JASMAC
Conference of the Japan Society of Microgravity Application

OR3-1

微小重力環境下での砂質土の流動特性の個別要素法解析
Discrete Element Method Analysis of Flow Characteristics of Sandy Soil in Microgravity Environment

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1. Introduction

Future lunar and planetary exploration landing missions, such as ARTEMIS program and Martian Moons Exploration (MMX) Mars Satellite Exploration Program, are expected to involve several operations on soft regolith, including landing and takeoff of landers, locomotion of rovers, ground drilling and excavation, and even installation of observation equipment1) .

However, "the gravity dependence of granular dynamics", which is essential for predicting and evaluating the motion, contact, and deformation behavior of regolith-machine systems, is not fully understood, and the knowledge of related mathematical model groups and their parameter sets remains insufficient. Under these circumstances, parabolic flight tests and drop tower tests have been conducted on the ground to measure the behavior of regolith and other granular bodies under low gravity conditions. However, it is known that the experiments on the ground are limited to a short period of time due to the limit of maintaining the gravity environment, and that rapid gravity transitions affect the initial conditions of granular materials. To solve this problem, the "Investigation of gravity dependence of soft terrain on planetary surfaces (Hourglass Mission)" was conducted in 2020 to investigate the gravity dependence of flow characteristics of various granular materials, such as regolith, and to obtain information that will contribute to future moon/planetary exploration mechines2). In this mission, an artificial gravity generator in Kibo module at International Space Station (ISS) was used to stably generate artificial gravity between 0.063 G ~ 2.0 G for a long period of time, and hourglass-shaped devices containing eight kinds of granular materials under vacuum conditions were used to observe their flow characteristics.

In this study, we aim to reproduce the dynamics of granular bodies in the low gravity environment obtained by the Hourglass mission, with a view to future lunar and planetary exploration missions. In the Hourglass mission, adhesion forces, such as van der Waals forces, which are negligible in Earth's environment, were observed to be dominant in the low-gravity environment. The effects of these forces are expected to vary depending on the type of granular materials and the gravity level. Note that, the effect of adhesive forces is not explicitly considered the ordinary mathematical models for soil-machine system. Based on the above, to estimate the parameter set with respect to gravity dependence of granular material dynamics by using the discrete element method (DEM), this study reproduces the flow behavior of granular materials under low gravity condition and the competitive relationship between the inter-particle adhesion force and gravity.

2. Theory

2.1 Contact force model

In this study, the DEM analysis was conducted using the commercial software package Rocky DEM.

The Hertz-Mindlin model3) was adopted for the contact model, which is important in theDEM. In this model, the normal direction force F_n is expressed by the following equation based on the Hertzian spring-dashpot contact model.

$$F_n = \widehat{K}_H s_n^{\frac{3}{2}} + \hat{C}_H s_n^{\frac{1}{4}} \dot{s}_n \tag{1}$$

where $\widehat{K}_H$ is the elastic modulus, $\hat{C}_H$ is the damping coefficient, s_n is the contact volume, and $\dot{s}_n$ is the time derivative of the contact volume. Meanwhile, the tangential force F_τ is expressed by the following equation based on the Mindlin-Deresiewicz modell3).

$$F_\tau = -\mu F_n \left(1 - \zeta^{\frac{3}{2}}\right) \frac{s_\tau}{|s_\tau|} + \eta_\tau \sqrt{\frac{6\mu m^* F_n}{s_{\tau,max}}} \zeta^{\frac{1}{4}} \dot{s}_\tau \tag{2}$$

$$\zeta = 1 - \frac{\min\left(|s_\tau|, s_{\tau,max}\right)}{s_{\tau,max}} \tag{3}$$

where $\boldsymbol{\mu}$ is the coefficient of friction. The static coefficient of friction $\boldsymbol{\mu_s}$ is used for $\boldsymbol{\mu}$ when there is no sliding between two contacting objects, while the dynamic coefficient of friction $\boldsymbol{\mu_d}$ is used for $\boldsymbol{\mu}$ when sliding occurs. $\boldsymbol{s_\tau}$ is the tangential relative displacement, $\dot{\boldsymbol{s}}_{\boldsymbol{\tau}}$ is the time derivative of the tangential relative displacement, and $\boldsymbol{s_{\tau,max}}$ is the maximum tangential relative displacement when sliding occurs.

