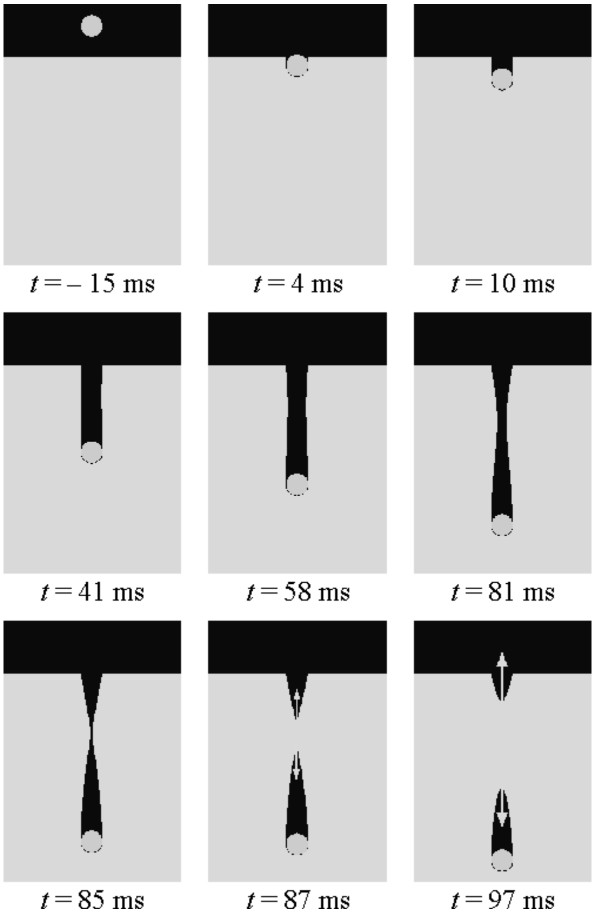


FIG. 3: Cross-section of the 3D-void collapse following from our Rayleigh-type model, for the same impact velocity and ball radius as in figure 1. The void is pressed together by the "hydrostatic" pressure from the side, leading to a singularity and an upward and downward jet.

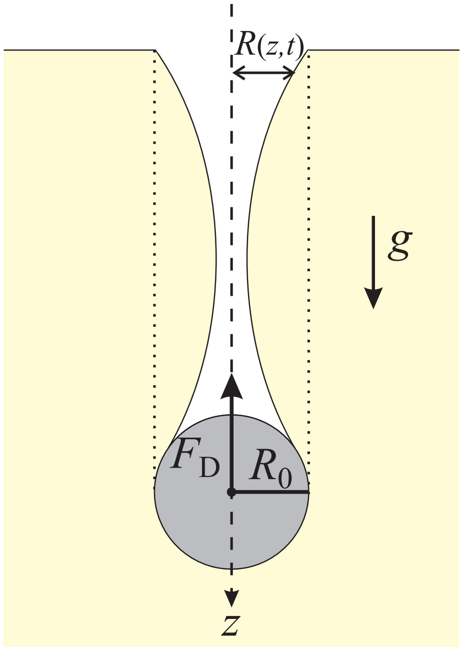


FIG. 4: Sketch of the void collapse. When the accelerated sand grains from the sidewalls of the cylindrical cavity collide on the axis of the cavity, two jets are formed: One downward into the entrained air bubble formed above the sphere, and one upward straight into the air.

air for the jet formation. We redid the discrete particle simulations with an air pressure reduced to nearly zero (vacuum), giving nearly indistinguishable results for the jet formation. The ambient air, however, can play a role during the evolution of the jet, provided that the impact velocity v_0 is very high. For (3D) experiments with very high impact velocities we observed that after the splash the crown goes *inwards* rather than outwards, due to the pressure reduction behind the fast projectile (Bernoulli's law). The crown in fact can fully close and the jet then hits the closed crown, leading to an explosion-like collision (see the supplementary material) which spreads material all over the place.

To work out the essentials of the void collapse, we now construct a "minimal" continuum mechanical model. First, the delay curve $z(t)$ of the ball in the sand can be obtained from a simple force balance model involving drag, gravity, and added mass. It describes the experimental results obtained for a falling ball equipped with a thin tail rod, which allows for easy depth measurements [19]. The delay curve $z(t)$ of the ball is inverted to obtain $t_{pass}(z)$, the time when the ball passes the layer of sand at depth z. This sets the initial conditions for the collapse of the two-dimensional void, namely $R(z, t_{pass}) = R_0$ and $\dot{R}(z, t_{pass}) = 0$. Here, $R(z,t)$ is the time and depth dependent radius of the void, see figure 4.

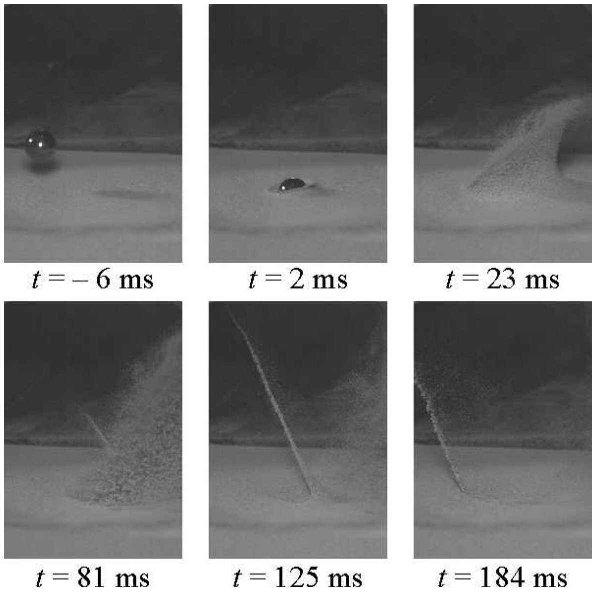
Next, the collapse of the void formed by the ball has to be described. It is driven by the ("hydrostatic") sand pressure $p(z)$ at depth z. For small z the pressure simply is $p(z) = \rho_s g z$, for larger z it saturates [17]. Here, ρ_s is the sand density, assumed to be constant. If we neglect the dissipative processes both between the different layers of sand and between the sand grains in one layer, the dynamics for fixed depth z is determined by the Euler equation,

