STUDY ON THE INFLUENCE OF ROTATION SPEED ON DRILLING PERFORMANCE OF LUNAR SOIL SAMPLING DRILLS

by

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The Moon's complex environment, including low gravity, vacuum, and extreme temperature fluctuations, as well as the unique physical properties of lunar soil, pose significant challenges for deep sampling of lunar soils. A 3-D model of the moon-soil-drilling interaction has been constructed and the smoothed particle hydrodynamics method in the non-linear finite element analysis software ABAQUS was used to examine the effects of four different drilling speeds (8.37 rad/s, 10.47 rad/s, 12.56 rad/s, and 14.66 rad/s) on the drilling performance. The simulation results indicate that as the rotation speed increases, the efficiency of core extraction from the lunar soil improves and the force load on the drill decreases. At a rotation speed of 12.56 rad/s, the transport effect of the lunar soil particles is optimal.

Key words: *lunar exploration, lunar soil coring, drill bit, drilling performance, numerical simulation*

Introduction

As human exploration of the Moon advances, the acquisition of deep lunar soil has emerged as a critical requirement for scientific research, including the extraction of lunar resources. The deep lunar soil not only holds important information about the early geological evolution of the Moon, but is also important for assessing the potential of lunar resources and understanding the formation and evolution of the solar system [1].

In recent years, scientists have conducted extensive research on lunar soil sampling technology. Jiang *et al.* [2] analyzed the influence of lunar soil structure on the drilling process and load fluctuations by combining experimental data with machine-soil interaction. Pang *et al.* [3] through a combination of experiments and simulations, identified critical parameters affecting core extraction efficiency in twist drills operating in shallow lunar soil and subsequently proposed guidelines for optimizing drill design and adaptive drilling techniques. Lai [4] examined the properties of lunar soil profiles and associated drilling loads, and examined

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how factors such as particle composition, rock occurrence, density, and the lunar surface environment affect drilling forces. Shi *et al*. [5] developed a load model for drilling loose lunar soil based on passive earth pressure theory and validated its effectiveness through experimental methods. Liu *et al.* [6] used discrete element method simulations to analyze how drilling parameters influence force dynamics and sample volume during deep lunar soil sampling operations. Tian *et al.* [7] evaluated the impact of drilling design on core recovery efficiency and drilling resistance while optimizing drilling parameters using performance analysis techniques. Khademian *et al.* [8] explored how irregularities in lunar soil particles affect mechanical behavior and performance under different gravitational conditions. Nagaoka *et al.* [9] introduced the counter screw drill technology and presented innovative approaches to increasing drilling efficiency.

In summary, scientists have studied lunar soil sampling patterns and interactions between lunar soil and drilling tools, making remarkable research progress. However, most existing studies focus primarily on sampling lunar soil at the surface or at depth, with relatively few focusing on deep drilling. In addition, a significant part of the current knowledge comes from experiments carried out under Earth's environmental conditions, neglecting the influence of the Moon's low gravity and vacuum on the drilling process. In response to this research gap, this paper establishes a 3-D numerical simulation model to study the interaction between lunar soil and drilling tools under lunar environmental conditions. In particular, it examines how drill bit rotation speed affects deep drilling performance in the complex environment characterized by lunar vacuum and low gravity. The insights gained from this study could prove invaluable for future investigations into deep lunar soil sampling technologies.

Create the finite element simulation analysis model

The material and configuration of the drill are critical to the efficiency of lunar soil core drilling and chip removal. Due to its excellent wear resistance, diamond is an ideal choice for drilling applications [10]. Therefore, the drill selected for this study is a composite diamond drill made by sintering fine diamonds with a hard alloy matrix under extreme ultra-high pressure and high temperature conditions. The geometric model of the drill is shown in fig. 1.

