D specimen and digital test for granular materials

Echantillons Nigitalumériques et Tests Numériques pour les Matériaux Granulaires

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ABSTRACT

Digital method is a powerful tool to investigate the micro behavior of granular materials without damage to the actual aggregate skeleton. The micro quantities such as particle mass centers, particle orientations, particle volumes, particle movements and particle rotations observed in regular laboratory tests were quantified by using imaging techniques provided in this study. 3D digital specimens can be generated and visualized in numerical simulations by incorporating digital data from image analysis, which represents the real microstructure of materials.

RÉSUMÉ

Les méthodes numériques discrètes constituent un outil puissant pour étudier le comportement, à l'échelle microscopique, des matériaux granulaires, sans dommage pour la microstructure réelle du matériau. Les micro-grandeurs telles que les centres de gravité des particules, leur orientation, leur volume, les déplacements et les rotations des particules observés dans un essai de laboratoire classique, sont simulées et quantifiées en utilisant les techniques d'imagerie présentées dans cette étude. Des échantillons numériques 3D peuvent être générés et visualisés dans les simulations numériques en incorporant les données numériques provenant de l'analyse d'image, représentant ainsi la microstructure réelle du matériau.

Keywords : Digital method, micro quantities, digital specimen, numerical simulations, image analysis, granular materials

1 INTRODUCTION

Granular Materials are assemblies of discrete particles which interact only at the contacts. Many geomaterials such as soils, aggregates, and concrete can be modeled as granular materials which are discontinuous and heterogeneous. Research on granular materials has been carried out in order to understand engineering problems such as shear banding, liquefaction and dilatation. It has been widely recognized that the micro feature plays a significant role on the overall behavior of a granular material. Various digital methods have been utilized to examine the microstructures of materials. The most popular tools include Radiography, Nuclear Magnetic Resonance (NMR, Lizak et al 1991), Laser-Aided Tomography (LAT, Konagai et al. 1992), and X-ray Computed Tomography (XCT, Lee and Dass 1993). These advanced imaging techniques are able to diagnose the internal structure without damaging the materials. Compared to MRI and LAR, XCT has the advantages of powerful penetrating and high sensitivity to material density. Furthermore, the specimen needs no special treatment as MRI requires. A computer-based testing and evaluation system using image digital techniques for design of construction materials can be established to investigate the durability of material in service life and save the cost for conventional laboratory tests. Micro quantities such as particle locations, orientations, volumes, and movements are also able to be quantified by computers using digital techniques, which are usually difficult to be measured in conventional laboratory tests. The fabric rearrangement as well as stress and strain distributions during shear loading can be further investigated with those micro quantities, which will be helpful to the understanding of engineering phenomenon such as shear banding, liquefaction and dilation.

The digital data obtained from image analysis of a specimen can also be directly input into numerical models to digitally rebuild the material structure for simulations. In this way, simulations of the macro and micro behavior of granular materials under various loading conditions are based on the real material systems which take particle shape effect into consideration. The simulation results can also be evaluated through the application of digital analysis in conventional laboratory tests. Digital specimen and digital test provide fundamental tools for both simulation and evaluation of properties of granular materials.

2 IMAGE PROCESSING AND DIGITAL ANALYSIS

The philosophy of digital techniques is to scan a material using XCT or other imaging tools, and obtain the sectional images to investigate the internal structure by computational techniques. The original images can not be directly used for computer diagnosis since they carry complex information. Image processing is therefore needed to convert the original images into high quality binary images, i.e. pure black & white images. A segmentation threshold needs to be determined in order to complete this procedure. Methods to determine the segmentation threshold have been provided by various researchers (Roberts et al 1984; Jain and Dubuisson 1992; Leu and Chang 2005; Lindquist et al.1996). Figure 1 presents an original image and its binary image. The quality of image has been improved after image processing.