2.2 Rolling resistance model

Since spherical particles were used in this study, the effects of particle shape and surface irregularities were considered by the rolling resistance model. Here, Type C: linear spring rolling limit model3) was adopted in this study. The rolling resistance moment M_r^t in this model is obtained by the following equation.

$$M_r^t = min\left(\left|M_{r,e}^t\right|, M_{r,lim}\right) \frac{M_{r,e}^t}{\left|M_{r,e}^t\right|} \tag{4}$$

where $\boldsymbol{M_{r,e}^t}$ is the rolling resistance moment if the rolling resistance were purely elastic.

2.3 Adhesive force model

In this study, in addition to gravity and contact force, adhesion forces were considered. Note that, the influence of electrostatic forces was neglected, and only van der Waals forces were considered. Specifically, we used the van der Waals force model based on Hamaker's (1937) model. The details of the model are described below.

In the van der Waals force model, the magnitude of the adhesion force varies with the distance between two objects, i.e.

$$F_{n,adh}(r) = \begin{cases} -\dfrac{AD_1D_2}{12(D_1 + D_2)d^2} & \text{particle} - \text{particle} \\ -\dfrac{AD}{12d^2} & \text{particle} - \text{boundary} \end{cases} \tag{5}$$

where $F_{n,adh}(r)$ is the van der Waals force, A is the Hamaker constant, D_i is the diameter of each particle in contact, and d is the particle surface distance. To reproduce the results of the Hourglass mission, three parameters need to be set: Hamaker constant, Adhesive Distance, and Minimum Distance Ratio. The Hamaker constant was set to 15×10^{-20} J by referring to the Hamaker constant for oxides[4)], since silica sand, which is mainly composed of quartz (SiO2), is the target of the analysis, as described below. Adhesive Distance is the maximum distance between two objects at which van der Waals force acts, and was fixed at 1×10^{-5} m, which is about one-tenth of the particle size. Minimum Distance Ratio ($= f_{min}$) is the parameter used when calculating the particle surface distance d, and is defined by the following equation to avoid that the Van Der Waals force becomes infinite when d approaches zero.

$$F_{n,adh}(r) = df_{min}\, max(R_1, R_2) \tag{6}$$

In this study, we adjusted the van der Waals force parameters by varying the value of the f_{min}.

3. Discrete Element Method analysis

3.1 Granular materials

In this study, DEM analyses were performed for silica sand #5 and #8. Observations by the Hourglass mission showed that the silica sand #5 flowed even in microgravity condition, whereas silica sand #8 did not flow completely at 0.063 G and remained deposited on the slope. To reproduce this result, we assumed the relationship between gravity and van der Waals force acting on sand particles as shown in Figure 1. The black lines represent the gravity, for gravity levels of 0.063G and 1.0G, respectively. The red line is the maximum value of van der Waals force between particles, corresponding to the case where the Minimum Distance Ratio in equation (6) is 6 nm. The grey area in graphs show the range of the size distribution of silica sand #5 and #8. For silica sand #5, which has a large grain size, gravity is greater than van der Waals force, even under the gravity of 0.063G, and the sand in the hourglass can flow. On the other hand, in silica sand #8, the influence of van der Waals force becomes dominant at 0.063G.

