# 3D Shape Characterization and Image-Based DEM Simulation of the Lunar Soil Simulant FJS-1

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**Abstract:** This paper describes a procedure used to characterize the three-dimensional (3D) grain shape of lunar soil and undertake simulations of lunar soil by image-based discrete element method (DEM). Given that detailed 3D grain-shape information is unavailable for real lunar soil, a simulant material, FJS-1, is used in this study. We use the high-resolution micro X-ray CT system at SPring-8, a synchrotron radiation facility in Japan, to visualize precise 3D images of the granular assembly of FJS-1. A newly developed image-analysis procedure is then applied to identify individual grains. Using the obtained grain-shape data, a sufficient number of FJS-1 grains are directly modeled for DEM simulation using an efficient modeling scheme. A series of particle flow simulations are then performed with the modeled grains. The resulting slope angles are in good agreement with experimental results. We discuss the effect on the slope angle of grain parameters such as contact stiffness, restitution coefficient, and interparticle friction.

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**CE Database subject headings:** Space exploration; Moon; Soil mechanics; Granular materials; X-rays; Radiography; Slope stability; Discrete elements.

# Introduction

Since the announcement in 2004 of a new vision for the United States space exploration program, lunar exploration has become one of the most pressing problems to be tackled. Various engineering fields (including civil, mechanical, and chemical) are expected to be involved in this program. Above all, lunar exploration requires a full understanding of the physical and chemical properties of lunar surface soil, as most of the raw materials necessary for human settlement on the moon will have to be produced from the soil. Although Heiken et al. (1991) produced a comprehensive report on the properties of lunar soil, it remains necessary to consider various additional aspects of the soil to ensure the level of technology required for exploration, such as oxygen production, countermeasures to lunar dust, and the construction of a base for long-term stay (Malla et al. 2006). For example, it is necessary to evaluate the electrostatic force acting on the grains, as this may provide the bulk cohesion of lunar soil. Interparticle friction in a vacuum may also be different from that on earth. To ensure efficient exploration planning, these

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new aspects should be carefully studied in advance, both experimentally and numerically.

Experimental approaches rely upon the availability of samples of lunar soil. Given the limited amount of lunar soil retrieved during the Apollo missions, a number of simulant materials have been produced in order to perform extensive experiments (Marshall Space Flight Center 2005); however, the degree of similarity of lunar soil and simulant material (in terms of physical and chemical behavior) remains a controversial problem.

From a mechanical viewpoint, the overall mechanical behavior of granular materials is strongly affected by grain properties such as size, shape, and crushability. Among these properties, grain shape has a considerable influence on the bulk mechanical properties (Oda and Kazama 1998; Shinohara et al. 2000; Pena et al. 2007). According to the reference publication on lunar soils (Heiken et al. 1991), their grain shapes are highly variable, ranging from spherical to extremely angular, although the grains are generally somewhat elongated and are subangular to angular. Some grains are highly irregular, containing reentrant surfaces; such grains are known as agglutinates. These grain-surface irregularities affect the compressibility and shear strength of the soil. In particular, for soils with a high bulk density, as reported in Heiken et al. (1991), the relative density of the lunar soil surface is about 74% at 0-30 cm deep and 92% at 30-60 cm deep, the soil is expected to exhibit very high shear resistance. Therefore, it is important to correctly evaluate the significance of grain shape within lunar soil.

Given the expense of conducting experiments using real lunar soil under the special circumstances encountered on the Moon, particle simulation methods such as the discrete element method (DEM) provide powerful alternatives to performing mechanical tests; however, it has been noted that DEM simulations cannot quantitatively predict the behavior of real granular materials, mainly because of their irregular grain shape. The use of an accurate grain-shape model, using polyhedral particles (Cook and Jensen 2002; Tutumluer et al. 2006), requires substantial computation time and resources.



To address this problem, Matsushima and Saomoto (2002) proposed an efficient image-based modeling method for irregularly shaped grains using a cluster of spheres; the approach showed a high level of adaptability into two-dimensional (2D) and (3D) DEM. In applying this technique, Matsushima et al. (2003a) and Matsushima (2004) performed simple shear simulations of natural sands, arriving at results that were in good quantitative agreement with experimental results. The representation of irregular grain shapes using clusters of spheres is much simpler in terms of a numerical algorithm than the use of polyhedral particles, as such an approach is free of the singularity problem at edge-to-edge, point-to-edge, and point-to-point contacts. This simplicity ensures the stability of the computation.

