

Comparisons between Two-Dimensional and Three-Dimensional Fabric Characterizations Based on Scalar Parameters for Sands

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ABSTRACT

Soil particles that have been deposited through water or air generally align their largest projected surface area normal to the depositional direction, which generates a cross-anisotropic fabric of granular soils. Researchers have used both two-dimensional (2D) and three-dimensional (3D) images to determine scalar fabric parameters of granular soils, including void ratio, coordination number, and average branch vector length. This study aims to evaluate the accuracy and effectiveness of 2D images to characterize fabric in 3D soils based on scalar parameters. The X-ray computed tomography (X-ray CT) is used to reconstruct the 3D volumetric images of three air-pluviated sand specimens, including crushed limestone, Griffin sand, and glass beads. Then, six slices are obtained by vertically cutting the 3D volumetric image in an angle increment of 30 degrees. The 3D and 2D images are analyzed to determine scalar fabric parameters. The results show that coordination numbers and average branch vector lengths computed from 2D images underestimate these values in 3D granular soils. The void ratios computed from 2D images vary a large range depending on slicing directions, which cannot provide reliable fabric characterizations for 3D granular soils.

INTRODUCTION

Soil particles that have been deposited through water or air generally align their largest projected surface area normal to the depositional direction, which generates a cross-anisotropic fabric of granular soils. The influences of fabric anisotropy on the mechanical behavior of soil, such as strength, permeability, and compressibility, were investigated by many experimental and numerical (e.g., discrete element method) studies (Hansen 1948; Strahler 1957).

Fabric can be quantified by directional and scalar parameters (Fonseca et al. 2013a; b). The directional parameters included spatial distributions of particle long axes, contact normals, and branch vectors. The scalar parameters include void ratio, coordination number, and average branch vector length. The previous researchers used both two-dimensional (2D) and three-dimensional (3D) images to evaluate directional and scalar parameters for fabric characterizations in granular soils. For example, Oda (1972), Oda and Nakayama (1989), Kuo et al. (1996) and Yang et al. (2008) injected resin into the pores of sand specimens to solidify them and then cut them into thin slices. They analyzed the slices to infer fabric anisotropy in 3D soils. To characterize fabric in 3D sand specimens, the X-ray computed tomography (X-ray CT) must be used to scan the specimen and reconstruct the microstructure. Many researchers have used X-ray CT to investigate fabric anisotropy in 3D sand specimens. (Fonseca et al. 2013a, 2013b; Alam et al. 2018; Imseeh et al. 2018; Alshibli and Cil 2017; Druckrey et al. 2016; Wiebicke et al. 2015, 2017a, 2017b; and Sun et al. 2018).

The accuracy and effectiveness of using 2D images for inferring fabric characterizations of

3D soil specimens were rarely investigated. In a recent study, Sun and Zheng (2019) evaluate the accuracy of using 2D image-based directional parameters for estimating fabric anisotropy in 3D granular soils. The results showed that 2D images produced satisfactory predictions for long axis fabric and branch vector fabric. The 2D images produced satisfactory predictions for contact normal fabric for rounded to well-rounded sands, but underestimated or contained large uncertainties to predict contact normal fabric for very angular to sub-rounded soils.

This study focused on evaluating the accuracy of 2D image-based scalar parameters for estimating fabric anisotropy in 3D granular soils. In this study, crushed limestone, Griffin sand, and glass beads were used to generate air-pluviated specimens. Then, these specimens were scanned by X-ray CT scanner to generate 3D volumetric images. 2D images were obtained by vertically cutting the 3D volumetric images. 3D and 2D image processing techniques were used to analyze 3D and 2D images to determine scalar fabric parameters (i.e., void ratio, coordination number, and average branch vector length). The effectiveness and accuracy of 2D image-based scalar fabric parameters were evaluated by comparing results from 2D and 3D images.

