HIGH-SPEED X-RAY IMAGING OF A BALL IMPACTING ON SAND

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Summary When a ball is dropped in fine, very loose sand a cavity is formed inside the sand bed, which subsequently collapses, creating a jet and entraining an air bubble. At a fixed depth below the surface, the shape and dynamics of a horizontal cross section of the cavity are studied by means of high-speed x-ray tomography. Repeating the procedure at different depths provides a full, time-resolved reconstruction of the cavity within the sand bed. Using this reconstruction we test several hypotheses on the process of sand jet formation.

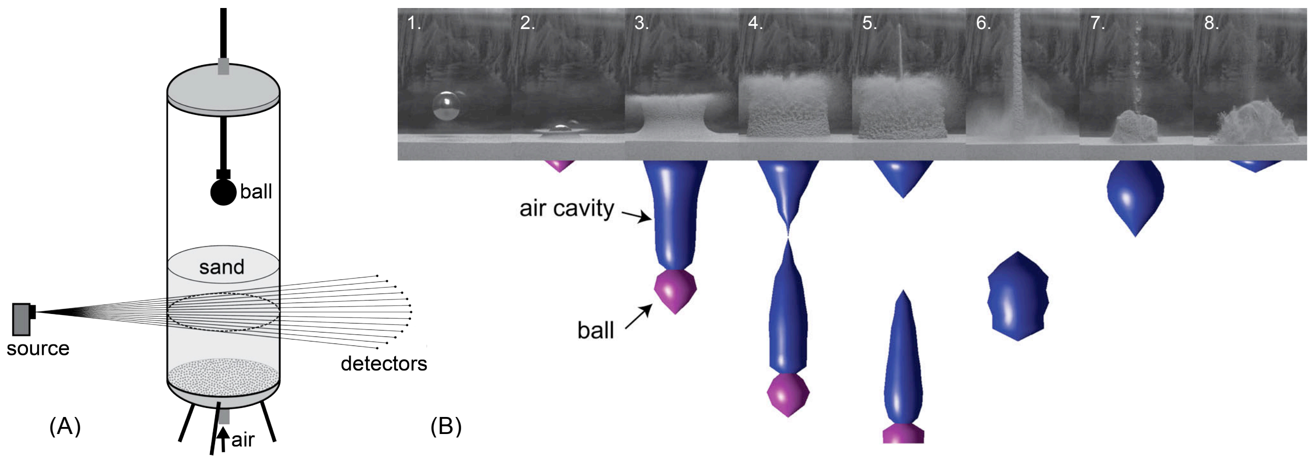
INTRODUCTION

When a ball impacts on a layer of fine, very loose sand, one observes a splash of sand particles, followed by a vigorous jet [1-4]. This is reminiscent of what happens when an axisymmetric object falls onto a liquid, where the impact creates a crown splash and an air cavity is created [5]. This cavity collapses under the influence of hydrostatic pressure, pinches, and the focussing of pressure onto the symmetry axis leads to the production of two jets: A strong upwards jet is visible above the liquid surface and a smaller downwards one penetrates the air bubble which is entrapped below the pinch-off point [6].

It has been conjectured that the sand jet is produced by a similar mechanism as the liquid jet, but to date a direct observation of the formation of the jet in sand is still lacking. The reason for this is that the sand bed is impenetrable for visible light, and one needs to resort to other techniques to image the sequence of events within the sand. Here we will directly image the motion of the ball, the creation of the air cavity, its subsequent collapse and the formation of the jet using high-speed x-ray imaging techniques.

EXPERIMENT

A cylindrical container with an inner diameter of 14.0 cm is filled with very fine sand (average diameter 40 μm) up to a height of approximately 30 cm. In order to create a loose packing we use the same procedure employed in [1-4]: dry air is blown through the porous bottom of the container such that the sand bed is fluidized. Subsequently the airflow is slowly turned off and the bed is allowed to settle into a very loose packing with a volume fraction of approximately 42%. A metal sphere with a diameter of 3.0 cm is then dropped from a fixed (but variable) height onto the surface of the sand by means of an electromagnetic release mechanism [8].



