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Particle Grading Effect on Mechanical Properties of Lunar Soil Simulant FJS-1

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ABSTRACT

This paper presents some mechanical test results of a lunar soil simulant, FJS-1, to clarify the effect of grain size distribution on bulk mechanical properties of lunar surface soil under low confining pressure. The samples used are the original FJS-1 imitating an average grading of lunar soil, two sieved FJS-1 samples, whose grain sizes are less than 0.1mm and from 0.1 to 0.4mm, respectively. First, the maximum and minimum void ratio tests of those samples revealed both pore-filling effect and inter-granular adhesion effect of fines. Next, according to small-scale triaxial compression tests and self-standing height tests, the internal friction angle ranges from 30 to 50 degrees, and the bulk cohesion is about 0-175(Pa) depending on the void ratio, which are consistent with the previous estimation of typical lunar soil. Finally, based on the experimental results, we propose a simple micromechanics model that describes the experimental results in a consistent manner.

INTRODUCTION

Mechanical properties of lunar surface soil have been extensively studied during and after Apollo project, and their comprehensive knowledge was well summarized in Lunar Sourcebook (Heiken et al. 1991). This includes lunar soil grain information such as grading, shape, and mineralogy, and bulk mechanical properties such as densities profiles in depth, average cohesion, internal friction, and compressibility. What is still unclear, however, is the inter-relation among such properties, in particular, the relation between the grain properties and the bulk properties. For instance, the best estimates of the cohesion and the internal friction angle of lunar surface soil (Apollo model) are 0.1 to 1 kPa and 30 to 50 degrees, respectively (Mitchell et al. 1974), that must be the function of grading, grain shape, density (void ratio) and others. Such mechanical information is essential in planetary science research (e.g., understanding of the surface soil evolution process in solid planets) as well as the future lunar exploration and engineering.

Some attempts have been made along this line. Perko et al. (2001) discussed the effect of grain surface cleanliness on bulk cohesion of lunar soil. Walton (2007) summarized the adhesion force of lunar fine soil as an origin of bulk cohesion.

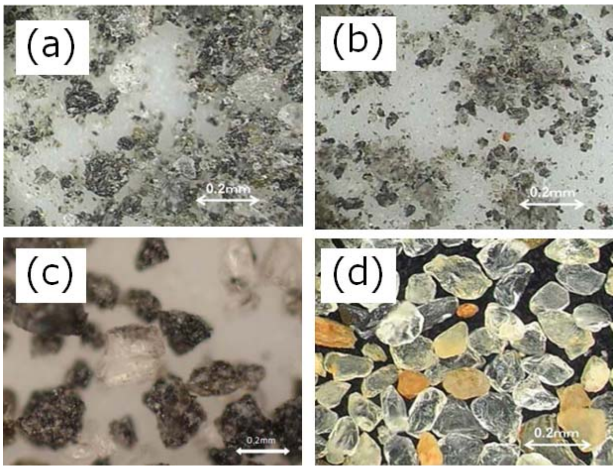
Matsushima et al. (2009) clarified the grain shape effect on the internal friction of lunar soil using Discrete element method (DEM) simulation of lunar soil simulant, FJS-1 (Kanamori et al. 1998). Recently, Katagiri et al. (2010, 2014) applied this technique into real lunar soil (Apollo sample No. 60501) and manifested that the variation of internal friction angle (30 to 50 degrees) is primarily dependent on the relative density, while the void ratio is strongly affected by grain shape. It also turned out the agglutinate content has the primary importance in considering grain shape property. This implies that remote-sensing soil maturity map may be related to soil mechanical properties map.

Their DEM simulations, however, do not consider the fine particles. It is in general difficult to simulate widely dispersed (well-graded) granular systems in DEM because of the limitation of computational cost. Therefore, it is important to understand the effect of fine particles on bulk mechanical properties and to develop a model to describe the effect of fine particles in a simpler manner.

To this end, the present study deals with some experiments using not only the original FJS-1 having the average grading of lunar soil (Heiken et al. 1991), but also two sieved FJS-1 samples to investigate the effect of fines. We performed maximum and minimum void ratio measurement (JSSMFE 1990), small-scale triaxial tests, and self-standing tests. Based on the experimental results, we propose a simple model to describe the particle grading effect on bulk mechanical properties of FJS-1.