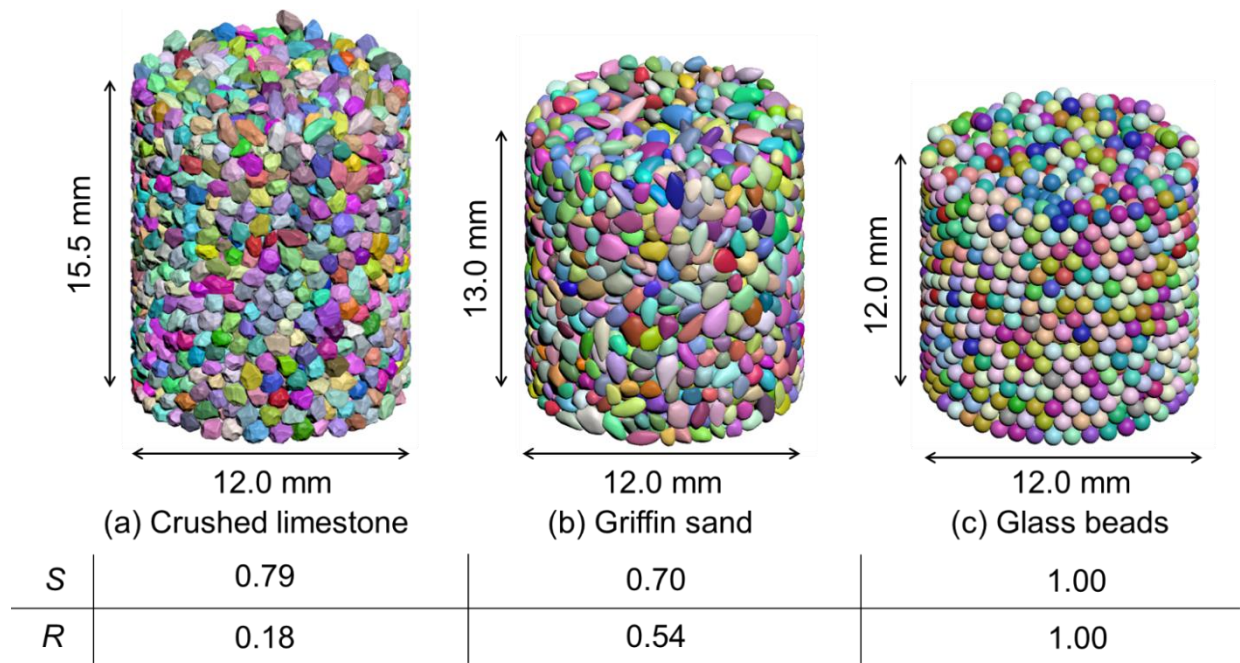


Figure 1. 3D soil specimens scanned by X-ray CT

3D AND 2D IMAGES OF SOIL SPECIMENS

In this study, three types of granular soils were selected. They were crushed limestone containing very angular to angular particles, Griffin sand containing subrounded to rounded particle, and glass beads containing well-rounded particles. For each soil, we manually picked out 2925 particles ranging from #30 (0.595mm) sieve to #16 sieve (1.19mm). Then, these particles were funneled into a cylinder with a diameter of 12mm. Then, the cylinder with soil particles was shaken on a vibration table to generate a dense specimen with a relative density of 85%. The heights of crushed limestone, Griffin sand, and glass beads specimens were 15.5mm, 13.0mm, and 12.0mm, respectively.

The soil specimens were scanned by X-ray computed tomography (X-ray CT) with a spatial resolution of 12 μm/voxel. An improved watershed analysis (Sun et al. 2019b) was used to

separate particles and air, and segment contacting particles, as shown in Fig. 1. Then, we digitally cut the volumetric images to generate cross-sections with an angle increment of 30° , yielding six slices for each specimen, as shown in Fig. 2.



Figure 2. Six slices of selected soil specimens.

