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14. ABSTRACT
This research investigated nonlinear structural deformations driven by dynamic coupling of mechanical and fluid components in particulate media. The understanding of such deformations is of importance for the performance of Air Force systems. In particular, the interactions with the interstitial fluid, typically air, have been largely neglected in prior studies, yet are likely to become important at high strain rates. Using non-invasive high-speed x-ray and video imaging techniques, the dynamics of rapidly moving interfaces in three-dimensional particulate systems were tracked. Key research objectives achieved were a) the development of quantitative x-ray radiography techniques for tracking the local packing density variations inside granular beds, b) the detailed characterization of the interactions between moving interface, particulate bed material and interstitial gas, and c) the measurement of the drag experienced by fast-moving objects inside fine-grained granular beds both in the presence and the absence of interstitial gas.

15. SUBJECT TERMS
particulate media, impact, drag, interface motion, deformations, high-speed x-ray imaging and particle tracking, quantitative characterization of local packing density changes

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Summary of Scientific Results

The research project investigated the interaction between fine grains and the surrounding interstitial gas in a granular bed. This interaction can lead to qualitatively new phenomena not captured in a simple, single-fluid model of granular flows. This was demonstrated by the granular jet formed by the impact of a solid sphere into a bed of loose, fine sand. Unlike jets formed by impact in fluids, this jet is actually composed of two separate components, an initial thin jet formed by the collapse of the cavity left by the impacting object stacked on top of a second, thicker jet which depends strongly on the ambient gas pressure. This complex structure is the result of an interplay between ambient gas, bed particles and impacting sphere. The project consisted of systematic experiments that combined measurements of the jet above the surface varying the release height, sphere diameter, container size and bed material with x-ray radiography below the surface to connect the changing response of the bed to the changing structure of the jet. We found that the interstitial gas trapped by the low permeability of a fine-grained bed plays two distinct roles in the formation of the jet. First, gas trapped and compressed between grains prevents compaction, causing the bed to flow like an incompressible fluid and allowing the impacting object to sink deep into the bed. Second, the jet is initiated by the gravity driven collapse of the cavity left by the impacting object. If the cavity is large enough, gas trapped and compressed by the collapsing cavity can amplify the jet by directly pushing bed material upwards and creating the thick jet. As a consequence of these two factors, when the ambient gas pressure is decreased, there is a crossover from a nearly incompressible, fluid-like response of the bed to a highly compressible, dissipative response. Compaction of the bed at reduced pressure reduces the final depth of the impacting object, resulting in a smaller cavity and in the demise of the thick jet.

Personnel involved

Heinrich M. Jaeger, Professor of Physics, University of Chicago, Project PI
John R. Royer, Ph.D. student, University of Chicago
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Publications resulting from the 6-month project

John R. Royer, Eric I. Corwin, Peter J. Eng, and Heinrich M. Jaeger, "Gas-Mediated Impact Dynamics in Fine-Grained Granular Materials", Phys. Rev. Lett. **99,** 038003 (2007).

John R. Royer, Eric I. Corwin, Bryan Conyers, Andrew Flior, Mark L. Rivers, Peter J. Eng, and Heinrich M. Jaeger, "Birth and growth of a granular jet", Phys. Rev. E, submitted.

One additional manuscript currently in preparation.

Invited presentations by the PI resulting from the 6-month project

1/29/08 AFOSR Workshop on Particulate Mechanics in Extreme Environments: High-Speed Imaging of Granular Jets and Impacts

2/15/08 University of Twente, The Netherlands: Physics Far From Equilibrium: From Nano-Assembly to Granular Jets

2/22/08 California Institute of Technology, Mechanical Engineering Seminar: Granular Jets, Streams and Droplets

Additional presentations by graduate student John Royer at the 2008 AFOSR Workshop on Particulate Mechanics in Extreme Environments, and at the 2008 March Meeting of the American Physical Society, New Orleans.