MATERIALS USED IN THE EXPERIMENTS

Figure 1 shows the materials used in this study. The original FJS-1 has the similar grain size distribution as the typical lunar soil (Heiken et al. 1991). Two sieved FJS-1, type A and B, whose grain sizes are less than 0.1mm and from 0.1 to 0.4mm, respectively. Their grain size distribution is shown in Figure 2. We also tested Toyoura sand, commonly used in Japanese geotechnical society for comparison. Toyoura sand is a sub-angular sand, having the similar grain size distribution as type B specimen. According to the visual inspection, FJS-1 grains are more angular than Toyoura sand grains.



(a) Original FJS-1, (b) Sieved FJS-1(D<0.1mm)
(c) Sieved FJS-1 (0.1<D<0.4mm), (d) Toyoura sand

Figure 1. Microscope photos of the materials

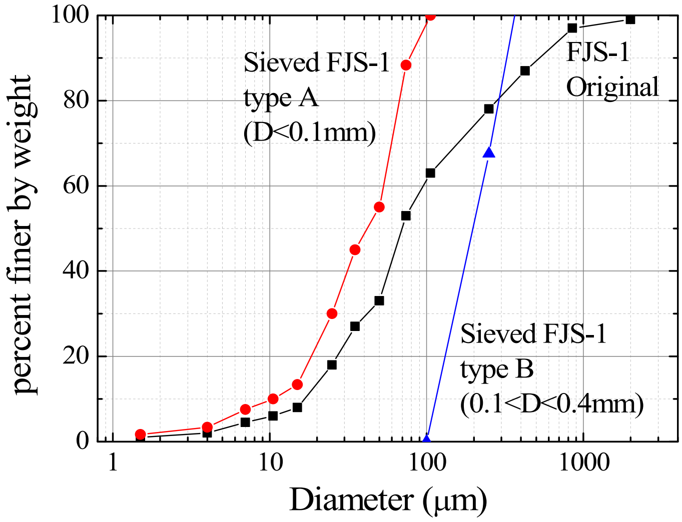


Figure 2. Grain size distribution

MAXIMUM AND MINIMUM VOID RATIOS

Maximum and minimum void ratios, $e_{\max}$ and $e_{\min}$, respectively, were measured according to the testing protocol JSF T161-1990 (JSSMFE 1990). The results are summarized in Figure 3. The figure also includes the result obtained in Ueda et al. (2010) and Apollo model (Houston et al. 1974, Mitchell et al. 1974). The comparison among the original and sieved FJS-1 specimens indicates two effects; the pore-filling effect of well-graded granular material (Yerazunis et al. 1962, Ueda et al. 2010) and the effect of inter-granular adhesion of fines (Walton, 2007). The former causes the reduction of the void ratios because relatively smaller grains fill the pores formed by larger ones. This effect can be predominantly seen in the minimum void ratio in the original FJS-1. The latter causes the increase of the void ratios because the inter-

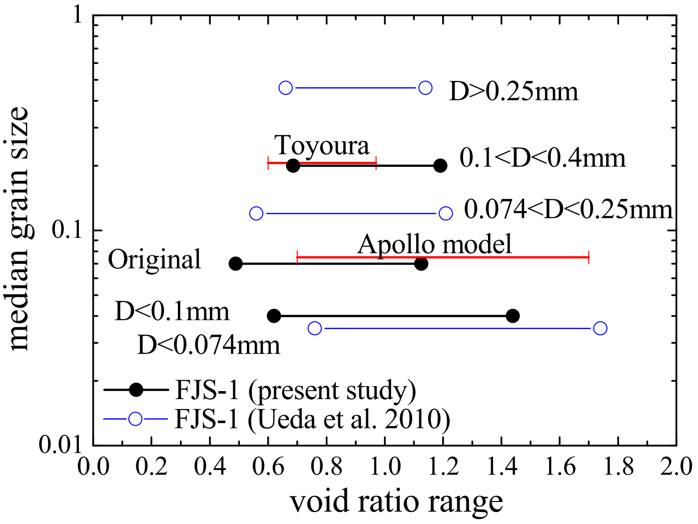


Figure 3. Void ratio range of the materials used

granular adhesion contributes for granular systems to forming larger pores. This effect can be seen clearly in the maximum void ratio in the sieved FJS-1 specimen (D<0.074mm, D is the grain diameter), since the larger amount of fine grains leads to larger pores especially in the loose condition. Note that the inter-granular adhesion is not so large as holding large pores in the specimen under vibration process in the minimum void ratio test.