$$\rho_s(\partial_t v(r,t) + v(r,t)\partial_r v(r,t)) = -\partial_r p(r,t). \qquad (1)$$

Here, $v(r,t)$ is the velocity field in the sand. With continuity $\partial_r(rv(r,t)) = 0$, and with the boundary conditions $v(R(t),t) = \dot{R}(t)$ at the void's wall and $v(R_\infty, t) = 0$ far away from the void, one obtains a Rayleigh-type [20, 21] ordinary differential equation for each $R(z,t)$, namely

$$(R\ddot{R} + \dot{R}^2)\log\frac{R}{R_\infty} + \frac{1}{2}\dot{R}^2 = \frac{1}{\rho_s}p(z) = gz. \qquad (2)$$

The radius R_∞ is of the order of the system size, but the results only weakly (logarithmically) depend on this parameter. The dynamics following from this Rayleigh-type model is shown in figure 3, resembling the void collapse



$t = -6$ ms $t = 2$ ms $t = 23$ ms

$t = 81$ ms $t = 125$ ms $t = 184$ ms

FIG. 5: Impact of the steel ball on soft, loose sand under an angle of approximately 45 degrees. Frames 2-4: forwardly directed splash; frames 4-5: a backward jet emerges; frame 6: clustering within the jet.

in the discrete particle simulations figure 2, in the 2D experiments (see the supplementary material), in experimental work on the void collapse in transparent fluids [4, 5, 6, 7, 8, 15], in boundary integral simulations of the complete hydrodynamical equations [18], and therefore presumably also in the 3D experiments in sand shown in figure 1. Just before and at the singularity ($R(t) = 0$ and diverging velocity), the dynamics is determined by $R\ddot{R} + \dot{R}^2 = 0$, which has the solution $R(t) \sim (t_s - t)^{1/2}$, where t_s is the time of the singularity. The velocity therefore has a square-root divergence $\dot{R}(t) \sim (t_s - t)^{-1/2}$.

Having shown that the void collapse is driven by "hydrostatic" pressure, we now can deduce scaling arguments [22], for the limiting case of large impact velocity v_0, which is the relevant one in the geophysical context. The time up to void collapse in depth z is the sum of the time z/v_0 it takes the ball to get there and the collapse time itself, which scales as $\sim R_0/\sqrt{gz}$. The depth z_c where the walls of the void first touch (i.e., the position of the singularity) can be obtained from minimizing this sum with respect to z, resulting in $z_c/R_0 \sim Fr^{1/3}$, where $Fr = v_0^2/(gR_0)$ is the Froude number. From this one obtains that the time of the collapse t_c scales as $t_c \sim (R_0/v_0)Fr^{1/3} \sim \sqrt{R_0/g}Fr^{-1/6}$ [22]. For large v_0 these scaling laws are consistent both with our continuum model and with our discrete particle simulations.

We now come to the question how things change under an *oblique* impact [35]? We performed experiments under an angle of 45^o. All other experimental conditions are as in figure 1. The series of events can be seen in figure 5. Remarkably – but consistent with our theoretical model – the jet now points backwards, along the void created by the impacting ball. The backwards jet is also observed in the discrete particle simulations (see the supplementary material). Note that this is different for an oblique impact on *water*, where the jet still goes upwards.

We conclude the paper with speculations on possible implications of our findings on the impact mechanism within the geophysical context [13, 23, 24, 25, 26, 27]. However, we would like to caution the reader because – as pointed out above – lack of reproducibility of the details typify geophysical events. Moreover, though our decompactifying procedure minimized the *relative* energy stored in the ground as compared to the energy of the projectile, the *absolute* energy scales in our experiments are of course very different as compared to geophysical events. Nonetheless, we believe that the following speculations may stimulate discussions in a geophysical context: (i) After the impact of a solid body on a planet, it may be the upward jet and *not* the splash which is the dominant source of planetary material transferred into space [25]. Similarly, an oblique jet resulting from an oblique impact allows for an enhanced sidewards transport of material, as compared to the splash. (ii) The collapsing jet may contribute to the central peak often found in impact craters [13, 14]. (iii) The downward jet will considerably change the layering of the sediments underneath a crater, as it provides a mechanism how surface material can be transported deep into the ground (see the supplementary material). In addition, a granular eruption will rearrange the sediment. Our suggested mechanism may shed new light on the sediment layering data found underneath the Chicxulub crater, which is a source of major controversy [28, 29, 30, 31].

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[32] Similar peaks are observed in many craters of the terrestrial planets [13, 14]

[33] The 3D simulations we did are too strongly affected by finite size effects. Nevertheless, also for these simulations a jet emerges.

[34] In our experiments we are in the region where the pressure increases linearly with depth [17].

[35] In a geophysical context, exactly vertical impacts are of course very unlikely. 50% of all impacts on terrestrial planets occur with an angle between 30^o and 60^o [23].