The particle shapes of crushed limestone, Griffin sand, and glass beads were quantified by sphericity and roundness. Sphericity quantified how close of a particle to a perfect sphere. It was defined by Krumbein and Sloss (1951):

$$S = \sqrt[3]{\frac{d_2 d_3}{d_1}} \quad (1)$$

Where d_1 , d_2 , and d_3 are particle length, width, and thickness. The d_1 , d_2 , and d_3 values can be determined by a principal component analysis technique (Quan et al. 2018). The points on the 3D particle surfaces are projected onto orthogonal directions. Each direction represents a principal component. The first principal component captures the largest variance of points, which determine the d_1 of the particle. Each succeeding component, in turn, captures the largest variance for the remaining data points under the constraint that it is orthogonal to the preceding components. Therefore, the second and third components identify the d_2 and d_3 of the particle, respectively. The 3D particles in Fig. 1 were analyzed by the principal component analysis. The determined average S values for three soils are shown in Fig. 1.

The roundness measures the angularity of particles. Based on the maximum projection of particle, (Wadell 1932, 1933, 1935) defined the roundness as:

$$R = \frac{\text{average radius of curvature of corners}}{\text{radius of the largest inscribed circle}} = \frac{1}{r_{in}} \left(\frac{1}{N} \sum_{i=1}^N r_i \right) \quad (2)$$

Where r_i is the radius of the i -th circle fitting to the i -th corner to compute the radius of curvature, N is the total number of corners, and r_{in} is the radius of the maximum inscribed circle of the particle.

Zheng and Hryciw (2015, 2016) established a computational algorithm, which can automatically identify the maximum projections of the particles, identify corners and corner circles, and compute R values. The 3D particles in Fig. 1 were analyzed by the computational geometry code. The determined R values for three soils are shown in Fig. 1.

SCALAR PARAMETERS FOR FABRIC CHARACTERIZATION

The fabric anisotropy can be quantified by directional parameters and scalar parameters (Fonseca et al. 2013a, 2013b). The scalar parameters were used in this study. The most commonly used scalar parameters included void ratio, average branch vector length, and coordination number.

Void ratio (VR) is defined as the volume of voids to the volume of soil particles. For the volumetric images, the volume can be quantified as the number of voxels (pixels for 2D case). Thus the void ratio can be calculated by:

$$e = \frac{N_{\text{total voxel}} - N_{\text{particle voxel}}}{N_{\text{particle voxel}}} \quad (3)$$

Where $N_{\text{total voxel}}$ is the total number of voxels of the specimen, $N_{\text{particle voxel}}$ is the number of voxels within soil particles, and $N_{\text{total voxel}} - N_{\text{particle voxel}}$ is the number of voxels within voids.

Branch vectors connect contacting particles' centroids. Sun et al. (2018) developed a modified Delaunay triangulation to determine the branch vectors of granular soils in 3D and 2D images as shown in Fig. 3. Once the branch vectors obtained, the average branch vector length (BV) can be determined. For example, a total of 12189, 12551, and 9209 branch vectors were determined from 3D images of crushed limestone, Griffin sand, and glass beads, respectively. Then, the average branch vector lengths were computed as 1.10mm, 1.06mm, and 1.00mm, respectively.

The coordination number indicates the average contacts number of a single particle in a soil specimen. It can be calculated by:

$$CN = \frac{2N_c}{N_p} \quad (4)$$

Where N_p is the number of particles in the specimen, and N_c is the number of contacts. Both N_p and N_c in a granular soil specimen can be determined by the improved watershed analysis (Sun et al. 2019b).

The void ratios (VRs) for crushed limestone, Griffin sand, and glass beads are computed as 0.78, 0.70 and 0.68, respectively, from 3D images. These values are plotted against sphericity and roundness in Fig. 4. The void ratios computed from six slices of each sand are also shown in Fig. 4, which varies in a wide range depending on slicing directions.