The present paper describes the application of the above modeling method in terms of FJS-1, a lunar soil simulant. A small amount of FJS-1 (but containing a sufficient number of grains) is precisely visualized in 3D using micro-X-ray CT analysis undertaken at SPring-8, Japan (Matsushima et al. 2004). A newly developed image-analysis technique enables us to identify individual grains in the CT-reconstructed image of the sample. Using this information on grain size and shape, a certain number of the simulant grains are directly modeled in a DEM simulation. Finally, a series of particle flow simulations are performed to demonstrate the performance of the DEM approach. The resulting slope angle is related to the angle of repose, the maximum angle of a granular slope at rest, and the bulk shear strength under very low pressure. The simulation results obtained using various models are discussed in comparison with experimental results.

# **Microscopic Imaging of FJS-1 Grains**

# **Basic Properties of FJS-1**

FJS-1 was produced in Japan (by Shimizu Corporation) by crushing Mt. Fuji basalt and adjusting the grain size to match that of lunar soil (Kanamori et al. 1998). The grain-size distribution of FJS-1, as measured in our laboratory, is shown in Fig. 1. The sample contains more than 20% by weight of fine particles (less than 0.074 mm in diameter). To obtain a clear X-ray CT image, we only analyze particles with diameters between 0.1 and 0.64 mm. Fig. 2 shows an image of particles taken using a digital microscope. The overall shape of the particles is very angular, and their surfaces are very rough; these features may give the sample a high shear strength.



Fig. 2. Microphotographs of FJS-1 grains

#### Micro X-Ray CT Measurement

To measure the 3D grain shapes within FJS-1, we used the Micro X-ray CT facility at SPring-8, Japan, the world's largest thirdgeneration synchrotron radiation facility (Matsushima et al. 2004). In contrast to conventional medical or industrial X-ray CT devices, the high flux density of the X-ray beam at SPring-8 enables X-ray CT with extremely high spatial resolution (Bonse and Busch 1996).

The system (SP- $\mu$ CT) consists of an X-ray light source, a double crystal monochromator, high-precision stages, and a high-resolution X-ray image detector (Fig. 3) (Uesugi et al. 1999, 2000; Tsuchiyama et al. 2005). The intense X-rays from the storage ring are first monochromatized using a Si (311) double-crystal monochromator to ensure that the subsequent CT process is simple and accurate. Given that the amount of original energy is immense, the available monochromatized X-ray energy at the sample stage is as much as 9–72 keV. Passing through the specimen, the X-ray arrives at an X-ray image detector, consisting of a thin scintillator, an optic system, and a charge-coupled device (CCD) camera. The effective pixel size is largely dependent on the choice of optics and the CCD camera.

The X-ray energy used in the following experiments was 25 keV. An image was taken every 0.5 deg over 180 deg of rotation, meaning that 360 images were used for each CT reconstruction.

Fig. 4 shows an example of a cross-sectional CT image of FJS-1 grains placed in a cylindrical vessel with an inner diameter of about 0.5 mm. The image was obtained at a spatial resolution of 1.0  $\mu$ m using a program based on the convolution back projection (CBP) method (Nakano et al. 2000). The brightness of each portion (pixel intensity) of the 8-bit image corresponds to the CT value [value of the linear attenuation coefficient (LAC) of



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Fig. 4. Example of obtained CT image



Fig. 6. CT image after binarization

X-rays obtained by CT reconstruction], which in turn is directly related to the specific gravity of the constituent minerals. A detailed discussion of the mineral composition of the sample is not within the scope of this study. From a mechanical perspective, the grains contain very few internal cracks, indicating that only minor grain crushing occurs.

# Image Processing to Detect Individual Particle Shapes

Our purpose is to obtain 3D shape information for all of the individual grains captured in the CT images (for example, Fig. 4). The first stage of this process is called "binarization," which involves distinguishing the portion of solid grains from other areas within the image (voids and areas of vessel). Fig. 5 shows the frequency distribution of pixel intensity (scale from 0 to 255) for



Fig. 5. Frequency of pixel intensity

the CT image shown in Fig. 4. The distribution has a maximum at a pixel intensity of around 120, which corresponds to the solid portion  $(SiO_2)$ . Therefore, the threshold pixel intensity was chosen as the minimal intensity value in Fig. 5; Fig. 6 shows the resulting 1-bit image.