Lunar soil consists of loose mineral particles that form a loose soil structure with weak cohesive forces, where the particles are connected only by small contact forces. Under the lunar microgravity environment, the physical and mechanical properties of lunar soil particles can be considered as a soil medium with both frictional and cohesive properties. Studies have shown [11, 12] that the Mohr-Coulomb model is suitable when the internal friction angle is greater than 22°. The mechanical parameters of the deep lunar soil and the material parameters of the drill selected for this study are listed in tab. 1 [13].

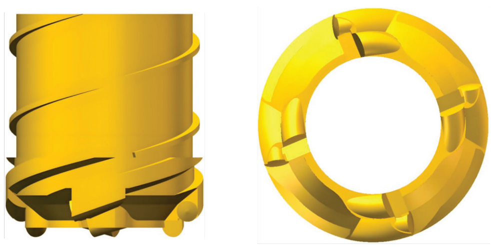

Figure 1. Geometric drill model; (a) front view and (b) top view

Table 1. Mechanical parameters of lunar soil and drill

	Density [kgm^{-3}]	Elastic modulus [MPa]	Poisson's ratio	Friction angle [°]	Cohesion yield stress [Pa]
Lunar soil	1710	10	0.42	51	2400
Drill bit	3500	1E6	0.2	–	–

This study uses the large-scale non-linear finite element analysis software ABAQUS to simulate the complex interactions between the drill bit and the lunar soil, uses the explicit solver for simulation analysis [14, 15], and defines a dynamic analysis step (explicit, general). Since the drilling process involves significant geometric deformations, the large deformation switch is activated during the analysis (Nlgeom = on). A general contact model is defined between the lunar soil and the drill bit, with a coefficient of friction of 0.1 and normal contact specified as hard contact. Since the rigidity of the drill is much greater than that of the lunar soil, it is treated as a rigid body in the analysis. During the drilling process, the drill is only allowed to move along the drilling direction and rotate around the rotation axis, while all other degrees of freedom are completely restricted.

In order to ensure the accuracy and computational efficiency of simulation analysis, the lunar soil model is set as a cylinder with dimensions R80 mm × H30 mm and divided into high quality hexahedral meshes, where the element type is C3D8R and the total number of elements is 123795. Due to the complex geometry of the composite drill, it is meshed with tetrahedral elements, where the element type is C3D4 and the total number of elements is 112072. The drill and lunar soil models after finite element meshing are shown in fig. 2. The analysis assumes that the sides and bottom of the lunar soil remain solid and are not affected by the drilling process. The drill is constrained in all degrees of freedom except rotation around the rotation axis, ω, and feed rate, V_z, as shown in fig. 3.

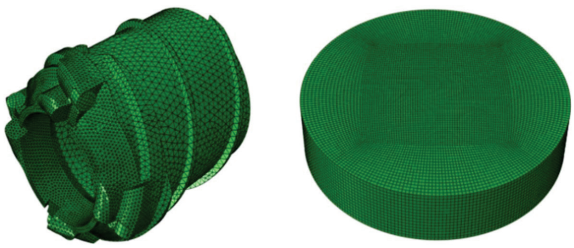

Figure 2. Finite element model mesh of the drill bit and lunar soil

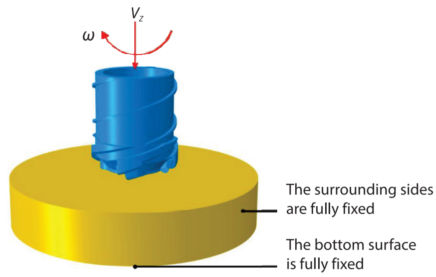

Figure 3. Finite element model of lunar soil-drill bit and boundary conditions

Smoothed particle hydrodynamics (SPH) is a mesh-free numerical technique that represents continuous media by discretized particles and is capable of effectively dealing with the dynamic behavior of granular materials, which is particularly suitable for large deformation problems[16, 17]. To observe the movement of lunar soil particles during the drilling process, this study uses the SPH method of ABAQUS software to simulate the complex contact behavior between the drill bit and the lunar soil.