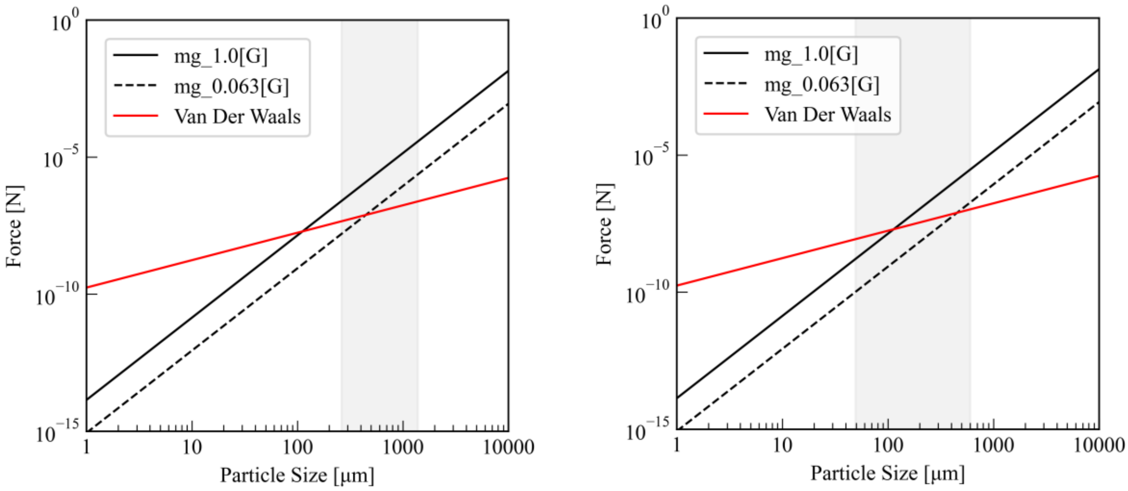

Figure 1. Competitive relationship between gravity and adhesive force against sand particle size of silica sand #5 (left) and silica sand #8 (right).

3.2 Analysis conditions

Figure 2 shows the model used in the DEM analysis. Here, the dimension of hourglass is the same as apparatus used in in the experiment of Hourglass mission. The orifice diameter is 5 mm and the hopper angles are 60° and 120°. To reproduce the size distributions of the silica sand #5 and silica sand #8 in the DEM analysis, a histogram of the cumulative mass% for each particle size was created based on sieving interval. The sieving interval corresponds to the cumulative mass distribution data[2]. Particle sizes are generated according to their proportions using the function of Rocky DEM. The amount of mass packed in hourglass is the same as in the experiment.

As in the experiment, the hourglass was flipped 180° under artificial gravity caused by the centrifugal force generated by the orbital rotation. The radius of rotation was set to 117.33 mm as in the experiment, and the magnitude of the artificial gravity was adjusted by the angular velocity of the orbital rotation. The analysis time was set to a sufficient time to obtain a steady state for each artificial gravity, and the flow was verified by flipping 180° for 0.6 s at an arbitrary time.

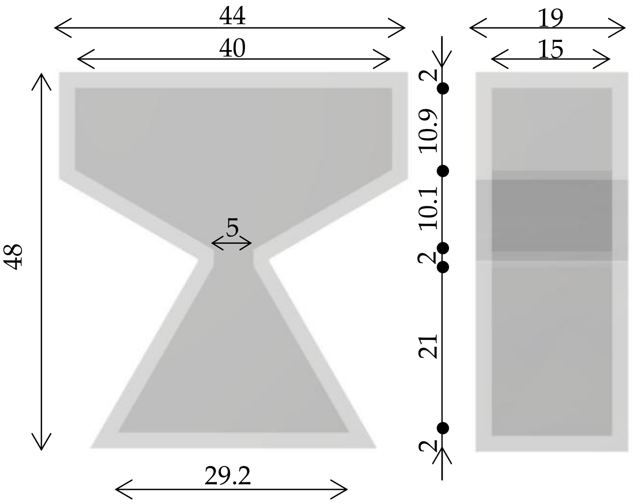

Figure 2. DEM model of hourglass-shaped devise.

3.3 Results

Since the compositions of silica sand #5 and #8 were the almost same, the parameters related to van der Waals forces were assumed to be the same. By the trial and error-comparison with the experimental results, we decided that 6 nm was the optimum value for the Minimum Distance Ratio. Figures 3 and 4 show the comparison of the residual condition of silica sand #5 and silica sand #8, respectively. Here, the artificial gravity conditions are 0.063 G and 1.0 G. In the case of silica sand #5, both the experiment and the DEM analysis reproduced the flow of most of the particles regardless of the gravity level. On the other hand, in silica sand #8, the DEM analysis reproduced the tendency to accumulate on sides and adhere to walls because of the predominant effect of adhesion force, even though the van der Waals force was set at the same value with silica sand #5. The results are also consistent with the experiment, i.e., the lower the gravity, the smaller the effect of gravity, and thus the greater the amount of deposition.