Given that each grain is in contact with neighboring grains, the next step is to distinguish individual grains. For this purpose, we adopt an "erosion" process. Fig. 7 shows a 2D schematic illustration of this process (although the actual process was performed in 3D). White pixels represent a solid grain, and black pixels represent voids. In the adopted erosion process, any white pixel with at least one neighboring black pixel (those marked '\*' in the figure) is changed to black. In this way, the pixels along the grain edge are eliminated and the grain becomes smaller (eroded). After repeating this process several times, all of the grains are separated. Fig. 8 shows the results of applying the process two times, four times, and seven times.

After the erosion process, we perform "cluster labeling" (Hoshen and Kopelman 1976) to identify each individual grain. Cluster labeling is an image-processing scheme used to identify connectivity between pixels and label every individual cluster of



Fig. 7. Description of erosion process

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pixels. The results are also shown in Fig. 8, where different brightness indicates different clusters.

In the final process, the pixels eroded at the previous step are attributed to the neighboring cluster (Fig. 9) such that the original pixel information regarding the grains (white areas in Fig. 6) is restored. Fig. 9(a), obtained after the second erosion, shows that some neighboring grains are mistakenly recognized as a single cluster, while Fig. 9(c), obtained after the seventh erosion, shows that individual grains are mistakenly recognized as consisting of several different clusters. Therefore, the cluster labeling after the fourth erosion [Fig. 9(b)] appears to give the best result.

Fig. 10 shows the resulting grain-size distribution after the fourth erosion. In the figure, the equivalent grain diameter for each irregularly shaped grain is computed as that of a sphere with the same volume. Considering that the grains used in the CT experiment ranged from 0.1 to 0.64 mm in diameter, the result contains many erroneous fine grains that result from image-processing errors. Fig. 11 shows the number of grains with respect to grain size. According to the figure, grains with a diameter of less than 0.03 mm are potentially phantom grains. The generation of these grains might primarily reflect the complexity of



(a) after the 2nd erosion, (b) after the 4th erosion, (c) after the 7th erosion





Fig. 10. Resulting grain-size distribution after fourth erosion



Fig. 11. Frequency distribution of measured grain diameter

grain shapes within the FJS-1 sample. Grains that contain necks or locally thin portions may become separated during the erosion process and erroneously recognized as several small independent grains. Furthermore, highly irregular grain surfaces lead to the generation of artifacts within the X-ray CT imaging technique itself. These artifacts lead to imaginary thin structures near the grain surface, resulting in the observed grain detection errors.

Considering the above, we neglect the imaginary fine grains smaller than 0.03 mm and finally obtain 3D shape information for about 400 FJS-1 grains. From this point, performing a shape analysis on these grains is straightforward. Fig. 12 shows the classic Zingg diagram (Zingg 1935) that categorizes grain shapes into blades, disks, rods, and equidimensional shapes based on the elongation ratio (b/a) and flatness ratio (c/b), where *a*, *b*, and *c* are the long, intermediate, and short axes of the best-fit ellipsoids, respectively. The averages and standard deviations of b/a and c/bare listed in Table 1. The 3D shapes of selected FJS-1 grains, as determined by CT analysis, are shown in Fig. 13.



Fig. 12. Zingg diagram showing grain-shape properties of FJS-1

 Table 1. Statistical Information on Shapes of FJS-1 Grains

	Average	Standard deviation
Elongation ratio $(b/a)$	0.723	0.132
Flatness ratio $(c/b)$	0.694	0.143



Fig. 13. Examples of 3D shapes of FJS-1 grains obtained from CT image

# **DEM Modeling**

This section describes image-based modeling of FJS-1 using a DEM simulation. The proposed modeling method describes arbitrary irregular grain shapes using a certain number of primitive elements (circular elements for 2D modeling and spherical elements for 3D modeling), mutually connected in a rigid way. Given that these types of primitive elements only require the most simple contact-detection algorithm, a discrete element simulation undertaken using these grains has high computational performance.