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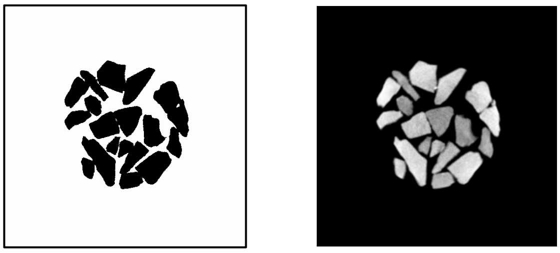


Figure 1 Binary image and gray image by image processing

Image analysis is another important procedure to obtain and analyze the digital data from binary images. Individual Bitmaps are first generated from binary images, each containing 512 by 512 pixels. Each pixel is assigned a value of 255 to white (represents void) or 0 to black (represents aggregates). The location of each pixel is recorded and the values of adjacent pixels are compared. The individual aggregate/void cross section can be identified and its mass center locations, perimeter, area etc. can be computed using the digitized data. (Fu et. al., 2008) Figure 2 illustrates the idea of particle identification. Table 1 is an illustration of a Bitmap.

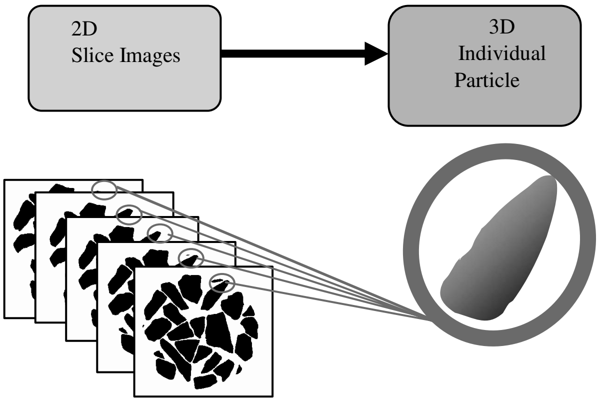


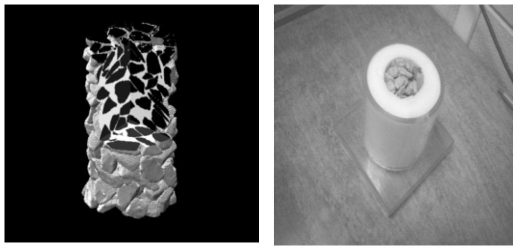
Figure 2 An illustration of 3D particle identification from sectional Images of a specimen

Table 1 An illustration of a bitmap generated by image analysis

Slice No.5	512 Columns									
	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	255	0	0	255	0	0
	0	0	255	255	255	0	0	255	255	0
	0	0	255	255	0	0	255	255	255	0
512 Rows	0	0	255	255	0	0	0	0	0	0
	0	0	0	0	0	0	0	255	255	0
	0	0	0	0	255	0	0	255	255	0
	0	0	255	255	255	0	0	255	0	0
	0	0	255	255	255	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0

3 DIGITAL SPECIMEN REPRESENTATION IN DEM SIMULATIONS

The digital data acquired from image processing and image analysis carry the geometric information of material's aggregate skeleton, which is essential to build the true digital specimen for Discrete Element Modeling (DEM) of real materials. Figure 3 is the 3D visualization of a digital specimen rebuilt from a real compression test. Most previous DEM simulations generated ideal specimens which were composed of either spheres or ellipsoids. The particle shape effect was ignored in those studies, which however, plays an important role to the load transfer pattern in the granular material. With the digital data, the irregular particles in real materials can be represented using clusters of small balls (Wang et. al, 2007).