Compared with Toyoura sand, FJS-1 type B (0.1<D<0.4mm) has larger $e_{\max}$ and $e_{\min}$ primarily because of their more angular grain shape. The reason of the difference between the Apollo model (Heiken et al. 1991) and the original FJS-1 sample is not very clear. One possible reason is the difference in grain shape; the Apollo sample contains certain amount of agglutinate grains having very angular concave shape that causes the increase of void ratio (Katagiri et al. 2010, 2014). Another reason may be the difference in confining pressure in the measurement.

SMALL-SCALE TRIAXIAL COMPRESSION TESTS

In order to perform triaxial compression test under low confining pressure, a small-scale apparatus has been newly developed. The height and the diameter of the specimen is about 10mm and 5mm, respectively, although the basic setup is the same as the conventional triaxial apparatus. Very thin rubber membrane (thickness=0.075mm) is used to avoid the membrane tension effect, and still the tension correction was adopted in the obtained data. Figure 4 shows a snapshot of the experiment where the specimen has been bulged after compression. The results on Toyoura sand sample agree well with those obtained by conventional triaxial test (Ishikawa 2013), which proves the validity of the proposed apparatus.

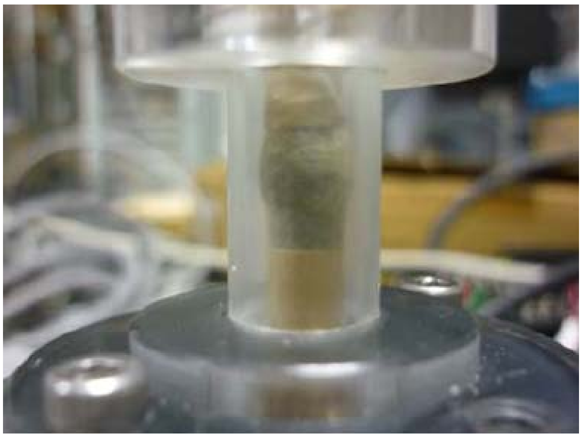


Figure 4. Small-scale triaxial test device

Figure 5 summarizes the relations between the average stress ($p = (\sigma_a + 2\sigma_c)/3$) and the deviatoric stress ($q = \sigma_a - \sigma_c$),where σ_a and σ_c are the axial stress and the lateral confining stress, at the peak state of the original FJS-1 samples for different initial void ratio and confining pressure. It can be seen from the figure that it is difficult to evaluate the bulk cohesion. We also tried some tests under lower confining pressure, but the results did not have sufficient accuracy. According to Heiken et al. (1991), the best estimates of the bulk cohesion of the Apollo model is 0.1 to 1.0 (kPa), which could not be detected in the proposed apparatus.

Figure 6 shows the summary of the internal friction angle, ϕ, with respect to the initial void ratio for the original FJS-1, and the two sieved samples. Most of the plots range from 30 (deg.) to 50 (deg.) in ϕ, which agrees well with the best estimates of the Apollo sample (Heiken et al. 1991). The main difference among the samples are regarded as the difference in the void ratio range observed in Figure 3. This observation is important in the model proposed in the subsequent sections.

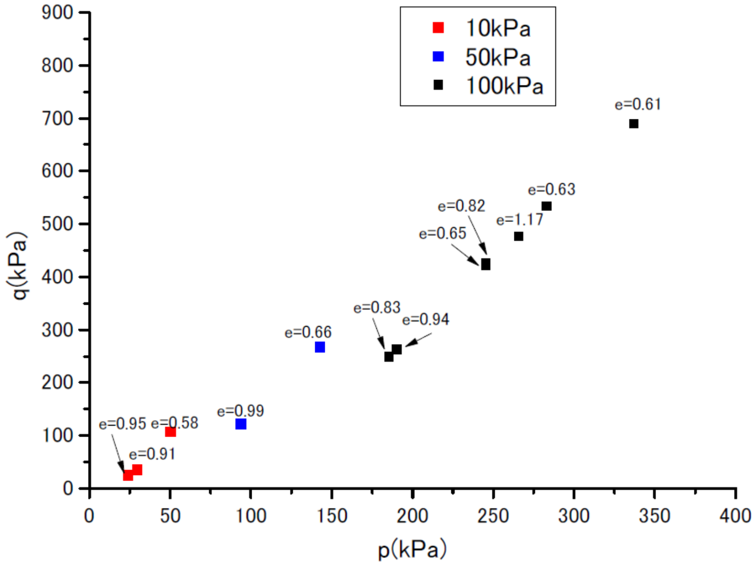


Figure 5. relation between average stress p and the peak deviatoric stress q in the small-scale triaxial tests for the original FJS-1