The key feature of the proposed method is that the sizes and locations of the primitive elements are automatically computed to ensure optimal model accuracy. The algorithm is based on a virtual time-marching scheme in which a kind of virtual attraction is assumed between each surface point of a target irregularly shaped grain and the element closest to the point. As a result of this attraction, elements tend to move to reduce the distance from the surface point, and an optimized converged solution is obtained after a sufficient number of calculation steps. A detailed explanation of this method can be found in Matsushima and Saomoto (2002). Fig. 14 shows the resulting 3D models corresponding to the grains shown in Fig. 13, each of which is composed of ten spheres. Fig. 15 shows models of a selected grain constructed using different numbers of primitive elements. All three models appear to provide a reasonable reproduction of the grain.

To evaluate the accuracy of the model, we introduce the following surface error index:

$$E_{S} = \frac{1}{NR_{\text{eq}}} \sum_{j=1}^{N} \left| \overline{d}^{j} - \overline{r}^{j} \right| \tag{1}$$

where N=number of surface points on the target grain;  $R_{eq}$ =radius of the circle whose volume is equivalent to that of the target grain;  $d^{j}$ =distance between the *j*th surface point and the centroid of the element representing the surface point; and  $\vec{r}^{j}$ =radius of the element. According to the above definition,  $E_{s}$  indicates the average distance between the original grain surface



and that of the modeled grain, normalized by the average grain radius. Fig. 16 shows the distribution of  $E_S$  for the ten-element models for 300 FJS-1 grains. The average  $E_S$  value is about 0.059, which means that the average error of the model is equal to 5.9% of the grain radius. Fig. 17 shows the average surface error index for models with different numbers of elements. It is clear that the modeling accuracy increases with increasing number of elements.

#### **DEM Simulation**

This section presents the results of a series of DEM simulations on particle flow and the resulting slope angle at rest, as undertaken using the FJS-1 granular model. DEM is a simulation method of frictional granular assembly, first proposed by Cundall (1971) and Cundall and Strack (1979), in which grain-to-grain interaction is modeled using a spring-dashpot-slider system. The 3D DEM program used in this study was developed by Matsushima (2004), and allows the combination of a certain number of spherical elements in a rigid way to describe an irregularly shaped grain. Therefore, judgments regarding contacts and the calculation of contact forces in the program are performed for each spherical element, while the equation of motion is solved for each grain (cluster of spheres). Given that the grains are no longer simply spheres, it is necessary to treat the moment of inertia as a tensor. Therefore, the three principal values of the



Fig. 14. Examples of modeled grains consisting of ten spheres each



Fig. 15. Example of grain modeling using different numbers of elements



Fig. 17. Accuracy of modeling result

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#### Table 2. Flowchart of DEM Program Used in Present Paper

<ul><li>(2) Input data-file reading</li><li>(3) Loop for calculation steps</li></ul>
(3) Loop for calculation steps
· · · · ·
(4) Set the contact-judgment box
(5) Loop for each spherical element
(6) Loop for neighboring elements
(7) Contact judgment: if not, go to (9)
(8) Calculation of reaction force
(9) Next neighboring element: go to (6)
(10) Next element: go to (5)
(11) Loop for each grain (cluster of spherical elements)
(12) Sum up the reaction forces
(13) Solve the equation of motion and rotation and obtain the next position of its gravity center
(14) compute the positions of each constituent spherical element
(15) Next grain: go to (11)
(16) Output
(17) Next calculation step: go to (3)
(18) End

tensor in the program and their orientations for each grain are computed at the start of the simulation, and their rotations are calculated according to Euler's equation of rotational motion. It should be noted that this equation is nonlinear and has to be solved in an iterative way.

Sliding along grain-to-grain contacts occurs when the tangential contact force exceeds the normal force multiplied by the interparticle friction coefficient, as used in the usual DEM code. The study design does not allow for grain breakage (detachment of connected spheres). The flowchart followed by the program is shown in Table 2.

The typical DEM parameters used in this study are listed in Table 3. There is currently no systematic way to determine these parameters for natural granular materials, mainly because their grain properties (for example, grain size, shape, crushability) are complex and have a profound effect upon the bulk mechanical properties. For example, the spring constants at a point contact between two spherical grains are related to the stiffness of the grains, which can be ideally derived from the Hertz–Mindlin theory (Johnson 1985); however, in natural granular materials this relationship is affected by the surface roughness at the contact, and this cannot be physically defined. Therefore, these parameters have to eventually tune up to the bulk behavior of the target granular material. The results of such a parametric study are described in the last part of this section.