a. 3D visualization b. Real specimen in a test

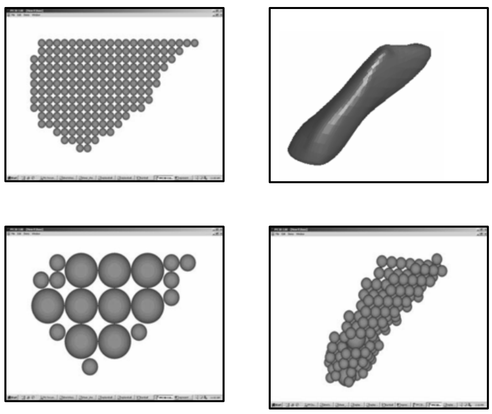
Figure 3 3D visualization of digital specimen for a compression test on loose aggregates. (Fu el al, 2008)

In clustering DEM, small balls are generated using the mass center coordinates and radii quantified by image analysis of real specimen. Small balls are slaved together in order to rebuild one irregular particle. A very large number of small balls are needed to represent all irregular particles in the specimen. As a result, huge memory space would be required in such simulations. To save simulation time and memory space, it is necessary to develop a burn algorithm to reduce the number of small balls. Following steps are required to burn the small balls.

Step1, scan all the balls used to represent the certain particle. Find cubic-pack groups and the centers of the cubic-pack. Using the center coordinates and diameter of the cubic-pack, generate one bigger ball to replace each cubic pack group.

Step2, repeat step 1 till the number of balls is within the specified range or no cubic-pack group can be found and replaced.

Figure 4 and Table 2 is an illustration of this procedure in both 2D and 3D.



2D particle 3D particle

Figure 4 An illustration of the burn algorithm in clustering DEM

Table 2. DEM simulation result analysis applying burn algorithm

Dimension	required number of balls		Reduced number of balls	Reduced (%)
	Before	After		
2D	207	19	188	90.82%
3D	3837	147	3690	96.17%

For a 2D DEM simulation, 207 small balls were required to represent one irregular particle, while 19 balls were used after applying algorithm, a reduction of 91%. For the 3D DEM simulation, 3837 small balls were required to represent one irregular particle. After the burn algorithm, only 147 balls were used in the simulation, a reduction of 96%. The Burn Algorithm made it possible to simulate irregular particle assemblies in a personal computer, which generally has low memory space.

Figure 5 is an illustration of a digital specimen rebuilt in a clustering DEM simulation after applying burn algorithm.

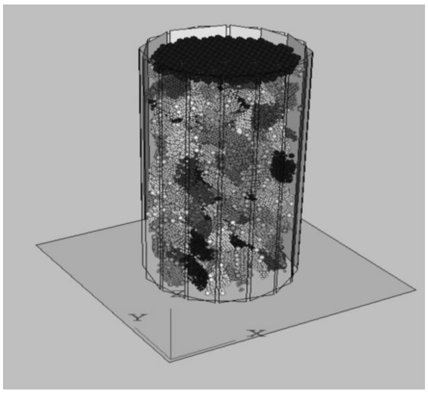


Figure 5 3D representation of specimen in DEM simulation of a compression test on loose aggregates using burn algorithm (Fu et al, 2008)

4 DIGITAL TEST OF GRANULAR MATERIALS

The microstructure of a granular material can be captured by digital techniques before and after an increment of loading. If the change of locations and orientations of the individual particles are recorded, the fabric rearrangement of the material can then be investigated based on mathematical relationships. A similarity index (SI) can be used to trace the particles after test, which is defined as follows:

$$SI_p = |x_b - x_a| + |y_b - y_a| + \left|z_b - (z_a + \frac{\Delta h}{h} * z_a)\right| \quad (1)$$