The three sand specimens were prepared at the same relative density of 85%. The void ratios of sand specimens do not display a clear relationship with particle sphericity as shown in Fig. 4(a). However, Fig. 4(b) shows that more angular soils tend to develop larger void ratios under the same relative density. The same observations have been made by Zheng and Hryciw (2016b).

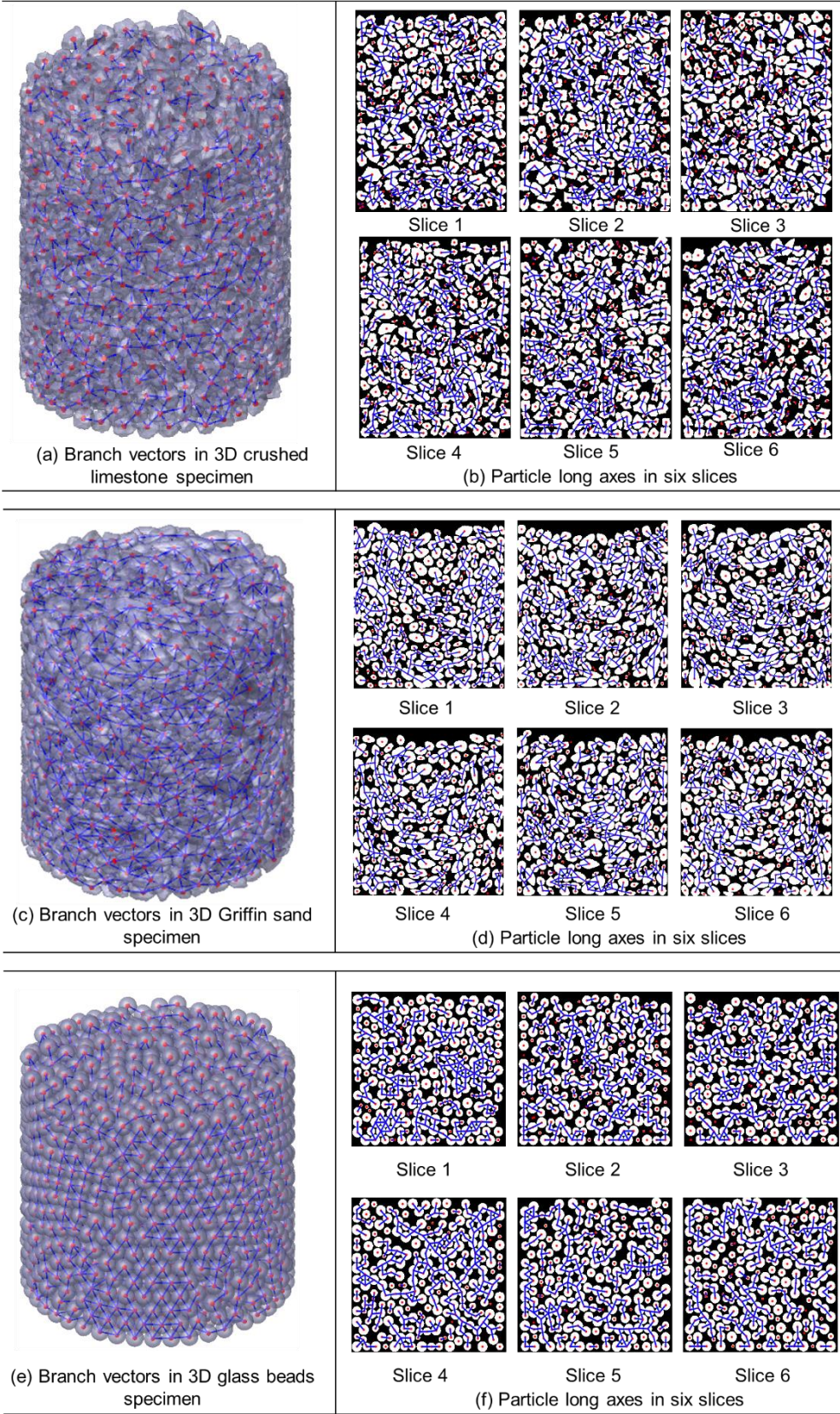


Figure 3. Branch vectors of 3D and 2D images of three soil specimens.