A total of 600 FJS-1 grains (duplicates of the original 300 grains) were placed within the gravitational field on the earth to make an initial rectangular specimen with dimensions of about 1.3 mm high by 1.0 mm wide and 0.2 mm deep (Fig. 18).

Table 3. D	DEM Para	meters Use	d in	Present	Study
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Density of grain (g/cm <sup>2</sup> )	2.7
Spring constant (normal) (g/s <sup>2</sup> )	1.0e4
Spring constant (shear) $(g/s^2)$	2.5e3
Damping coefficient (normal) (g/s)	1.0e - 2
Damping coefficient (shear) (g/s)	0.5e - 2
Interparticle friction angle $(\phi_{\mu})$ (deg)	27°
Time increment (s)	1.0e-6



Fig. 18. Initial configuration of modeling specimen

Smooth, flat plates were set at the bottom and on both sides of the specimen, while a periodic boundary was assumed at the front and back of the specimen. After fixing a certain number of lower grains to the bottom plate, the right-hand side plate was removed to allow granular flow arising from gravitational force. Fig. 19 shows snapshots of the flow. A final stable condition was obtained at time t=0.2 s. The small number of grains means that the final slope surface is uneven, making it difficult to rigorously determine the slope angle; therefore, we estimated the angle as the height of the slope divided by the width.

Fig. 20 shows the final slope configurations obtained using different models. A clearly smaller slope angle is obtained from the one-element model (sphere packing) relative to the other



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models. This finding implies that the assembly of spheres leads to different bulk properties in contrast to those obtained using nonspherical grains.

Fig. 21 shows the experimental results obtained using FJS-1



(a) initial condition (FJS-1)



(b) FJS-1



(c) glass beads (spherical)

Fig. 21. Photographs of experimental results



Fig. 22. Effect of modeling accuracy on obtained slope angle

and spherical glass beads. The FJS-1 sample was screened to produce the same grain-size range as that in the simulation (0.1-0.64 mm). In the experiment, the material was loosely deposited in a rectangular shape [Fig. 21(a)], and the right-side aluminum plate was removed to enable measurement of the resulting slope angle at rest, as in the simulations [Figs. 21(b and c)]. Flow of the lower grains was restricted by a ridge at the edge of the bottom plate. In contrast to the simulation result, the final obtained slopes are extremely even, and we can easily determine the slope angle. To assess the effect of specimen size, we performed several experiments with different specimen widths (from 5 to 30 mm). The resulting slope angles show little variation within this range.

Fig. 22 shows a comparison of the slope angles obtained from the simulations and the experiments. The slope angle obtained for the one-element model is similar to that obtained for the spherical glass beads. The numerical result converges to the experimental value with increasing number of elements; even the two-element model provides a reasonable result. However, in terms of the initial void ratio of the specimen (Fig. 23), the two-element model records a much smaller value than the ten-element model. It is well known that elliptical particles are more easily compacted than circular particles (Rothenburg and Bathurst 1992; Matsushima and Konagai 2001), and it is natural to consider that the two-element model will exhibit behavior similar to the ellipsoid model. In contrast, natural grains with irregular shapes record



Fig. 23. Effect of model type (number of elements per grain) on initial void ratio

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much higher maximum void ratios than spheres (Rowe 1962). Therefore, the relation between the bulk density and bulk shear strength in the two-element model should be quite different from that in the ten-element model.

Please note that the computed void ratio in Fig. 23 is affected by the wall due to the insufficient number of grains used in the simulation; this results in a rather large void ratio in the tenelement model compared to an experimental value.

Figs. 24–26 show the effect of contact stiffness, the restitution coefficient, and interparticle friction angle, respectively, on the final slope angle for the one- and ten-element models. The restitution coefficient,  $e_b$ , is computed from the following equation:

$$e_b = \exp\left(-\frac{h}{\sqrt{1-h^2}}\pi\right), \quad h = \frac{c_n}{2\sqrt{k_n \cdot m}} \tag{2}$$

where m=gain mass; and  $k_n$  and  $c_n=$ contact spring coefficient and the damping coefficient in the direction normal to the contact plane, respectively. It is clear that contact stiffness and the restitution coefficient have a relatively minor effect upon the resulting slope angle, while the interparticle friction angle has an effect when it is less than 15°.