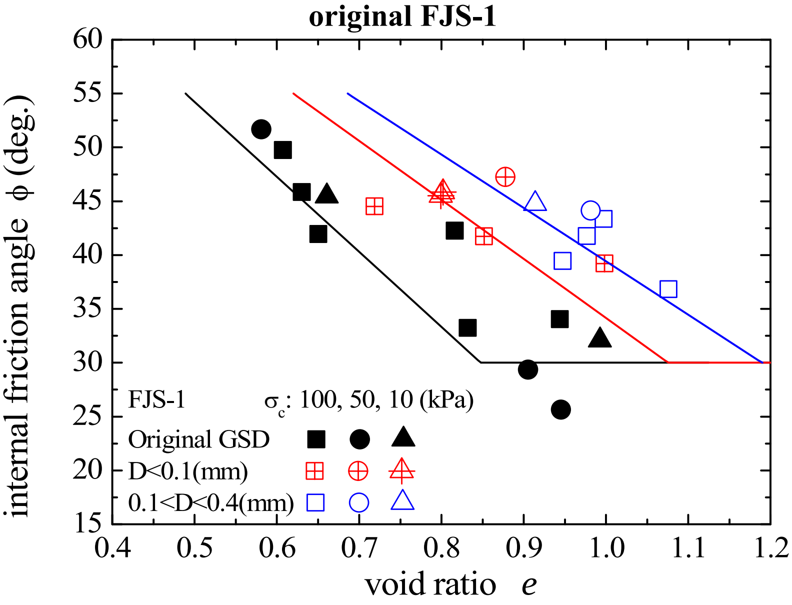


Figure 6. $\phi - e$ relations obtained from triaxial tests

SELF-STANDING TESTS

In order to measure the very small bulk cohesion of FJS-1 samples due to inter-granular adhesion, we performed a series of self-standing tests as shown in Figure 7. A specimen is prepared in an acrylic cylindrical tube for a certain void ratio. Then the bottom plate is pushed up slowly, and the top of the specimen gradually comes out of the tube (Figure 7a). Finally it collapsed (Figure 7b) and the self-standing height is measured by the difference between the original specimen height and height of the remained specimen. Figure 8 shows the result of the original FJS-1 and the sieved one (type A, D<0.1mm). It can be seen clearly that the sieved FJS-1 type A whose average grain size is smaller than the original FJS-1 has larger self-standing height. The other sieved specimen (type B; 0.1<D<0.4mm) did not stand at all because the inter-granular adhesion is too small.

(a) before collapse **(b) after collapse**

Figure 7. Specimens of self-standing test

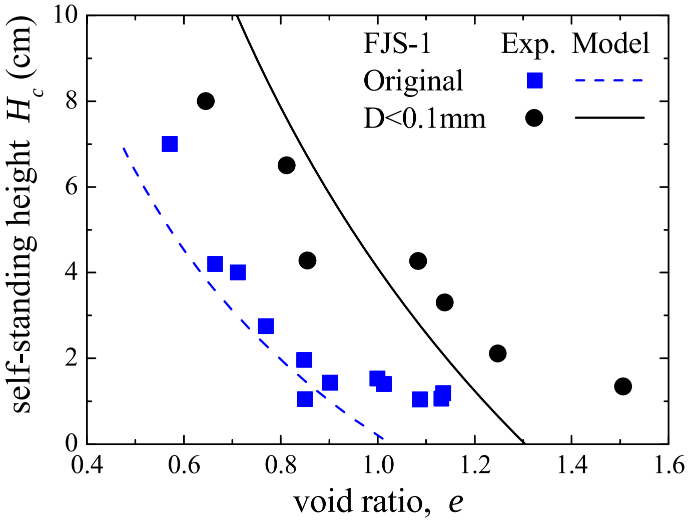


Figure 8. Self-standing height for various specimens

A MICRO-MECHANICAL MODEL

Here we construct a mechanical model that reproduces the aforementioned test results consistently. First, the self-standing height, H_c, is described by the classical Rankine theory of earth pressure as follows:

$$H_c = \frac{4c}{\gamma_t} \tan(45° + \frac{\phi}{2}) \tag{1}$$

where c and ϕ are the bulk cohesion and internal friction angle, respectively, and γ_t is the unit weight of the granular sample, i.e.,

$$\gamma_t = \frac{\rho_S}{e+1} g \tag{2}$$

where ρ_S is the grain density, e is the void ratio, and g is the gravitational acceleration.

