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Influence of friction on sampling disturbance of lunar surface in direct push sampling method based on DEM

Xingwen Gao [*,1], Dewei Tang [2], Honghao Yue [2], Shengyuan Jiang [2], Zongquan Deng [2]

Harbin Institute of Technology, Harbin 150001, China

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Abstract

The direct push sampling method is one of the most commonly used sampling methods in lunar regolith exploration. However, the disturbance of in situ bedding information during the sampling process has remained an unresolved problem. In this paper, the discrete element method is used to establish a numerical lunar soil simulant basing on the Hertz-Mindlin contact model. The result of simulated triaxial test shows that the macro mechanical parameters of the simulant accurately simulate most known lunar soil samples. The friction coefficient between the simulant and the wall of the sampling tube is also tested and used as the key variable in the following simulation and study. The disturbance phenomenon is evaluated by the displacement of marked layers, and a swirling structure is observed. The changing trend of the friction coefficient on the soil simulant void ratio and stress distribution is also determined.

Keywords: Discrete element method; Sample disturbance; Lunar soil sampling; Direct push sampling method

1. Introduction

The sampling of regolith under the lunar surface is one of the key mission goals of many lunar exploration programs, and the direct push sampling method which is vastly used in geologic detections is also used in lunar regolith sampling. However, the sampling method has an important disadvantage in that the in situ bedding information of lunar regolith can easily be altered during the sampling process. In 1970s, the direct push sampling method was used in the early American Apollo missions. In the Apollo 11, 12, and 14 missions the area ratio was 140%, the diameter was 19.7 mm, and the height was 350 mm. In these three sampling missions, the core recovery was low and the sample was highly disturbed. The Apollo 15 mission increased the sample diameter to 4.13 cm and reduced the area ratio to 7.4%, resulting in a core recovery of approximately 100% with little disturbance. However, the Apollo 15 had a maximum depth of only 70 cm as well as a large diameter and a high sampling rate which only worked in low void ratio lunar conditions (Carrier et al., 1971; Carrier et al., 1972; Allton, 1989). Thus, controlling sampling disturbances on lunar soil has been a difficult problem in engineering implementation.

Since Hvorslev (1949)'s description of the sampling disturbance problem, many scholars have performed research on different aspects of sampling disturbances. For example, Baligh (1985) proposed the application of the strain path method for the estimation of sampling disturbance and calculated the vertical strain path of one point at the centerline of the sampler. Baligh et al. (1987) studied the effect of different structural sizes of the sampler, outside diameter to thickness ratio (B/t) of the sampler tube and shape of

* Corresponding author.
E-mail addresses: gaoxing_hit@163.com (X. Gao), dwtang@hit.edu.cn (D. Tang), block@hit.edu.cn (H. Yue), jiangshy@hit.edu.cn (S. Jiang), dengzq@hit.edu.cn (Z. Deng).
[1] PhD student, Research Center of Aerospace Mechanism and Control.
[2] Professor, Research Center of Aerospace Mechanism and Control.

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cutting edge on the sampling disturbance. The results showed that with a decrease in B/t, the attenuation of soil engineering properties increased gradually, while an increase in B/t did not offset the side effects caused by the blunt end sampler. Handy (1985) used the arch effect theory to calculate the lateral earth pressure coefficient of parallel rigid inter-wall soil, and described the soil arch as the small principal stress trace. Vesic (1972) put forward of cylindrical cavity expansion theory to solve the problem of soil deformation during the pile penetration process. Randolph et al. (1991) established a one-dimensional analysis method of a soil plug under the static loading condition of a pipe string and performed a numerical analysis. Paikowsky (1989) established the sphere in the groove model for describing the shear resistance mechanism between granular media and interface, modified the silo theory by combining it with the soil arching effect, and estimated the characteristics of static plugs. Gao et al. (2006, 2002) carried out an experimental study on the influence of sampling disturbance on the engineering properties of soil, and carried out the finite element simulation of soil strain distribution and the influence on soil disturbance during the soil sampling process. The results showed that the bigger the diameter of the soil sampler was, the smaller the effect on the soil indicators. The above studies all attempted to explain the influence mechanism of sampling tube structures on sampling disturbances by analyzing the force of the soil as well as the deformation. However, these studies considered the soil as a continuous medium, which cannot truly reflect the microscopic changes of the lateral shear processes in soil, including the large displacement of particles where sliding or even separation may occur.

