Image-Based Modeling of Lunar Soil Simulant for 3-D DEM Simulations

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ABSTRACT
This paper describes an entire procedure to realize an image-based DEM (Discrete Element Method) simulation with lunar soil. Since the detailed grain shape information of the returned sample of the lunar soil is not available, one of its simulants, FJS-1, is used in this study. High resolution micro X-ray CT system at SPring-8, a synchrotron radiation facility in Japan, makes it possible to visualize 3-D image of FJS-1 granular assembly in details. Then a newly developed image analysis procedure is adopted to identify each individual grain from the others. Using the obtained grain shape data, a sufficient number of FJS-1 grains are directly modeled for DEM simulation. A preliminary simulation is performed using these FJS-1 DEM grains and its performance is discussed.

INTRODUCTION
Lunar exploitation requires a full understanding of physical and chemical properties of lunar soil. Although a comprehensive report for Lunar soil properties is available now (Heiken et al. 1991), it is still necessary to conduct various additional tests in every detailed exploitation process. Since the amount of the returned sample of lunar soil is very limited, we usually perform tests with its simulants. However the similarity/difference in physical and chemical behavior between the real lunar soil and the simulants is still a controversial problem. From the mechanical point of view, an overall mechanical behavior of granular materials is greatly affected by their grain properties such as grain size, grain shape, crushability and so on. Among them, the grain shape has a significant influence on bulk physical properties. According to the reference (Heiken et al. 1991), the grain shapes of lunar soil are highly variable, ranging from spherical to extremely angular, but as a general trend, the particles are somewhat elongated and are sub-angular to angular. Some of them have very irregular, often reentrant surfaces. These particle surface irregularities especially affect the compressibility
and shear strength of the soil. Moreover, considering the survey that the relative density of the lunar soil surface is about 74% in 0-30cm deep and 92% in 30-60cm deep, the soil is expected to exhibit very high shear resistance. Therefore, it is quite important to correctly evaluate the grain shape effect in the lunar soil.

Since it is impossible from a practical standpoint to conduct comprehensive experiments with the real lunar soil, particle simulation methods such as Discrete Element Method (DEM) are powerful alternatives to perform various mechanical tests under small gravity in vacuum. However, most of the previous simulations using DEM were performed with circular or spherical particles from a viewpoint of computational efficiency. Recently Matsushima and Saomoto (2002) proposed an image-based modeling method of irregularly-shaped grains and showed its high adaptability into 2-D and 3-D DEM. Following this work, quantitative comparison between the experiment of a natural sand and the corresponding simulation was made successfully by Matsushima et al. (2003) and Matsushima (2004). This paper presents the application of this method into FJS-1, a lunar soil simulant in Japan. A small amount of FJS-1 (but contains sufficient number of grains) is visualized in high quality by micro X-ray CT at SPring-8 (Matsushima et al. 2004), a synchrotron radiation facility in Japan. Then a newly developed image analysis technique enables us to identify each grain from the other in the image of the assembly. Using this grain shape information, a certain number of the simulant grains are directly modeled for DEM simulation. Finally some preliminary simulation is performed to show its performance.

BASIC PROPERTIES OF FJS-1

FJS-1 was produced in Japan (by Shimizu Corporation) by crushing Mt. Fuji basalt and by adjusting particle size to the lunar soil (Shimizu corporation, 1997). Its particle size distribution measured in our laboratory is shown in Figure 1. It contains more than 20% by weight of fine particles (less than 0.074mm in diameter). In order to obtain a clear X-ray CT image, we only use the particle whose diameter is ranging from 0.1 to 0.64mm in this study. Figure 2 shows an example of particle image which is taken by a digital microscope. Their overall shape is very angular and their surface is also very rough, which may cause the shear strength and the angle of repose high.

![Figure 1. Grain size distribution of FJS-1](image1)

![Figure 2. Microphotographs of FJS-1 grains](image2)
MICRO X-RAY CT FOR PARTICLE SHAPE MEASUREMENT

In order to measure 3-D grain shape of FJS-1 we used the Micro x-ray CT at SPring-8, the world's largest third-generation synchrotron radiation facility (Matsushima et al. 2004). Differently from usual medical or industrial x-ray CT device, high flux density x-ray beam at SPring-8 makes very high spatial resolution of X-ray CT possible (Uesugi et al. 1999, Uesugi et al. 2000). The detailed experimental setup is available in the reference (Matsushima et al. 2004). Figure 3 shows an example of cross-sectional CT image of FJS-1 grains put in a cylindrical vessel whose inner diameter is about 0.5mm. Its spatial resolution is 1.0µm. The brightness of each portion (pixel intensity) of this 8-bit image is corresponding to the CT values (the value of linear attenuation coefficient (LAC) of x-ray obtained by CT reconstruction), which directly related to the specific gravity of its constituent minerals. The detailed discussion on the mineral composition is out of scope of this study. From mechanical point of view, the grains contain very few cracks inside the grains, which implies that grain crushing hardly occurs.

IMAGE PROCESSING TO DETECT INDIVIDUAL PARTICLE SHAPE

Our purpose is to obtain 3-D shape information of all individual grains from such CT images. The first process is called ‘binarization’, the process to distinguish the solid grain portion from others (void and vessel). Figure 4 shows the frequency of pixel intensity (0 to 255) of the CT image shown in Figure 3. The curve has a maximal value around 120 in pixel.

Figure 3. An example of CT image

Figure 4. Frequency of pixel intensity

Figure 5. CT Image after binarization

Figure 6. Erosion process
intensity which corresponds to the grain portion (SiO₂). Therefore the threshold pixel intensity was chosen to the minimal intensity value shown in the same figure. The resulting 1-bit image is shown in Figure 5.