According to the results of previous studies on the interparticle friction angle (Horn and Deere 1962; Rowe 1962; Mogami 1969), the interparticle friction angle of glass beads is around  $17^{\circ}$ , while that of natural sand is around  $23-26^{\circ}$ ; therefore, it is reasonable to set the angle higher than  $15^{\circ}$ . It is also a significant result that the slope angle shows no increase in this range, even with a higher





50 45 10-elements model 40 slope angle (deg) 35 1-element model 30 25 20 15 10 0 10 20 30 40 inter-particle frictional angle(deg) Fig. 26. Effect of interparticle friction on slope angle

interparticle friction angle; this finding implies that grain rotation is the predominant mechanism in terms of determining the slope angle. Previous studies have also discussed the importance of grain rotation in terms of the shear strength of granular assembly (Oda and Kazama 1998; Matsushima et al. 2003b).

Finally, Fig. 27 shows the final slope configurations with larger numbers of grains (3,000). The slope appears more even than the result obtained with 600 grains (Fig. 20). The resulting slope angles ( $28.3^{\circ}$  for the one-element model and  $39.8^{\circ}$  for the ten-elements model) are not too dissimilar to those obtained with 600 grains (Fig. 22), and are very similar to the experimental values obtained for spherical glass beads ( $28.6^{\circ}$ ) and FJS-1 ( $40.1^{\circ}$ ), respectively.



(a) 1-element model (3000 grains)



(b) 10-element model (3000 grains)

**Fig. 27.** Final slope configurations obtained using larger number of grains

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## Conclusions

This paper attempted to characterize the 3D shape of the lunar soil simulant FJS-1 and perform an image-based DEM simulation of the simulant soil. The irregular 3D shape of grains within FJS-1 was successfully obtained using micro-X-ray CT visualization combined with a proposed image-processing technique. An efficient DEM modeling method for irregularly shaped grains was then applied to produce different FJS-1 DEM models with varying degrees of accuracy. We then successfully used these models to perform a series of particle flow simulations. The resulting slope angles obtained for the most accurate models are in quantitative agreement with the experimental results. The one-element model (spherical assembly) shows bulk properties different from the to nonspherical assembly. We also considered the effect of other DEM parameters such as contact stiffness, restitution coefficient, and interparticle friction angle. The slope angle is unaffected by the magnitude of contact stiffness and the restitution coefficient. The interparticle friction angle is sensitive to the slope angle only if the interparticle friction angle is less than 15°.

As the next step, it is important to study the effect of the fine content of the material on the bulk mechanical properties, although the mechanics of well-graded granular assembly is not yet fully understood. The incorporation of electrostatic force into a DEM model is another task that remains to be accomplished.

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# References

- Bonse, U., and Busch, F. (1996). "X-ray computed microtomography (μCT) using synchrotron radiation (SR)." *Prog. Biophys. Mol. Biol.*, 65, 133–169.
- Cook, B. K., and Jensen, R. P., eds. (2002). Proc., Discrete Element Methods: Numerical Modeling of Discontinua, ASCE, Reston, Va.
- Cundall, P. A. (1971). "A computer model for simulating progressive, large-scale movements in blocky rock systems." *Proc., Symp. ISRM*, Nancy, France, Vol. 2, 129–136.
- Cundall, P. A., and Strack, O. D. L. (1979). "A discrete model for granular assemblies." *Geotechnique*, 29(1), 47–65.
- Heiken, G. H., Vaniman, D. T., and French, B. M., eds. (1991). Lunar sourcebook, Cambridge University Press, Cambridge, U.K.
- Horn, H. M., and Deere, D. U. (1962). "Friction characteristics of minerals." *Geotechnique*, 12, 319–335.
- Hoshen, J., and Kopelman, R. (1976). "Percolation and cluster distribution. I. Cluster multiple labeling technique and critical concentration algorithm." *Phys. Rev. B*, 14(8), 3438–3445.
- Johnson, K. L. (1985). Contact mechanics, Cambridge University Press, Cambridge, U.K.
- Kanamori, H., Udagawa, S., Yoshida, T., Matsumoto, S., and Takagi, K. (1998). "Properties of lunar soil simulant manufactured in Japan." *Proc., Space'98*, ASCE, Reston, Va., 462–468.