Next, ϕ is modeled as a function of relative density, D_r, as follows:

$$\phi = D_r(\phi_{\max} - \phi_{res}) + \phi_{res} \tag{3}$$

The key concept here is that D_r is described not by the measured maximum void ratio, $e_{\max}$, but the corrected one, $e_{\max}'$, to exclude the effect of inter-granular adhesion;

$$D_r = \frac{e_{\max}' - e}{e_{\max}' - e_{\min}} \tag{4}$$

$e_{\max}'$ is computed based on the void ratios in the well-sorted (poorly-graded) sample;

$$\frac{e_{\max}'}{e_{\min}} = \left(\frac{e_{\max}}{e_{\min}} \right)_{well-sorted} \tag{5}$$

Here we assume that the effect of inter-granular adhesion is negligible in the minimum void ratio.

The solid lines in Figure 6 shows the present model, in which we set

$$\phi_{\max} = 55(\text{deg.}), \qquad \phi_{res} = 30(\text{deg.}) \tag{6}$$

and $e_{\max}$ and $e_{\min}$ for the sieved sample of 0.1<D<0.4mm are used as the values of the well-sorted samples. The figure shows that $\phi(e)$ for the original FJS-1 and the sieved sample type A (D<0.1mm) can be well reproduced with the present model.

Regarding the bulk cohesion, we assume that the van der Waals force at a grain contact, f_{vdW}, is the primary source of the inter-granular adhesion (Perko et al. 2001), which yields;

$$c = \frac{f_{vdW} \cdot z_c}{\pi D^2}, \qquad f_{vdW} = \frac{AD}{24h^2} \tag{7}$$

where z_c is the average coordination number (number of contacts per grain), D is the grain diameter, A is the Hamaker constant and h is the substantial spacing between the grain surfaces at the contact.

The average coordination number, z_c, plays an important role in estimating the bulk cohesion from inter-granular adhesion. According to the isostatic theory (Guyon et al. 1990, Ouaguenouni and Roux, 1995, Edwards and Grinev 1999), z_c varies from 4 (rough surface) to 12 (smooth surface) in 3D non-spherical non-cohesive grains. Here we assume that this range linearly corresponds to the loosest and the densest states, which yields

$$\frac{z_c - (z_c)_{\min}}{(z_c)_{\max} - (z_c)_{\min}} = D_r \qquad (z_c)_{\min} = 4,\ \ (z_c)_{\max} = 12 \qquad (8)$$

The equations above together finally provides the relation between the void ratio and the self-standing height for the original FJS-1 and the sieved one (D<0.1mm), which is shown in Figure 8 as the solid lines. The parameters used are listed below:

$$A = 1.0\times 10^{-19}(J),\ \ \rho_S = 2.95(g/cm^3),\ \ h = 1.5(nm) \qquad (9)$$

The value of A comes from the data for mica-air-mica interaction (Israelachvili, 1991). ρ_S is the measured FJS-1 grain density (Ueda et al. 2010). Inter-granular spacing, h, is important but difficult value to be determined. It is affected by the surface roughness and cleanliness of the grains (Perko et al. 2001, Walton 2007). The minimum value of h is reported as 0.4(nm) (Walton 2007). In the present study, good quantitative agreement between the measurement and the model prediction is obtained with h=1.5(nm) as shown in Figure 8.

Finally, the computed cohesions in the model are 0 to 100 (Pa) for the original FJS-1 and 0 to 175 (Pa) for the sieved one (D<0.1mm) depending on the void ratio. These values are consistent with the best estimates of the Apollo model (Heiken et al. 1991).

CONCLUSIONS

We performed the maximum and minimum void ratio tests, the small-scale triaxial tests and the self-standing height tests for the original FJS-1, the lunar soil simulant, and two sieved samples. The obtained bulk cohesions and internal friction angles are consistent with the Apollo model (Heiken et al. 1991). More importantly, the present study revealed the effect of grain size distribution, which was regarded as two different effects; the pore-filling effect and the inter-granular adhesion effect of fines. We proposed the simple micro-mechanics model based on these effects, which reproduced the experimental results in a consistent manner.

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