Background

The impact of a solid object into a granular bed is a common and seemingly simple event. However, though this phenomenon has been studied since the 18th century [1], it still contains many surprises and continues to provide new insight into the unusual nature of granular materials. Granular materials constitute a unique state of matter which can flow like a liquid yet also support weight like a solid [2]. Both of these properties are exhibited during impact since material will initially flow out of the way of the impacting object until the object can no longer overcome the resistance of the bed and is brought to rest. This suggests the potential of impact experiments to characterize general properties of granular materials. Particularly notable are a number of engineering studies in the early 1960's motivated by questions about the load-bearing capability of the lunar surface [3-6]. These studies typically focused on the penetration depth of the impactor, and found that this depth depends strongly on details that do not enter for impact into simple solids or liquids, such as the grain diameter, bed packing density and ambient gas pressure. There have been a number of recent studies using low speed impacts to address related, unanswered questions in granular physics, such as how force is distributed through a granular pack [7, 8], and the functional form of the drag force on an object moving through a granular bed [9-14].

In 2001, Thoroddsen and Shen performed experiments dropping a solid sphere into a loose, _ne-grained granular bed and found a remarkable phenomenon. As reported in [15], the impacting sphere easily sinks into the loosely packed bed. After an initial, corona-like splash, a collimated jet of sand is ejected upwards, reaching heights over 40 cm. This granular jet is very reminiscent of liquid jets [16-19], despite the absence of any strong cohesive forces keeping the grains together. Thoroddsen and Shen, in analogy to what might be expected for liquids, attributed the jet to the gravity-driven radial collapse of the cavity left behind the sphere. Arguing that the jet height was set by the sphere diameter, impact velocity, gravity and an effective bed viscosity, they proposed a scaling relation for the jet height that collapsed their results for the measured range of grain diameter and release heights [15]. Subsequent experiments at the University of Twente, by Lohse and coworkers, studied the granular jets in more detail [20]. The Twente group also performed extensive simulations of two-dimensional particle-based systems and further developed the analogy to impact into a liquid via a hydrodynamic model. In this model the granular bed is treated as a simple fluid with hydrostatic pressure proportional to the depth. This pressure drives the walls of the cavity together until they collide at some depth below the surface with a diverging velocity, creating both upwards and downward jets along the vertical axis of symmetry. In [11] the Twente group focused on the bed properties, tracking the position of the sphere with a thin trailing thread attached as it descends through the bed and inferred the drag force on the sphere. Their results for a sphere released just above the surface could be fit by a simple drag force that depended linearly on the depth of the sphere below the surface. This drag force can be seen as arising from friction between the sphere and the bed, which is proportional to the hydrostatic pressure.

These previous experiments were all performed in open air at atmospheric pressure and only investigated aspects of the impact that were visible above the bed surface. They did not allow for direct visualization of the interior bed dynamics that lead to the formation of the jet. In the mechanism for jet formation proposed in [20] the ambient gas is limited to one aspect, namely that it introduces drag on the individual grains as they move out of the way of the impacting sphere. This leads one to expect a slightly larger jet in the absence of air. However, experiments by our group at reduced pressure revealed a dramatic decrease in the jet height [21]. For an ambient pressure $P_0 < 70$ kPa we found that the jet is actually composed of two stages, an initial thin jet followed by a sharp shoulder and a shorter thick jet. The height of the thick jet decreases with pressure until it is no longer observed below about 4 kPa, while the thin jet remains unchanged down to the lowest accessed pressure of 2 kPa. In order to image the initial stages of jet formation below the surface, high-speed x-ray imaging was used to track the motion of the descending sphere and subsequent collapse of the cavity walls. These x-ray images at atmospheric pressure revealed a large pocket of air trapped below the surface which drive up the sand above it, creating the thick jet. The change in jet structure at reduced pressure is accompanied by a global change in the response of the bed.

