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Drilling load modeling and validation based on the filling rate of auger flute in planetary sampling

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Abstract Some type of penetration into a subsurface is required in planetary sampling. Drilling and coring, due to its efficient penetrating and cuttings removal characteristics, has been widely applied in previous sampling missions. Given the complicated mechanical properties of a planetary regolith, suitable drilling parameters should be matched with different drilling formations properly. Otherwise, drilling faults caused by overloads could easily happen. Hence, it is necessary to establish a drilling load model, which is able to reveal the relationships among drilling loads, an auger's structural parameters, soil's mechanical properties, and relevant drilling parameters. A concept for the filling rate of auger flute (FRAF) is proposed to describe drilling conditions. If the FRAF index under one group of drilling parameters is less than 1, this means that the auger flute currently removes cuttings smoothly. Otherwise, the auger will be choked with compressed cuttings. In drilling operations, the drilling loads on the auger mainly come from the conveyance action, while the drilling loads on the drill bit primarily come from the cutting action. Experiments in one typical lunar regolith simulant indicate that the estimated drilling loads based on the FRAF coincide with the test results quite well. Based on this drilling load model, drilling parameters have been optimized.

1. Introduction

As the Earth's closest nature satellite, the Moon completely records the 4.5 billion years evolutionary history of the solar system. Hence, when human beings started extraterrestrial explorations, the Moon definitely was the preferred target.[1,2] The main goal of lunar exploration is to understand the geological evolution of early stars through analyzing the subsurface composition beneath the surface. Compared with other sampling methods, drilling and coring, due to its efficient penetrating and cuttings removal characteristics, has been widely applied to past planetary sampling missions.[3,4]

At present, China is performing a lunar exploration program, namely the Chang'E project, the third phrase of which will use a hollow drill with a coring mechanism to capture the lunar soil and bring it back to the Earth.[5,6] According to reports on the lunar regolith, the lunar surface is largely

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covered by a layer of lunar regolith material. The vertical extension of this regolith layer is estimated to be of the order of several meters.[7] Because mechanical properties of the lunar regolith on different sampling spots or even at different depths on one spot can be quite different, the loads on a drilling device necessary to achieve penetration may often be unpredictable and this fact could seriously affect the stability of drilling. In terrestrial drilling, many types of detecting instruments are commonly used to accurately acquire geological information in order to assist real-time drilling. However, due to the mass and power constraints, such additional instrumentation can often not be implemented in planetary missions. For example, the lunar penetrating radar (LPR) that will be applied on the Chang'E missions, is not accurate enough to obtain the geological information on the lunar surface and near the subsurface that would be required for a safe drilling action.[8] Therefore, to reduce potential risks in penetrating, drilling loads should be monitored online and be reasonably restricted.

In a piercing process, cuttings in the annular region between the coring tube and the auger's outer surface are exerted by the cutting action by the cutting blade and are removed in the upward direction by the action, which is generated from the spiral auger and the borehole.[9] In the cutting and conveyance process described above, the sampling drill suffers reaction forces, generating drilling loads. Research on granular soil's spiral conveyance indicated that the cuttings' removal action affected drilling loads directly.[10] When a drill tool has penetrated to a certain depth, the driving power used for the cutting action becomes stable at some level, while the driving power needed for the conveying action increases dramatically and becomes the main power consumer[11].

To prepare for future Mars exploration, the University of California, Berkeley conducted a large number of experiments in sandstone cuttings under Martian conditions, revealing that an ice sublimation phenomenon generated by heating could effectively alleviate an auger's choking, greatly reducing the penetrating velocity and the drilling power.[12,13] According to the requirements of Chinese lunar exploration missions, the Harbin Institute of Technology analyzed the effects on the coring rate and the rotary torque by a drill tool's mechanical structure parameters and optimized the structural parameters.[14,15] It can be obviously concluded that to a specific sampling drill tool, suitable drilling parameters may efficiently reduce uncertain drilling loads.

Due to the restricted hardware resources on a planetary probe, drilling parameters should be reasonably optimized to reduce the drilling power needed for penetration. Establishing a drilling load model and revealing the relationships between the drilling load and the regolith's mechanical properties, will contribute to optimizing drilling parameters. The failure mode and conveyance state of the lunar regolith under a drill tool's action are theoretically analyzed in this paper. By using the FRAF index to describe the cuttings removal states of the lunar regolith, a drilling load model containing two typical drilling conditions has been established. Experiments in one typical lunar regolith simulant indicate that this drilling load model based on the FRAF coincides well with test results and can be used to optimize drilling parameters. Optimization indices of drilling parameters are analyzed according to the requirements of future lunar exploration. Based on the validated drilling load model, drilling parameters are optimized for application in lunar regolith simulants.

The remainder of this paper is organized as follows. One typical lunar regolith simulant and one potential drill tool are prepared firstly. The filling rate of the auger flute index is employed to describe the drilling conditions for different drilling parameters. The drilling load model established based on the FRAF index is validated for one typical lunar regolith simulant afterward. Finally, drilling parameters are optimized based on this drilling load model.

2. Lunar regolith simulant and drill tool

In many drilling applications, in particular in natural environments such as planetary surfaces, whose structure and layering are not known in advance, drilling loads have highly unpredictable and non-linear characteristics. Before establishing a drilling load model, a large number of drilling experiments should be carried out first for acquiring useful drilling state signals, which can serve as a sound basis for modeling. Both the structural parameters of the auger and the mechanical properties of the lunar regolith are expected to have considerable influences on the drilling performance. Therefore, in order to find an optimized set of drilling parameters suitable for application on a planetary lander mission, these influence factors need to be studied and evaluated in advance.

2.1. Lunar regolith simulant

Lunar regolith is a general term for the layer or mantle of fragmental rock material, formed by frequent meteoritic impacts on the atmosphere.[16] Studies of the returned samples indicate that the lunar regolith mainly contains five basic compositions: rock debris, mineral fragments, breccia, agglutinate, and glass-bonded aggregates.[7,17] The relative proportions of each composition, depending on the mineralogy of source rocks, vary from place to place, and even at different depths on one spot, they may be quite different. In order to verify our drilling load model, the lunar regolith simulant should mimic the mechanical properties of the real lunar regolith as close as possible.

In this paper, HIT-LS1# soil as shown in Fig. 1(a) has been chosen as the sampling material. The main component of HIT-LS1# soil is brown volcanic ash originating from the Jilin Province, China.[6] After the pressing process, the particle size distribution of this simulant varies from 1 μm to 100 μm, which is similar to that of the returned samples from the Apollo 17 landing site.[18] The density of HIT-LS1# soil is about 1.878 g/cm^3. According to the research by Heiken, among all mechanical properties, the shear strength of the lunar regolith, such as cohesion and internal angle, affects the drilling loads directly.[7]As shown in Fig. 1(b), under a repeated triaxial shear test, the shear strength of HIT-LS1# soil is acquired as follows: the average cohesion $c = 45.9$ kPa and the average internal friction angle $\varphi = 48^\circ$. In this paper, the authors just consider the drilling interaction in a homogeneous lunar regolith. To acquire a homogeneous lunar regolith simulant for experimental validation, the lunar regolith simulant was compressed deliberately, which may result in a high cohesion.[19,20]. The drilling experiments will be conducted based on this typical lunar regolith simulant.