Since each grain has contacts with neighboring grains, the next step is to separate one from the others. For this purpose we adopt ‘erosion’ process. Figure 6 shows a 2-D schematic illustration of this process. Actual process is done in 3-D. White pixels represent the solid grains and black pixels signify the voids. In the adopted erosion process any white pixel having at least one neighboring pixel in black (putting ‘*’ in the figure) is changed into black. Therefore the pixels composing the grain edge will be eliminated and the grain becomes smaller (eroded).

Repeating this process several times provides with a condition in which all the grains are completely separated. Figure 7 shows the results of the erosion twice, 4 times and 7 times, respectively.

After the erosion process, we perform ‘cluster labeling’ (Hoshen and Kopelman 1976) to identify each individual grains. The results are also shown in Figure 7 where different color indicates different cluster.

In the final process, the pixels eroded at the previous step are attributed to the neighboring cluster (Figure 8). Figure 8(a), obtained after 2nd erosion, shows that some of the neighboring grains are recognized as a single cluster, while Figure 8(c), obtained after 7th erosion, shows that a single grain is recognized as consisting of several different clusters.

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

Figure 7. Erosion and cluster labeling

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

Figure 8. Clusters after attribution process
Therefore, the cluster labeling after 4th erosion (Figure 8(b)) seems to give the best result.

**Figure 9** shows the resulting grain size distribution after 4th erosion. In the figure the equivalent grain diameter for each grain is computed as that of the sphere having the same volume. Considering that the grains used in CT experiment ranges from 0.1 to 0.64 mm in diameter, the result contains a lot of fine grains coming from the image processing errors.

**Figure 10** shows the number of grains with respect to grain size. According to the figure, the grains whose diameter is less than 0.03 (mm) may not be the ‘real’ grains. Therefore, the following procedure is done without such fine grains.

In this way, we finally obtain the 3-D shape information for 423 FJS-1 grains some of which are shown in **Figure 11**.

**DEM MODELING**

This section describes the image-based modeling of FJS-1 for DEM (Discrete Element Method) simulation. The proposed modeling method describes an arbitrary irregular grain shape with a certain number of primitive elements (circular elements for 2-D modeling and spherical elements for 3-D modeling) mutually connected in a rigid way. Since such primitive elements only require the simplest contact detection algorithm, Discrete Element simulation with these grains keeps high computational performance.

The key feature of the proposed method is that the sizes and the locations of the primitive elements are automatically computed so that the best model accuracy possible is attained. The algorithm is based on a virtual time-marching scheme where 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. The detailed explanation is found in the reference [2]. **Figure 12** shows the resulting 3-D models corresponding to the grains in **Figure 11**, each of which is composed of 10 spheres.
DEM SIMULATION

A DEM simulation with FJS-1 granular model for measuring the angle of repose was performed as a simple example. DEM parameters are listed in Table 1. Stiffness of grains defined by spring constant at contact points is much smaller than that of real grains to make a computation time short. 600 grains were felled into a rectangular domain by the gravitational force in the earth to make an initial condition, whose size is about 1.3mm high, 1.0mm wide and 0.2mm deep (Figure 13). Smooth flat plates are set at the bottom and both sides of the specimen, while periodic boundary is assumed in front and back of the specimen. After fixing a certain number of grains attaching the bottom plate, the plate at the right side is removed to make a granular flow. Figure 14 is snapshots for different time steps. Three periodic units are shown in the figure with a striped pattern of the specimen. Figure 15(a) shows a side view at time t=0.08(s) when a static angle of repose is almost obtained, while Figure 15(b) shows a result with spheres whose DEM parameters (Table 1) and size distribution are exactly same as those of FJS-1. It is clear that the angle of repose of FJS-1 is much bigger than that of spheres purely due to the difference in grain shape.

Table 1 DEM parameters used in this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Density of grain</td>
<td>2.7 (g/cm³)</td>
</tr>
<tr>
<td>Spring constant (normal)</td>
<td>1.0e4 (g/s²)</td>
</tr>
<tr>
<td>Spring constant (shear)</td>
<td>2.5e3 (g/s²)</td>
</tr>
<tr>
<td>Damping coefficient (normal)</td>
<td>1.0e-2 (g/s)</td>
</tr>
<tr>
<td>Damping coefficient (shear)</td>
<td>0.5e-2 (g/s)</td>
</tr>
<tr>
<td>Interparticle friction angle ($\phi_\mu$)</td>
<td>27 (deg)</td>
</tr>
<tr>
<td>Time increment</td>
<td>1.0e-6 (s)</td>
</tr>
</tbody>
</table>

Figure 11. Examples of 3-D shapes of FJS-1 grains obtained from the CT image

Figure 12. Examples of the modeled grains each of which is composed of ten spheres

Figure 13. Initial configuration of the specimen
**Figure 16(a) and (b)** show experimental results for FJS-1 and glass beads, respectively. The diameter of the glass beads ranges from 0.1 to 0.2mm. Although many additional factors including the effect of specimen size, side wall friction and electrostatic force should be taken into account, their angles of repose are in good agreement with those obtained by the simulation.

**CONCLUSIONS**

This paper described the entire procedure to realize an image-based DEM simulation with FJS-1, a simulant of lunar soil. The angle of repose obtained by the simulation is in good agreement with those obtained by the experiment.
agreement with the experimental result, which implies that the proposed modeling method is effective in a quantitative sense. The simulation under the circumstances in the moon is straightforward, which may help to accumulate the information of the lunar soil.

ACKNOWLEDGMENT
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REFERENCES