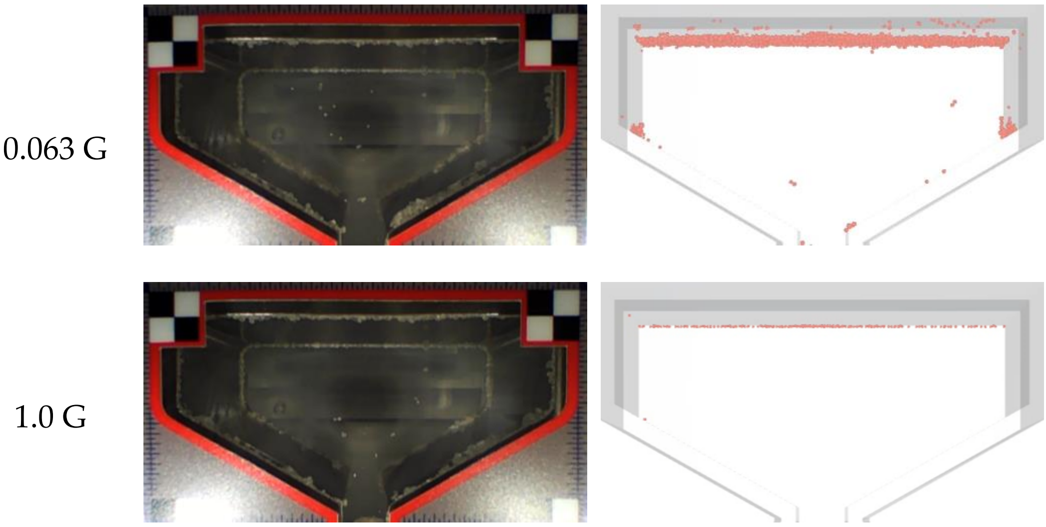

Figure 3. Comparison with experiment t(left) and DEM (right) for silica sand #5.

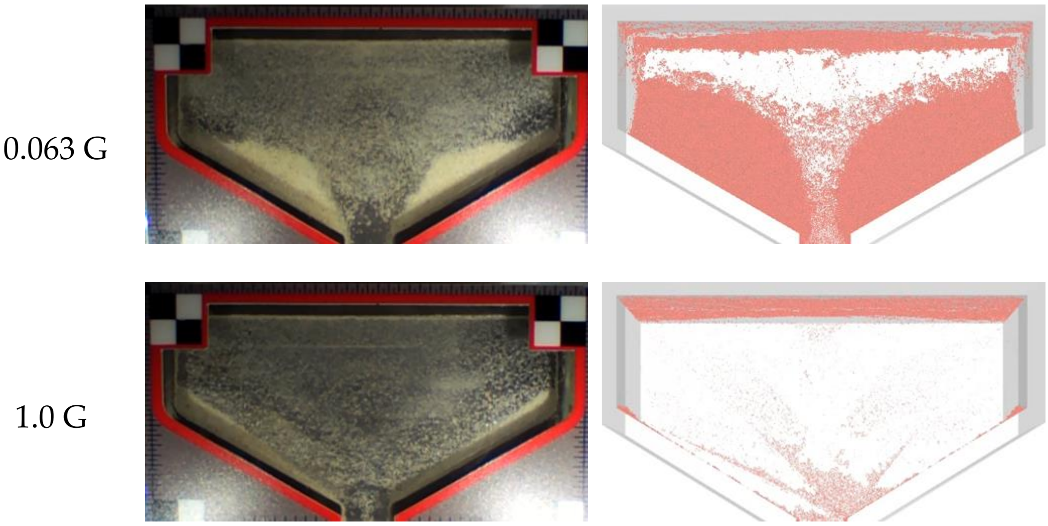

Figure 4. Comparison with experiment (left) and DEM (right) for silica sand #8.

4. Conclusion

In this study, DEM analysis was performed for a sandy soil flow experiment in the Hourglass mission at ISS. In particular, we attempted to reproduce the competitive relationship between gravity and adhesion forces. The results suggest that it is necessary to set appropriate van der Waals forces to investigate the gravity dependence of sand flow characteristics under low gravity condition.

References

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