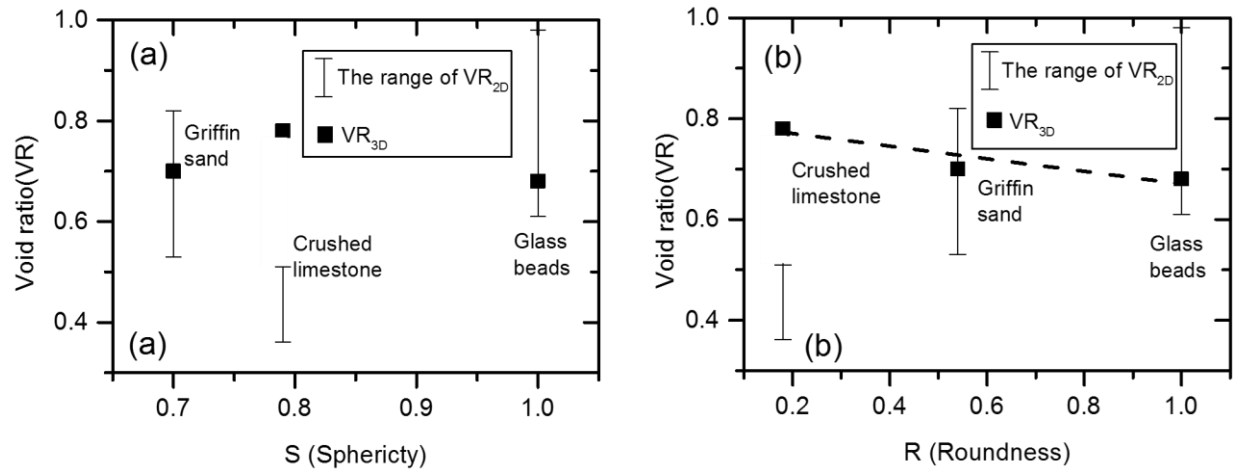


Figure 4. The void ratio from 2D and 3D images and their relationships with soil sphericity and roundness.

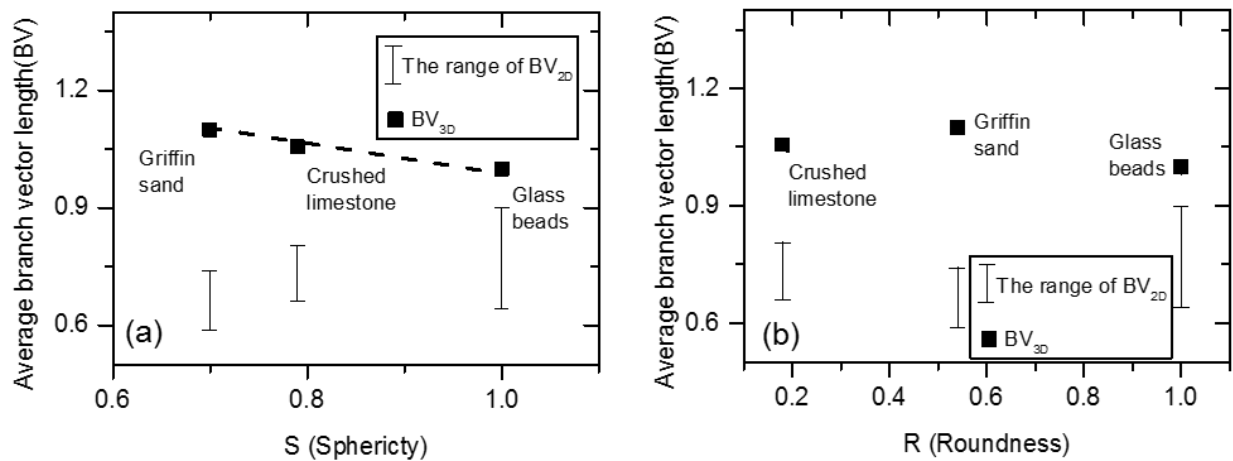


Figure 5. The branch vector length from 2D and 3D images and their relationships with soil sphericity and roundness.