Results analysis of the finite element simulation

When using rotary drilling techniques for lunar soil, the speed of the drill bit is one of the crucial factors in drilling performance. If the speed is set too high, the drill bit may be subjected to excessive stress, which can lead to structural failure. If the speed is set too low, drilling efficiency and core recovery rate will decrease. To investigate the influence of rotation speed on core recovery efficiency and drilling efficiency of lunar soil, this study assumes a constant feed rate and sets four different rotation speeds (8.37 rad/s, 10.47 rad/s, 12.56 rad/s, and 14.66 rad/s. The analysis extracts results such as drilling displacement, reaction force and reactionrque to determine the influence of rotational speed on lunar soil drilling efficiency.

At the same analysis time of 0.5 seconds, fig. 4 shows that the drilling direction shifts of the lunar soil at four different rotation speeds are 3.201 mm, 3.871 mm, 3.963 mm, and 4.091 mm, respectively. It can be observed that as the rotation speed increases, the displacement of the lunar soil in the drilling depth direction gradually increases, indicating that increasing the rotation speed can improve the drilling efficiency of the lunar soil. When observing the movement of lunar soil particles at a rotation speed of 8.37 rad/s, the edges in the lunar soil are clear and have the least disturbance, but the drilling efficiency is lowest at this speed. At a rotation speed of 12.56 rad/s, the edges inside and outside the lunar soil are clear and the drilling efficiency is relatively high, resulting in the best drilling performance.

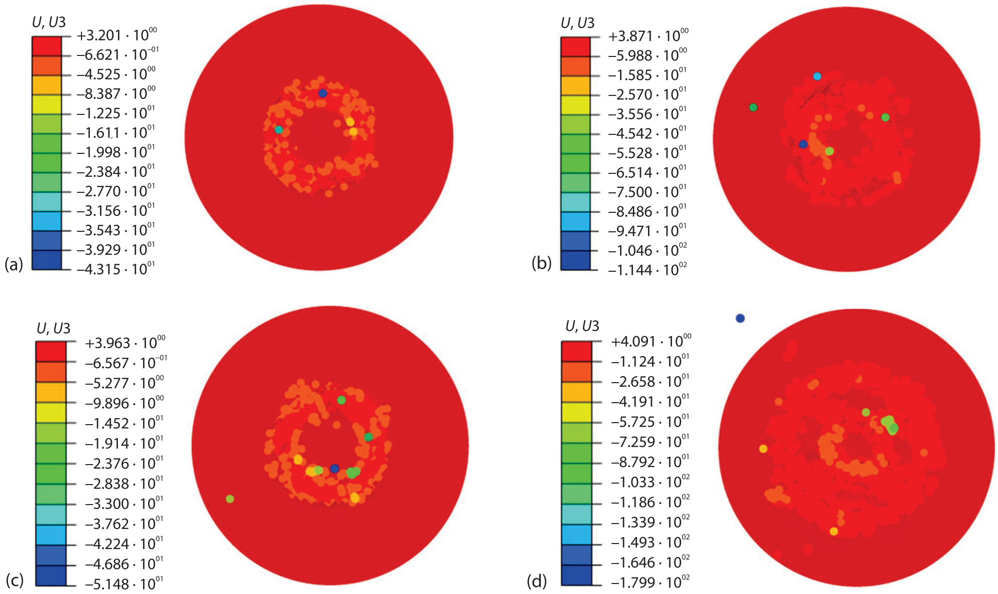

Figure 4. Displacement in the depth direction of lunar soil at different rotation speeds; (a) rotation speed 8.37 rad/s, (b) rotation speed 10.47 rad/s, (c) rotation speed 12.56 rad/s, and (d) rotation speed 14.66rad/s

The extraction and representation of the reaction forces and reaction moments on the drill string under four different simulation conditions as functions of drilling depth are shown in figs. 5 and 6, respectively. It can be seen that as the rotation speed of the drill string increases, both the reaction forces and reaction moments show a decreasing trend. The reason for this is that at higher rotation speeds, the friction force between the drill pipe and the lunar soil decreases, resulting in a reduction in the resistance that the drill pipe must overcome. This not only helps improve the core sampling efficiency of the lunar soil, but also reduces the structural strength requirements of the drill string, making it lighter and more efficient.