Where x,yb,z are mass center coordinates of individual particles subscript “b” represents before test and “a” represents after test; Δh is the vertical global deformation of the specimen; h is the height of the specimen. The particle with the smallest SI is recognized as the same particle before loading. If two or more particles after test are paired to the same original particle, then their volumes are compared and the one whose volume is closest to that original particle is recognized. The same procedure of finding another original particle giving the smallest SI is followed for the remaining particles. The magnitude of particle mass center movements can then be calculated as

$$DISP_k = \sqrt{u_k^{\ 2} + v_k^{\ 2} + w_k^{\ 2}} \quad (2)$$

Where

$$u = x^a - x^b ; v = y^a - y^b ; w = z^a - z^b \quad (3)$$

The superscript “a” denotes after the movements and “b” denotes before the movements. Particle orientations can also be quantified using the Feret Length theory. The Feret Length is an axis of a particle with maximum length. The angles of the Feret Length to the Cartesian axis-x, y, and z, define the orientation of a particle. With digitized information of particle boundary from image analysis, the Feret Length of an individual particle can be found by following equation:

$$d_i = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \quad (4)$$

$$L_{\max} = \max(d_i) \qquad i = 1, 2 \ldots, n \quad (5)$$

Where d_i is the distance between boundary points i and j, (i≠j) L_{max} is the Feret Diameter of an individual particle;

The orientation angle of Feret Diameter is calculated as:

$$\theta_x = \cos^{-1}\left(\frac{x_b - x_e}{L_{\max}}\right) \quad (6a)$$

$$\theta_y = \cos^{-1}\left(\frac{y_b - y_e}{L_{\max}}\right) \quad (6b)$$

$$\theta_z = \cos^{-1}\left(\frac{z_b - z_e}{L_{\max}}\right) \quad (6c)$$

$$\theta \in (0, \pi)$$

Where subscript “b” and “e” are two particle surface points that give the maximum distance; θ is the orientation angles against the axes.

The particle rotations are then calculated as the change of the particle orientations after loading.

$$\Delta\vec{\Omega} = \theta_b - \theta_a \quad (7)$$

Table 3 presents the particle mass center movements acquired from image analysis of a direct shear test on coarse aggregates. Table 4 is the quantified particle rotations and local rotations. The local rotations were the rotations of the local tetrahedrons formed by four adjacent particles. Those kinematic quantities are useful for the investigation of the fabric rearrangement of granular materials under shear loading. They are also basic quantities for the study of strain localizations in granular materials.

Table 3 Quantified particle mass center movements in a direct shear test

	mass center coordinates			Displacement		
Particle No.	x	y	z	dx	dy	dz
1	47.15	29.11	5.53	-0.14	-8.51	-0.16
2	81.65	29.81	9.34	-0.12	-8.65	-0.23
3	62.48	32.34	8.76	-0.15	-8.45	-0.29
4	116.66	31.61	5.99	-0.01	-8.84	-0.26
…	…	…	…	…	…	…
1280	34.84	33.93	4.84	-0.18	-8.39	-0.08

Table 4. Quantified particle rotations in a direct shear test

No.	Local Rotation (rad)			Particle Rotation (rad)		
	Δα	Δβ	Δγ	Δα	Δβ	Δγ
1	-0.01	0.00	0.00	0.11	-0.06	0.10
2	0.01	0.05	-0.02	-0.01	-0.02	0.00
3	0.00	0.02	-0.02	0.03	0.01	0.01
4	0.00	-0.01	0.01	-0.03	0.01	0.07
…	…	…	…	…	…	…
1280	-0.02	-0.10	-0.06	0.01	0.02	-0.04

Strain localization can be evaluated by the ratio of the local strains to the global strains of the entire specimen. The local strain in a tetrahedron is calculated as the average stress of four adjacent particles which form the tetrahedron.

The degree of strain localization can be defined as the effective local strains normalized by the effective global strain defined as

$$\varepsilon = \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 + \varepsilon_{12}^2 + \varepsilon_{23}^2 + \varepsilon_{13}^2} \quad (8)$$

Where ε is the effective strain; ε_{ij} is the strain in different directions(i,j=1, 2,3)

The quantified local strains and degree of strain localization from a direct shear test are presented in Table 5