With the development of the discrete element simulation method, it is possible to simulate and observe the soil force and flow at the meso-level (Cundall and Strack, 1979; Zhao et al., 2016). In this paper, the discrete element method is used to set up a numerical lunar soil simulant based on the Hertz-Mindlin interaction model (Hertz, 1881; Mindlin, 1949). The mesoscopic parameters are verified by the numerical simulation of the triaxial test, and the stress state, void ratio which is the volume of voids in soil divided by the volume of solids and structural perturbation of the sample obtained by the direct push sampling method are analyzed.

2. Lunar soil and its discrete element modeling

2.1. Sampling objects

In lunar exploration, the sampling object is sub-surface lunar soil. Compared with earth soil, lunar soil is characterized by a large particle density, good gradation, obvious angularity, high internal friction angle and low cohesion, caused by meteorite impact on the moon, cosmic rays and solar wind bombardment, as well as a huge temperature difference between day and night and the lack of atmosphere (Heiken et al., 1991). According to the results of the physical and mechanical performance test on the lunar soil samples obtained by Apollo, the particle size distribution is 1 mm or less, mainly distributed in the 30–1000 μm interval. The internal friction angle is between 25–50°, and the cohesion is 0.26–1.8 kPa. Among the physical and mechanical properties of lunar soil, the shear strength is the most important factor affecting the sampling process (Carrier et al., 1973a; Carrier et al., 1973b; Mitchell et al., 1972; Chen et al., 2016; Slyuta, 2014). The shear strength of lunar soil is affected by two parameters: the internal friction angle and the cohesive force.

2.2. Contact model

The concept of the discrete element method, derived from molecular dynamics, was proposed by Cundall (1971), and allowed a deeper understanding of the internal microstructure of the granular particles. The particle contact model is the basis of the discrete element method. As shown in Fig. 1, selecting a reasonable particle contact model for the lunar soil with high internal friction angle and low cohesion is the key to simulating the lunar soil sampling process.

The linear spring model uses a linear spring with stiffness k and a dampener with damping c to calculate the normal force between the particles, and the tangential stiffness is proportional to the normal stiffness. The accuracy of the model is rough, and it is suitable for describing the collision between particles. The contact-bond model (Jiang et al., 2007) achieves adhesion by tangential and normal-stiffness springs at a single contacting point between particles, and the shear stress between particles is also achieved by bonding and can provide a certain amount of normal tension. This model is suitable for simulation of soil with a certain viscosity. The Parallel-Bond model (Cundall, 1988) contains a set of constant-stiffness tangential and normal springs that can prevent the rotation of the two particles when they are in contact with each other. This model is suitable for simulating the bonding process of cohesive soil after loading. The Hertz-Mindlin model uses the Hertz theory to describe the normal interaction relationship between particles. Mindlin theory describes the tangential action relationship by adjusting the damping and restitution coefficient to adjust the normal and tangen-

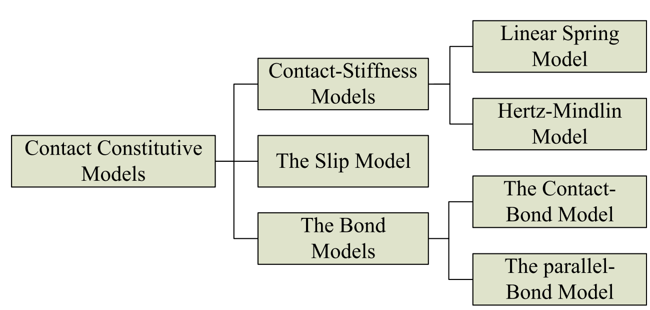

Fig. 1. Classification of contact constitutive models.