Despite the substantial amount of work studying the motion of a solid object moving through a granular medium [3-14, 20], and with the exception of the engineering studies in the early 1960's [3-6], the role of the gas pressure has been largely ignored. Gas-grain interaction have been previously studied in fluidized beds [22], where a granular bed is subjected to a continuous, externally imposed gas flow or rapid vibration. However, in this case it is simply the initially quiescent, interstitial gas that changes the dynamics. Recent work by the Twente group [23] and our recent x-ray studies [24] have begun to address this issue. Both sets of experiments found a monotonic decrease in both the rise of the top surface of the bed during impact and the final depth reached by the sphere at reduced gas pressure. The Twente group attributes the reduced drag at higher gas pressure to local fluidization of the bed around the sphere, while our x-ray work finds that the bed as a whole behaves more like an incompressible fluid at high pressure but compacts below the sphere at reduced pressure. The detailed role of gas pressure also has remained unresolved as far as the in the formation of the jet is concerned. In [23] the Twente group performed their experiments at reduced pressure using smaller spheres and release heights than in previous studies and did not observe the second, thick jet. They attribute the decrease in jet height at reduced pressure to the decreased penetration depth of the sphere and suggest that the thick jet is not generic but instead due to nearby container walls. Finally, the role of the grain diameter and the scaling for the jet height found in [15] also requires reexamination in light of the role of the gas pressure. In order to address these open questions about the role of the bed properties, container boundaries and the gas pressure in jet formation, it is important to investigate the dynamics in the bed interior as well as above the surface.

Experimental Set-up

Measurements above the bed surface. For optical measurements of the jet above the bed surface, a steel sphere was dropped into a 22 cm deep bed of spherical glass beads (MoSci Corp., grain diameter d = 53 μm, density 2.5 g/cm^3) in a cylindrical tube with a 14 cm inner diameter. The sphere diameter D_s was varied from 0.6 cm to 2.25 cm, and the release height varied from 110 cm to 2 cm. As described in [11, 20, 23], before each drop the bed was aerated from below by dry nitrogen entering through a diffuser built into the bottom of the container. After slowly turning off the nitrogen flow, the bed would reproducibly settle into a low-density state. We estimate the packing density to be about 0.55 after aeration in this large container. The system could be sealed and evacuated to reach ambient pressures P_0 as low as 0.15 kPa. The flow rate to the pump was limited to prevent air from bubbling up and disturbing the loose packing. Slowly cycling the pressure from atmospheric pressure down to 0.15 kPa and back before releasing the sphere did not change the dynamics of the jet, so we can safely conclude that the evacuation process did not disturb the loose packing of the bed. We checked for electrostatic charging by performing experiments in air at a high level of relative humidity (~50%) where electrostatic effects typically vanish [25] and observed no qualitative change in the impact dynamics. The sphere was held above the surface at the desired height by an electromagnet mounted to the top of the container.

After the bed was aerated and the chamber evacuated to the desired pressure, the sphere was released and the impact was recorded with a Phantom v7.1 high-speed camera. After each drop the sphere was retrieved using a permanent magnet at the end of a long rod and the experiment was reset. The high-speed videos where analyzed to obtain quantities such as the maximum jet height and the rise of the bed. For all plots presented here, error bars correspond to statistical variations from five or more realizations of the experiment under identical conditions. We also performed experiments in a sulfur hexafluoride (SF_6) atmosphere instead of ambient air in order to examine the role of the gas density. To ensure that all the air was replaced with SF_6, the chamber was first evacuated below 3 kPa, and then SF_6 was let into the chamber to bring the pressure back to atmospheric level. The bed was subsequently aerated from below as in the other experiments, using SF_6 in place of nitrogen, then sealed and pumped down to the desired pressure. To investigate jet formation in larger grains, a 11.4 cm diameter sphere (a 12 lb shot put) was dropped into a steel drum filled with corncob grounds with an average grain diameter of about 1 mm. The drum was 57 cm in diameter and filled 87 cm deep. The corncob grounds (density 0.7 g/cm^3) ranged in size from 0.8 mm to 1.4 mm and where rough and non-spherical. The bed was too permeable to aerate because of the large grain diameter, so it was prepared in a loosely packed state by rapidly pouring the grains into the drum. The drops were performed in the stairwell of a 5 story building, allowing us to reach drop heights up to 27 m.