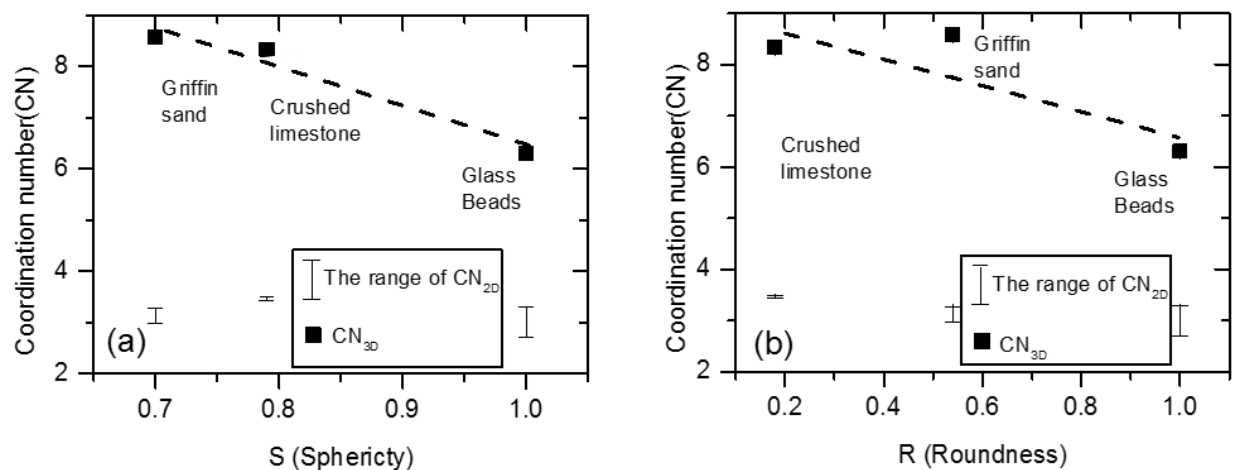


Figure 6. The coordination number from 2D and 3D images and their relationships with soil sphericity and roundness.

The average branch vector lengths (BVs) computed from 3D and 2D images are plotted against sphericity and roundness in Fig. 5. The 2D image-based average branch vector lengths of three soils significantly underestimate the average branch vector lengths in 3D soils. In addition, there is no clear relationship between average branch vector lengths and particle shape.

The coordination numbers (CNs) computed from 3D and 2D images are plotted against sphericity and roundness, as shown in Fig. 6. The CNs from 2D images significantly underestimate CNs in 3D soils. The CNs decrease as increasing sphericity and roundness, suggesting elongated and angular soils have larger CNs. The same observations have been made by Zheng and Hryciw (2017).

CONCLUSION

In this study, crushed limestone, Griffin sand, and glass beads specimens were scanned by X-ray scanner. Both 2D slices and 3D images of the specimens were analyzed to determine scalar fabric parameters, including void ratio, average branch vector length, and coordination number.

The average branch vector length and coordination number from 2D images significantly underestimated these fabric parameters in 3D soil. The void ratios computed from 2D images varied a large range depending on slicing direction, and cannot provide reliable estimations in void ratios in 3D soils.

In addition, particle shape influences the soil fabric. The angular soils tend to develop large void ratios under the same reality density. Elongated and angular soils tend to develop larger coordination numbers. However, the average branch vectors did not show a clear relationship with particle shapes.

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