- Malla, R. B., Binienda, W. K., and Maji, A. K., eds. (2006). Proc., Earth and Space 2006, ASCE, Reston, Va.
- Marshall Space Flight Center. (2005). Proc., Lunar Regolith Simulant Materials Workshop, Book of Abstracts, Marshall Institute.
- Matsushima, T. (2004). "3-D image-based discrete element modeling for irregularly-shaped grains." *Numerical Modeling in Micromechanics* via Particle Methods—Proc., 2nd Int. PFC Symp., 28–29 October, Kyoto, Japan, Leiden: A. A. Balkema, 421–427.
- Matsushima, T., and Konagai, K. (2001). "Grain-shape effect on peak strength of granular materials." *Computer Methods and Advances in Geomechanics, Proc., 10IACMAG*, Desai et al., eds., Balkema, Vol. 1, 361–366.
- Matsushima, T., and Saomoto, H. (2002). "Discrete element modeling for irregularly-shaped sand grains." *Proc.*, *NUMGE2002: Numerical Methods in Geotechnical Engineering*, P. Mestat, ed., LCPC, Paris, 239–246.
- Matsushima, T., Saomoto, H., Matsumoto, M., Toda, K., and Yamada, Y. (2003a). "Discrete element simulation of an assembly of irregularlyshaped grains: Quantitative comparison with experiments." *Electric Proc., 16th Engineering Mechanics Conf.*, ASCE, New York.
- Matsushima, T., Saomoto, H., Tsubokawa, Y., and Yamada, Y. (2003b). "Grain rotation versus continuum rotation during shear deformation of granular assembly." *Soils Found.*, 43(4), 95–106.
- Matsushima, T., Saomoto, H., Uesugi, K., Tsuchiyama, A., and Nakano, T. (2004). "Detection of 3-D irregular grain shape of Toyoura sand at SPring-8." X-Ray CT for Geomaterials: Proc., Int. Workshop on X-ray CT for Geomaterials, Otani and Obara, eds., Balkema, Rotterdam, The Netherlands, 121–126.
- Mogami, T. (1969). Soil mechanics, Gihodo, Tokyo (in Japanese).
- Nakano, T., Nakashima, Y., Nakamura, K., and Ikeda, S. (2000). "Observation and analysis of internal structure of rock using X-ray CT." J. Geol. Soc. Japan, 106(5), 363–378.
- Oda, M., and Kazama, H. (1998). "Microstructure of shear bands and its relation to the mechanisms of dilatancy and failure of dense granular soils." *Geotechnique*, 48(4), 465–481.
- Peña, A. A., Garcia-Rojo, R., and Herrmann, H. J. (2007). "Influence of particle shape on sheared dense granular media." *Granular Matter*, 9, 279–291.
- Rothenburg, L., and Bathurst, R. J. (1992). "Micromechanical features of granular assemblies with planar elliptic particles." *Geotechnique*, 42(1), 79–95.
- Rowe, P. W. (1962). "The stress-dilatancy relations for static equilibrium of an assembly of particles in contact." *Proc. R. Soc. London, Ser. A*, 269, 117–141.
- Shinohara, K., Oida, M., and Golman, B. (2000). "Effect of particle shape on angle of internal friction by triaxial compression test." *Powder Technol.*, 107, 131–136.
- Tsuchiyama, A., Uesugi, K., Nakano, T., and Ikeda, S. (2005). "Quantitative evaluation of attenuation contrast of X-ray computed tomography images using monochromatized beams." *Am. Mineral.*, 90, 132–142.
- Tutumluer, E., Huang, H., Hashash, Y. M. A., and Ghaboussi, J. (2006). "Imaging based discrete element modeling of granular assemblies." *Proc., Multiscale and Functionally Graded Materials Conf. 2006* (FGM2006), Honolulu.
- Uesugi, K., Suzuki, Y., Yagi, N., Tsuchiyama, A., and Nakano, T. (2000). "Development of high spatial resolution X-ray CT system for rocks and mineral samples." *Nucl. Instrum. Methods Phys. Res. A*, 467– 468, 853–856.
- Uesugi, K., Tsuchiyama, A., Nakano, T., Suzuki, Y., Yagi, N., Umetani, K., and Kohmura, Y. (1999). "Development of micro-tomography imaging system for rocks and mineral samples." *Proc. SPIE*, 3772, 214–221.
- Zingg, T. (1935). "Beitrag zur Schotteranalyse." Schweizerische Mineralogische und Petrographische Mitteilungen, 15, 39–140.