X-ray radiography inside the bed. X-ray imaging of the interior of the bed was done at the University of Chicago GeoSoilEnviroCARS bending magnet beamline (13BMD) at the Advanced Photon Source using high intensity beam with an energy width of 5 keV centered at 22.5 keV. A schematic of the x-ray setup is presented in Fig. 1. In order to obtain appreciable x-ray transmission through the bed, we were forced to use a thinner container and granular media with a lower atomic number. For the x-ray images presented here, spheres with D_s = 1.2 cm and 0.6 cm were dropped from 34 cm into a 8.5 cm deep bed of 50 μm diameter Boron Carbide (B_4C) particles. The bed was contained in a 3.5 cm inner diameter cylindrical polycarbonate tube with 1.6 mm thick walls. Like the larger system, this chamber had a diffuser at the base to aerate the bed and could be sealed and evacuated down to as low as 0.7 kPa.

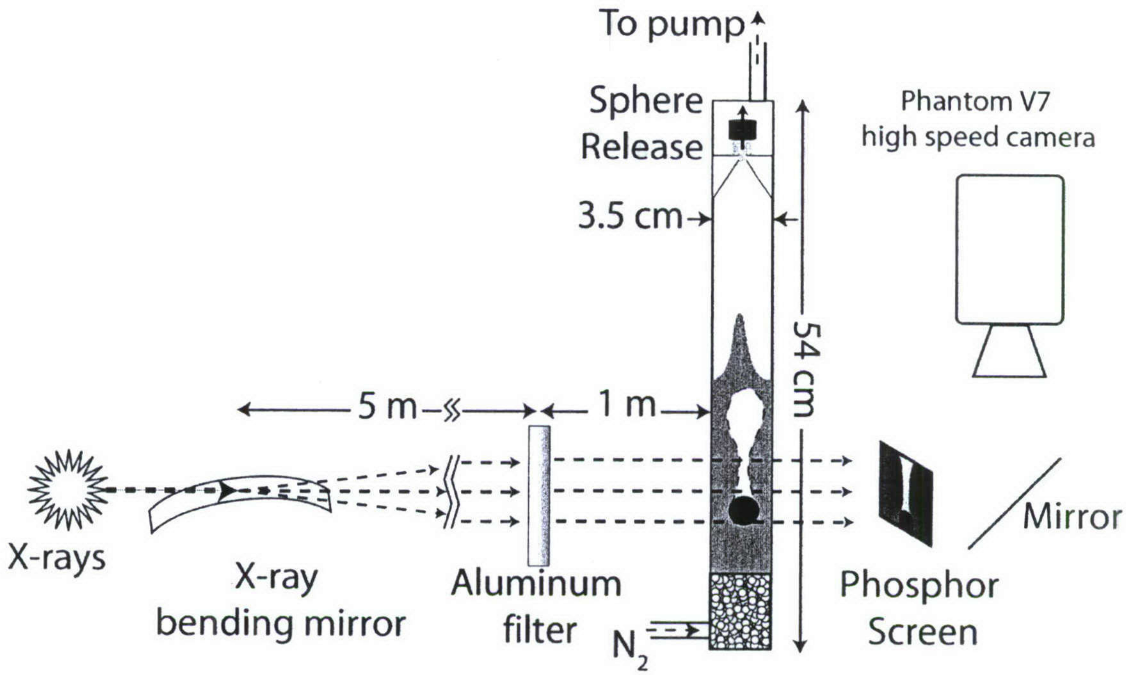
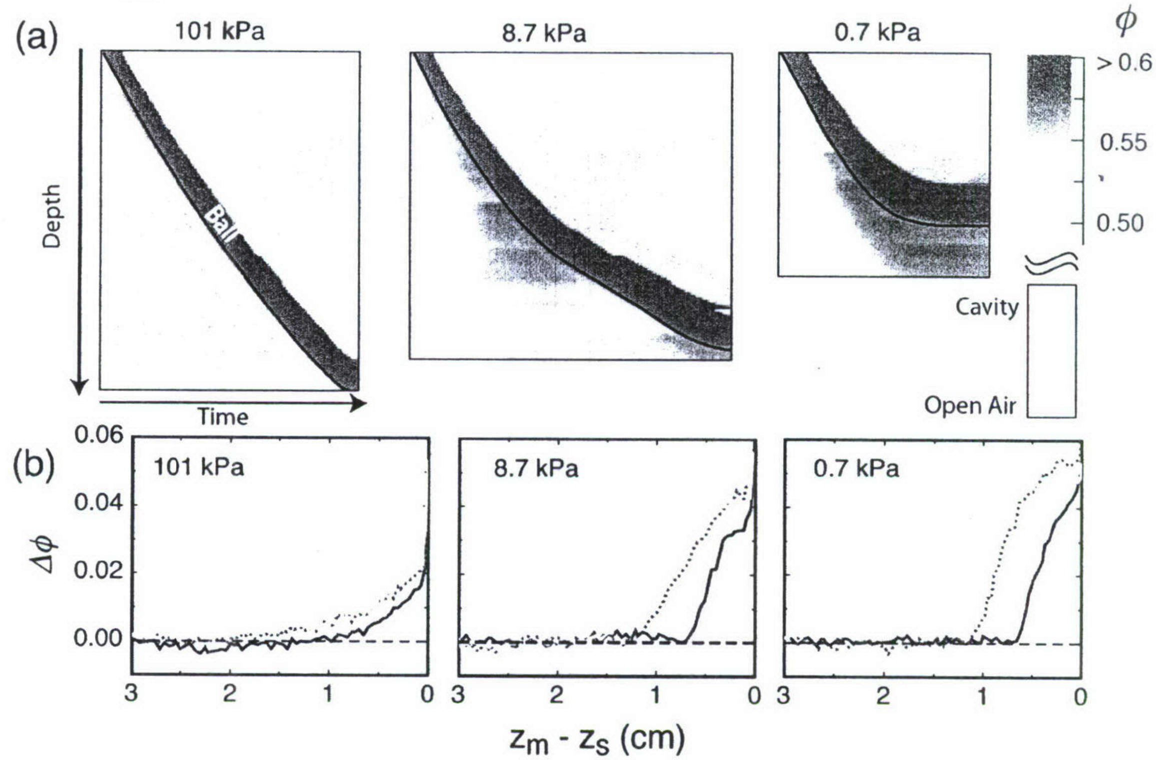


Fig. 1. Schematic of our radiography set-up at the Advanced Photon Source at Argonne.

Science Nugget



Visualization of the compaction fronts inside the granular bed that precede the sphere at reduced pressure. (a) False color space-time plots of the centerline of the composite x-ray movies for three different pressures. The bar on the upper right gives the translation between packing density and color in these plots. Plots of the sphere position $z_s(t)$ are over-plotted (black solid line) to indicate the boundary between the sphere (dark red) and the compacted sand in front of it. (b) Change in packing density measured along centerline of the sphere path at fixed depths z_m as the sphere is approaching. In each panel the three traces correspond to (from left to right) z_m = 1.0 cm, 2.0 cm and 3.0 cm. Data are plotted against the approach distance, i.e., the distance from the sphere bottom to z_m.

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