CHARACTERIZATION OF THE INTERNAL MICROSTRUCTURES OF GRANULAR MATERIALS USING COMPUTERIZED TOMOGRAPHY

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INTRODUCTION

In developing micromechanical models of constitutive behavior, granular materials are treated as ensembles of discrete particles. The macroscopic mechanical properties of these materials are derived from force-deformation relations [1], which describe the behavior of particle-to-particle contacts at the microscopic level. The occurrence and behavior of these contacts are controlled by the packing structures in the granular system. The packing structures used in many current approaches to modeling granular materials are either regular [2,3,4] or numerically-generated random packings [5]. To properly account for actual particle packings, however, it is desirable to develop an experimental technique for direct observation. In this paper, the microstructures of simplified materials (laboratory packed spherical particles) are investigated using X-ray computerized tomography (CT), which provides a non-intrusive way to obtain cross-sectional images of material samples. Series of these digital images are then processed to reconstruct the three-dimensional internal structure of the sample using numerical techniques. Scanning and image analysis results for a sample made of glass spheres are presented in this paper, demonstrating the potential of CT technology in identifying the microstructures of granular materials.

EXPERIMENTS

Several recent applications of X-ray computerized tomography technology to investigate civil engineering materials have been reported [6,7] using medical CT devices, which have limited resolution, typically in the range of 2 to 5 mm with 60 to 100 KeV X-ray source energy. An earlier study of applying industrial CT technology to investigate the material microstructures of granular materials was first reported in 1989 [8]. In the report, a high resolution industrial CT machine,
which had an X-ray source with energy level ranging from 300 to 420 KeV, was applied to obtain cross-sectional images of asphaltic concrete cores, demonstrating the application of CT technology to material microstructural characterization.

In the present study, an industrial computerized tomography machine manufactured by Scientific Measurement Systems, Inc (SMS) was used. This CT machine (SMS Model 101B+), owned and operated by Oak Ridge National Laboratory, has a 420 KeV X-ray source, spatial resolution in the range of 0.002 to 0.04 inch, and the capability of resolving density differences as small as 0.25 percent. Figure 1(a) depicts the 101B+ CT scanning setup. The material sample scanned for this study was made of 6 mm borosilicate glass beads with specific gravity $G = 2.23$. Approximately one thousand beads were tightly packed into a 2 inch diameter by 4 inch long cylindrical plastic container and capped with sulfur. To obtain three dimensional microstructural information, multiple scans were performed on the central portion of the sample at a 2 mm spacing in the axial direction, as shown in Figure 1(b). The 2 mm spacing was selected to assure that each glass bead would appear in at least two consecutive transverse images, which was required by the numerical algorithm developed for three dimensional reconstruction. This setup resulted in thirteen cross-sectional images, which were used to numerically reconstruct the middle 24 mm portion of the sample. The scanning parameters used are important because they control the resultant image resolution, i.e. the sizes of microstructural features which could be identified. For these scans, 60 detectors were used with their aperture set at 0.2 $\times$ 0.2 mm. Ray spacing was 0.1 mm, and exposure time was 0.02 sec.

![Fig. 1. CT setup.](image)

**ANALYSIS OF COMPOSITE STRUCTURES**

Figure 2(a) shows one of the thirteen raw CT images. The image has $752 \times 752$ pixels; each pixel is 0.0789 mm square. The raw pixel values, representing photon opacity, are in the range of -10,000 to 10,000. These values can be converted to material mass densities. The thick gray ring immediately surrounding the beads is a plastic container. Other rings outside the container are artifacts of the CT reconstruction process. The beads appear to have various diameters because their centers are either above or below the plane of this cross section. Void spaces between particles appear black. The “halo” surrounding each bead is a density smearing effect caused by limited spatial resolution of the scan.
The first step in image processing is to mask out the artifacts and the container, leaving only the material sample, as shown in Figure 2(b). Figure 3 plots two histograms corresponding to the raw, Figure 3(a), and masked, Figure 3(b), images. The abscissa of the histograms represents pixel values of the raw CT image and the ordinate is the number of occurrences for each pixel value. Comparison of these two histograms shows that eliminating the effects of the artifacts and container provides a more accurate representation of the pixel value profile of the sample. The histogram of the masked image is used for subsequent image analysis.

The next step is to extract information from each image on edges of beads and their connectivities. Several edge detection methods used in image analysis [9] could be applied to determine the edges between particles and air voids. However, close examination of the histogram of the masked image reveals that this histogram can be approximately divided into three regions, with pixel values in the range -8600 to -1250 (air voids), -1250 to 6200 (density smearing effects), and 6200 to 10000 (glass beads). The CT image shows that the region of density smearing ("haloing") is only 3 to 4 pixels wide, which is about 0.237 to 0.316 mm, or about 5 percent of bead size. Therefore, choosing a threshold value between -1250 to 6200 to determine the edges between beads and air voids offers a simple way to locate the edges with a maximum dimensional error of 5 percent. In this analysis, five different threshold values (0, 1000, 2000, 3000, and 3850) were used to identify the edges of beads. These edge points are then analyzed and connected into circles with their center locations and radii being calculated.

The evaluated circles on each cross-sectional image are used to reconstruct the three-dimensional internal structure of the sample. Because the axial spacing

![Sample CT image](image)

(a) raw.  
(b) masked.

Fig. 2. Sample CT image.

![Histograms of pixel values from sample image](image)

(a) raw.  
(b) masked.

Fig. 3. Histograms of pixel values from sample image.
between cross-sectional images is set at 2 mm (25 pixels) to assure at least two circles on two adjacent images belonging to the same sphere, circles for the same spheres can be grouped and used to determine the three-dimensional geometry of the spheres (glass beads) including their center locations in x-y-z coordinates and corresponding radii. Figure 4 depicts the reconstructed internal packing structures in the scanned middle portion of the sample. The analysis results indicate that there are 258 glass beads in this 24mm section. The threshold pixel value used in the pictured analysis was 3000. To accurately determine particle coordination numbers (i.e. average number of contacts per particle), boundary particles, which have contacts with the plastic container and are shown darker in Figure 4, were not used. The top and bottom layers of particles in this reconstructed sample were also not used in determining average contacts due to the lack of information on the contacts from adjacent particles outside the 24 mm middle portion.

Figure 5 shows the variation in numerical results using the five different threshold values as stated above. Figure 5(a) plots the distribution of calculated radii of the spheres, which vary from a minimum of 34 pixels (2.68 mm) using a 3850 threshold, to a maximum of 41 pixels (3.24 mm) using a 0 threshold. Figure 5(b) plots the distribution of the number of contacts for these spheres. The average radii and coordination numbers for different threshold values are shown in Figure 6(a) and 6(b), respectively. These results show that varying the threshold density value used for edge detection has very little effect on particle structure analysis, especially in the range of 0 to 2000, in which the average radius varies from 2.95 mm to 3.02 mm (less than a 2 percent) and the corresponding coordination number varies from 6.76 to 7.00.

Fig. 4. Reconstructed packing structure of a bead sample.
CONCLUSION

X-ray computerized tomography can be utilized as a non-destructive testing tool to characterize internal packing structures of granular materials. A simple and numerically efficient image processing technique has been developed to process CT images and reconstruct packing structures of spherical particles. The actual three-dimensional packing structures of a scanned sample are reconstructed. Microstructural parameters required in micromechanical modeling, such as particle sizes, spatial distribution, and coordination numbers, are obtained. This study has demonstrated the potential of computerized tomography to quantitatively identify microstructural parameters of granular materials.

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