Conclusion

To investigate the influence of drill bit rotation speed on the performance of deep lunar soil drilling, this study constructed a 3-D numerical simulation model of lunar soil-drill interaction using the SPH method. Finite element simulations of the deep lunar soil drilling process were carried out under four different conditions. The research results are the higher the rotation speed of the drill bit, the greater the displacement of the lunar soil in the drilling direction, resulting in higher core recovery efficiency. To obtain lunar soil samples with minimal

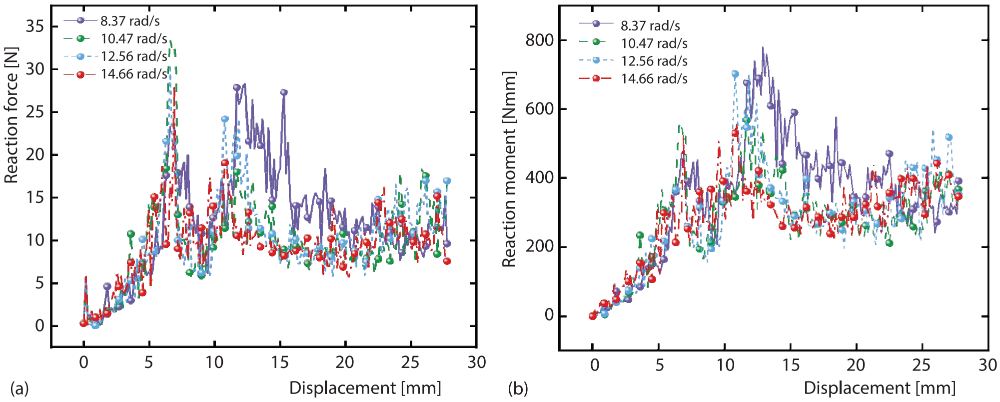

Figure 5. Curves of drill pipe reaction forces and reaction moments at four different speeds as functions of depth; (a) reaction force and (b) reaction moment

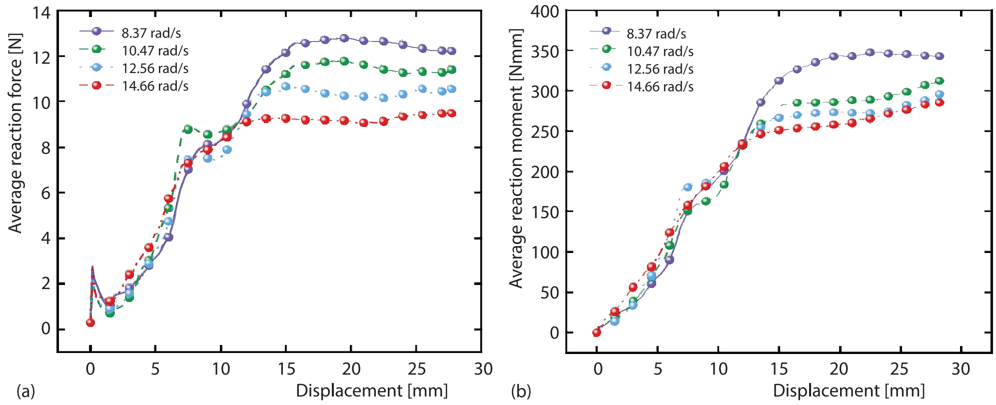

Figure 6. Curves of average drill string reaction forces and average reaction moments at four different rotation speeds as functions of depth; (a) average reaction force and (b) average reaction moment

disturbance and maximum efficiency, the core recovery effect is optimal at a rotation speed of 12.56 rad/s. For the same drilling depth, the reaction forces and reaction moments on the drill pipe are actually smaller at higher speeds, indicating that the force loads on the drill pipe can be reduced by a corresponding increase in speed, which represents a basis for a lightweight construction.

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