(A) Schematic of the experimental setup, consisting of the container filled with sand, release mechanism for the ball, x-ray source and detectors. (B) Snapshots of the impact experiment using a high-speed camera to image the events above the surface (top) and the analysis of the x-ray detector signals for the cavity and ball inside the sand bed (bottom).

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The container is positioned into our x-ray setup which consists of three powerful continuous industrial x-ray sources and three horizontal arrays of 32 fast x-ray detectors which are capable of measuring the transmitted x-ray intensity with a sample rate of 2,500 Hz [7]. The setup is sufficiently large to fit the full-sized experiment used in previous experiments [9] and is is fast enough to capture the impact events, which typically take place within a time span of about 500 ms [see figure (A)]. The transmission is determined by the extent to which the medium absorbs the x-rays and thus, using the Lambert-Beer law, the signal of the detector can be translated to the distance the x-rays travel through the sand. Since our prime objective is to measure air cavities inside the sand, we calibrate the set-up by inserting air cavities of known dimensions prior to conducting the impact experiments.

This way, each experiment provides us with the time evolution of a cross-section of the cavity at a certain depth below the surface of the sand bed. The reproducibility of the experiment allows us to repeat the impact procedure imaging at different depths, which thus leads to a full time-resolved description of the cavity dynamics within the sand.

RESULTS

In figure (B) we compare eight snapshots from a high-speed image recording of the visible events above the surface with the corresponding cavity reconstructed from the x-ray detector signals. In the second snapshot the ball starts penetrating into the sand and generating the splash. The sinking ball creates the cavity (3), which violently closes in the fourth snapshot, pinching off an air bubble. This closure leads to the formation of the jet, which slightly later protrudes above the splash (5). While the jet falls back onto the bed, the entrapped air bubble slowly rises through the sand (6) and upon reaching the surface (7) creates an eruption of sand grains (snapshot 8).

The setup allows for more than the reconstruction of the cavity in time that is illustrated in figure (B): By moving the container closer to the x-ray source we are able to increase the resolution considerably. This enables us to image the generation of the jet at the pinch-off point − i.e., inside the sand − and to determine its growth as a function of time. We measure the time-evolution of the closure of the cavity and compare it to the scaling laws that have been found for the collapse of an axisymmetric cavity in a liquid. For high values of the impact velocity we even found evidence for the secondary collapse that has recently been conjectured in the literature.

CONCLUSION

Cavity and jet formation after the impact of a ball on a layer of fine, very loose sand are studied by means of x-ray imaging techniques. We obtain a full, time-resolved reconstruction of the cavity within the sand bed and are able to image the production of the jet within the sand. We compare the time evolution of the cavity during closure with scaling laws that are known to hold in liquids.

References

[1] Lohse, D., Bergmann, R., Mikkelsen, R., Zeilstra, C., van der Meer, D., Versluis, M., van der Weele, K., van der Hoef, M., Kuipers, H. *Phys. Rev. Lett.* **93**, 198003, 2004.

[2] Royer, J.R., Corwin, E.I., Flior, A., Cordero, M.-L., Rivers, M.L., Eng, P.J., Jaeger, H.M. *Nat. Phys.* **1**, 164, 2005.

[3] Caballero, G., Bergmann, R., van der Meer, D., Prosperetti, A., Lohse, D. *Phys. Rev. Lett.* **99**, 018001, 2007.

[4] Royer, J.R., Corwin, E.I., Eng, P.J., Jaeger, H.M. *Phys. Rev. Lett.* **99**, 038003, 2007.

[5] A.M. Worthington: A Study of Splashes. Longman and Green, 1908.

[6] Gekle, S., Gordillo, J.M., van der Meer, D., Lohse D. *Phys. Rev. Lett.* 102, 034502, 2009, and references therein.

[7] Mudde, R.F., Alles, J., van der Hagen, T.H.J.J. *Meas. Sci. Technol.* **19**, 085501, 2008.

[8] For safety reasons the whole set-up is situated in a closed, shielded room and the electromagnetic release mechanism allows us to actuate the experiment remotely.

[9] In [5] Royer *et al.* were able to image the cavity using a parallel x-ray beam on a small-scale setup filled with boron carbide particles instead of sand. This setup was roughly an order of magnitude smaller than the other experiments discussed in [1-4] and later papers.