Grain-by-grain reconstruction of a granular bed from x-ray microtomography data

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Introduction

Mesoscale disordered materials are ubiquitous in industry and in the environment. Any fundamental understanding of the mechanical and transport properties of random materials must follow from a thorough understanding of their microstructure [1, 2]. However, in the overwhelming majority of cases, knowledge of the structure of random materials is limited to first- and second-order structural correlation functions, (i.e., the mean filling fraction and the structural autocorrelation function). Here we report the successful conjunction of micron-scale resolution x-ray microtomography together with three-dimensional (3-D) image processing to determine the full 3-D real-space structure of a model disordered material, a granular bed.

Methods and Materials

The experiment was performed at sector 20-ID of the Pacific Northwest Consortium (PNC) beamlines at the Advanced Photon Source. The area detector of our prototype tomography apparatus follows the general considerations of Koch, *et al.*, [3], with the exception that an inexpensive eight-bit room-temperature CCD camera was used as an initial cost-saving measure. A cooled CCD camera will be used in the final apparatus. The tomography sample stage consisted of two miniature linear translators for centering mounted atop an Aerotech ART-50 rotary stage. The rotary stage was itself mounted atop a homemade two-axis motorized tilt stage; these two degrees of freedom were used to ensure that the rotation axis was simultaneously perpendicular to the beam direction and to the effective CCD line scan direction with precision 10^{-5} radians. A standard filtered backprojection algorithm was used to reconstruct the tomographs from the rotational sequence of radiograms. A photon energy of 19.8 keV was used in the present study.

For the results reported here, the sample was a simple granular bed consisting of ~63 μm-diameter spherical glass beads in a vertical 1.0 mm inner-diameter glass cylinder. The beads were first poured into the cylinder through a paper funnel. Room humidity was sufficiently low that no clumping was apparent during pouring. The resulting granular bed was then vertically agitated for 1000 cycles with a maximum acceleration of 22.5 m/s^2. Next, the granular bed was mounted onto the tomography sample stage and the necessary rotational sequence of radiograms were collected for the same volume of the sample for sample-to-detector distances of 2 cm, 8 cm, 14 cm, and 20 cm. Tomograms whose raw data were collected at large sample-to-detector distances showed a gradually increasing degree of x-ray phase effects in the usual form of a halo of increased intensity just outside the boundary of the objects [4]. This phase effect also manifests itself in the tomograms as a 3-D halo of anomalous decreased absorption just outside each bead. For the purpose of locating each granule by 3-D image processing, this artifact is highly desirable as it provides an enhancement of the apparent absorption gradient across the boundary of the granules, leading to improved gradient edge detection. We employed a 3-D Sobel gradient-edge algorithm, and then used a Hough sphere transform to locate the center of each grain [5, 6].

Results

For the present sample, we find that our software for grain center location works best for the data collected at a sample-to-detector distance of 14 cm [6]. In Figure 1, we present a 2-D projection of the center locations of each grain in a subvolume of the granular bed.

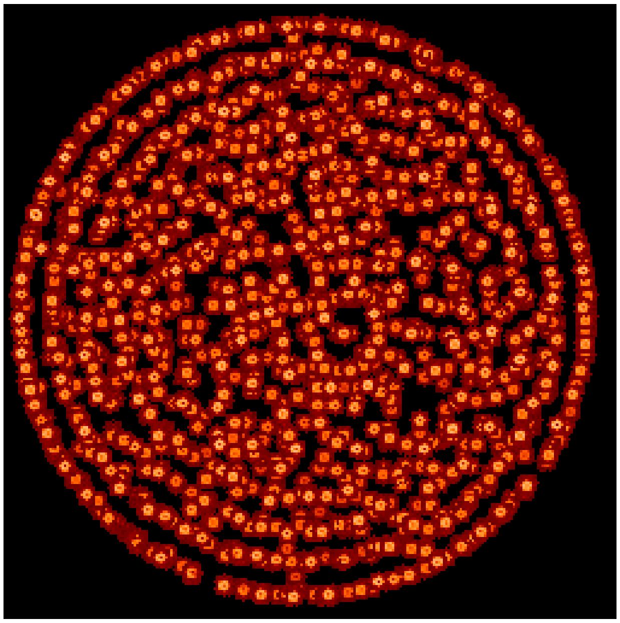

Figure 1: A projection down the vertical axis of the centers of grains for a sample subsection with a thickness of five grain diameters. Each circular disk represents the center of a grain and is drawn to 1/3 scale of the diameter of the actual grains so that the structure can be more easily observed.

Discussion

With complete knowledge of the grain-by-grain structure of this disordered material, we are able to calculate several high-order structural correlation functions that are otherwise unobtainable [6]. Additionally, we will discuss elsewhere the boundary-induced order apparent in Figure 1 [7].

In conclusion, we have demonstrated computerized grain-by-grain reconstruction of a granular bed starting from real-space voxel-absorption information obtained by x-ray microtomography. This capability enables future studies of the evolution of the connectivity network of granular beds under perturbation.

Acknowledgments

This research was supported by the Alfred P. Sloan Foundation; the Research Foundation; and the U.S. Department of Energy, Basic Energy Sciences, Office of Science, under Contract No. DE-FG03-97ER45628. Use of the Advanced Photon Source was supported by the U.S. Department of Energy, Basic Energy Sciences, Office of Science, under Contract No. W-31-109-Eng-38.

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