Table 5. Quantified local strains and degree of strain localizations

	Macro Strain						effective strain	degree of strain localization
No.	ε_x	ε_y	ε_z	ε_{xy}	ε_{yz}	ε_{xz}	ε_{eff}	
1	0.01	0.00	0.01	0.00	0.01	-0.01	0.02	0.18
2	-0.01	0.00	-0.06	0.02	0.01	0.01	0.07	0.52
3	0.00	-0.02	0.04	0.00	-0.02	-0.02	0.06	0.46
4	-0.02	-0.02	-0.02	0.03	0.04	-0.04	0.10	0.74
5	0.01	0.01	0.01	0.01	-0.01	0.00	0.02	0.15
6	0.00	-0.04	0.22	0.02	-0.06	0.06	0.26	1.95
7	-0.01	-0.02	0.00	0.01	-0.01	0.00	0.03	0.24
8	0.00	-0.89	-0.02	-0.03	-0.02	-0.31	1.00	7.49
9	-0.01	-0.01	0.08	0.00	0.00	-0.01	0.08	0.61
10	0.01	0.00	0.04	0.01	0.01	-0.02	0.05	0.39

5 CONCLUSIONS

The digital analysis method provided in this study is a valid tool to investigate the internal structures of granular materials. A Similarity Index was defined in order to automatically identify and recognize the individual particles within the material. The microstructure of the specimen can be rebuilt and visualized in 3D numerical models. With the digital data of the particle cross sections, particle movements and rotations can be quantified by computer manipulation. The particle-recognizing procedure relies on the mass centers of particle cross sections, and it is applicable to experimental tests in which particles have relatively small movements compared to their size. For particles that may experience large particle movements, it is suggested to compare images acquired at different time intervals during the fabric evolution, and apply the recognizing procedure to each time interval. The methodology for the quantification of particle rotations is not suitable for cubic-shaped particles whose ferret lengths are not apparent.

The digital specimen generated in the clustering DEM represents the actual microstructure of a real geomaterial, which is critical to the modeling of the micro behavior of the material, such as irregular particle kinematics, fabric evolutions, stress distributions, and strain distributions. The employment of the burn algorithm saved significant computation time by enabling the representation of irregular particles using much less number of balls.

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REFERENCES

Konagai, K., Tamura, C., Rangelow, P.and Matsushima, T., Laser-Aided tomography, A tool for visualization of changes in the fabric of granular assemblage, Structural Engineering/ Earthquake engineering, v 9, n 3, p 193-202, 1992.

Lee, X. and Dass, W.C., An experimental study of granular packing structure changes under load, Powders & Grains, v 93, (Ed: C. Thornton), p17-22, 1993.

Roberts, L. R., Scali, M. J., Grace, W. R., Factors affecting image analysis for measurement of air content in harden concrete, International Conference on Cement Microscopy, p 402-419,1984.

Jain, A.K., and Dubuisson, M.P, Segmentation of x-ray c-scan images of fiber reinforced composite materials, Pattern Recognition, v 25, p 257-270, 1992.

Leu, Sou-Sen, and Chang, Shiu-Lin, Digital image processing based approach for tunnel excavation faces, Automation in Construction, V14, p750-765, 2005.

Lindquist, W. B.and Venkatarangan, A, Investigating 3D geometry of porous media from high resolution images, Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy, V24, Issue 7, P 593-599, 1999.

Lizak, M.J, Conradi, M.K. and Fry, C.G., NMR Imaging of gas imbibed into porous ceramic, J. of Magn., Res., v 95, p 548-557, 1991.

Fu, Y.R, Wang, L.B, Tumay, Mehmet T, Li Q.B, Quantification and Simulation of Particle Kinematics and Local Strains in Granular Materials Using X-ray Tomography Imaging and Discrete Element Method, Journal of Engineering Mechanics V. 134, n2, p143-154, 2008.

Wang L.B, Park, Jin-Young, and Fu, Y.R., Representation of Real Particles for DEM Simulation using X-ray Tomography. Journal of Construction and Building Materials, V. 21, P338-346, 2007.